NATO Science for Peace and Security Series - C:
Environmental Security

Management of Weather and Climate Risk in the Energy Industry

Edited by
Alberto Troccoli

Springer

NATO OTAN
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Management of Weather and Climate Risk
in the Energy Industry

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Series C: Environmental Security

Management of Weather and Climate Risk in the Energy Industry

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FOREWORD

Meteorological and climate data are indeed essential both in day-to-day energy management and for the definition of production and distribution infrastructures. For instance, the supply of electricity to users can be disturbed by extreme meteorological events such as thunderstorms with unusually strong winds, severe icing, severe cold spells, sea level elevation associated with storm surges, floods …

To be protected against such events, it is not sufficient to act after they have taken place. It is necessary to identify their potential impacts precisely and assess the probability of their occurrence.

This book shows that this can only be done through an enhanced dialogue between the energy community and the climate and meteorology community. This implies an in-depth dialogue between actors to define precisely what kind of data is needed and how it should be used.

Météo-France has been in long-term cooperation with the energy sector, including the fields of electricity production and distribution. Drawing on this experience, it should be noted in this respect the importance of long-term partnership between actors as exemplified here by the message of EDF.

The production of meteorological and climate information relies on an integrated system ranging from field observations to numerical modelling of the atmosphere and the Earth. It is necessary to tailor, insofar as possible, the information produced to the users needs. Unfortunately, these vital climate services are not yet always available for all users. The community of meteorologists is aware of this need. That is why the World Meteorological Organization has decided during the third World Climate Conference (WCC-3) to establish a Global Framework for Climate Services, to ensure that climate information and predictions will be made available to decision-makers enduring the increasing impacts of climate variability and change.

The future Global Framework for Climate Services will contribute to make these services available to all sectors. Some of the key requisites to be developed during the implementation period include the strengthening and sustainability of countries' observational and research capabilities, as well as enhanced capacity-building for developing countries and improved interaction between climate information providers and final users, as initiated by ClimDevAfrica. This decision of improving Climate Services for Development was unanimously adopted at the opening of the WCC-3 High-level Segment, which followed three days of intense discussion among multidisciplinary international experts. I hope this book will also contribute to the capacity building needed for the implementation of those recommendations.

The Global Framework for Climate Services is a necessary step with a view to defining scientifically sound measures of adaptation to climate variability and change. In this view, it will be necessary to improve or implement many observations in the world and to make them easily accessible in a readily utilisable form. It will also be necessary to ensure perfect consistency between modelling results and observations. All these improvements need additional research, improved coordination and standardisation.

The public expects energy security, which means that the vulnerability of energy systems has to be minimized in accordance with the possible hazards impacting the energy systems, in a context of sustainable development. So I take this opportunity to commend the work done by all the experts involved, and to thank NATO for supporting the advanced research workshop which took place in October 2008. This book provides up-to-date and detailed information, which will be most useful both for meteorologists and for the energy sector.

Dr François Jacq[1]
President and Chief Executive Officer of Météo-France
October 2009

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AVANT-PROPOS

Les données sur la météorologie et le climat sont tout à fait essentielles à la fois pour la gestion de l'énergie au jour le jour et pour la définition des infrastructures de production et de distribution. Par exemple, l'approvisionnement en électricité des usagers peut être perturbé par des événements météorologiques extrêmes tels que des tempêtes avec des vents inhabituellement violents, des épisodes de givrage sévère, des périodes de froid intense et prolongé, des remontées du niveau de la mer associées à des tempêtes, des inondations …

Pour se protéger contre de tels événements, il ne suffit pas d'agir après qu'ils se soient produits. Il est nécessaire d'identifier leurs impacts potentiels avec précision et d'évaluer la probabilité de leur occurrence.

Cet ouvrage démontre que ceci ne peut se faire qu'à travers un dialogue plus poussé entre la communauté de l'énergie et la communauté du climat et de la météorologie. Ceci demande un dialogue approfondi entre les acteurs pour définir avec précision quelles données sont nécessaires et comment elles devraient être utilisées.

Météo-France collabore depuis longtemps avec le secteur de l'énergie, y compris dans les domaines de la production et de la distribution de l'électricité. S'appuyant sur cette expérience, on pourra noter à cet égard l'importance de partenariats à long terme entre les acteurs comme l'illustre ici le message d'EDF.

La production d'informations météorologiques et climatologiques se fonde sur un système intégré s'étendant des observations de terrain à la modélisation numérique de l'atmosphère et de la Terre. Il est nécessaire d'adapter autant que possible les informations produites aux besoins des utilisateurs. Malheureusement, ces services essentiels de climatologie ne sont pas encore toujours disponibles pour tous les utilisateurs. La communauté des météorologistes est consciente de ce besoin. C'est pourquoi l'Organisation Météorologique Mondiale a décidé lors de la troisième conférence mondiale du climat (CMC-3) d'établir un Cadre mondial pour les services climatiques, afin de s'assurer que les informations et les prévisions climatiques seront rendues disponibles aux décideurs confrontés aux impacts croissants de la variabilité et du changement climatiques.

Le futur Cadre global pour des services climatiques contribuera à rendre ces services disponibles pour tous les secteurs. Parmi les principales actions requises pour développer ces services figurent le renforcement et la pérennisation des moyens pour effectuer des observations et conduire des recherches, ainsi qu'un renforcement accru des capacités des pays en voie de développement, et une amélioration des interactions entre les producteurs de données climatologiques et les utilisateurs finaux, ainsi qu'a commencé à le faire le projet ClimDevAfrica. Cette décision d'améliorer les services climatiques pour le développement a été adoptée à l'unanimité à l'ouverture du segment de haut niveau de la CMC-3, qui a suivi trois jours de discussions intenses entre des experts internationaux de différentes disciplines. J'espère que cet ouvrage contribuera également au renforcement des capacités requises pour la mise en œuvre de ces recommandations.

Le Cadre mondial des services climatiques constitue une étape indispensable vers la définition de mesures scientifiquement fondées d'adaptation à la variabilité et au changement du climat. Dans ce but, il sera nécessaire d'améliorer de nombreuses observations dans le monde et d'en mettre en œuvre de nouvelles, ainsi que de les rendre aisément accessibles sous une forme facilement utilisable. Il sera également nécessaire d'assurer une cohérence parfaite entre les résultats des modèles et les observations. Toutes ces améliorations demanderont des recherches supplémentaires, une meilleure coordination et des activités de normalisation.

Le public s'attend à bénéficier d'une sécurité dans l'approvisionnement énergétique, ce qui implique que la vulnérabilité des systèmes énergétiques doit être réduite au minimum, en fonction des aléas susceptibles de survenir, et dans un contexte de développement durable. Je saisis donc cette occasion pour recommander la lecture de cet ouvrage, qui résulte d'un travail d'experts, et pour remercier l'OTAN d'avoir apporté son soutien à l'atelier qui s'est tenu en octobre 2008. Ce livre apporte des informations précises et à jour, qui seront extrêmement utiles aux météorologistes comme aux experts du secteur de l'énergie.

Dr François Jacq[1]
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Octobre 2009

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A USER'S VIEWPOINT

Electricity is a commodity that is strongly influenced by variability of climate, for both supply and demand. Consequently, EDF, the French Energy Group, has developed advanced collaborations with the scientific community to be able to anticipate as well as possible future climatic conditions.

Until the early 1960's, half of electricity production originated from hydroelectric power plants. Thus, the ability to forecast several weeks ahead, or even several months ahead, the reservoir status was a major challenge for EDF. Therefore, collaborations between EDF and scientists focused then on this aspect.

Starting in the 1980's, the sensitivity of electricity demand to cold weather spells increased significantly and the forecast of the air temperature became a priority for EDF. A good short-term forecast (ranging from a few hours to about ten days) of temperature over the entire French territory is essential to correctly plan the start-up of power plants and the purchase of electricity needed to fulfill the electricity consumption by EDF's customers. During winter, a 1°C error in the temperature forecast translates into a difference in electricity demand that is equivalent to the electricity consumption of the second and third largest French cities (Marseille and Lyon). Given such a challenge, EDF imposes stringent requirements on the provider of meteorological data concerning both the forecast delivery schedule and the accuracy of the forecast.

However, a good short-term forecast is not sufficient. Given the time scales associated with the operation of its electricity production plants, EDF must also obtain a forecast over several months in order to schedule in an optimal fashion the maintenance of its plants, acquire the fuel necessary to operate those plants, manage its energy storage, and anticipate extreme climatic events (cold weather spells as well as heat waves). EDF has high expectations in that domain and, accordingly, is a partner of various projects pertaining to seasonal forecasts to improve current forecasting approaches, which are now mostly based on historical temperature records.

As wind power production is expected to increase greatly over the coming years, the electricity system will be subject to variations of several thousands of MW depending on wind intensity. The ability to anticipate with accuracy those rapid variations is, therefore, essential to the electric industry from an economic standpoint. This ability must be based on a reliable forecast of winds and their geographical distribution.

Concerning the selection of future means of energy production for the long term, EDF is very interested in climate change research. The 2003 and 2006 summers showed that the temperature of rivers could reach high values upstream of power plants, which affects the cooling capacity at those plants. Will such events occur more frequently in the future? Are decisions that are currently based on historical records still relevant? Will future winters be as cold as in the past?

This brief overview shows that the electric industry has high expectations for climate forecasts. From the short term to the long term, from the local scale to the global scale, scientific collaborations must lead to better scientific tools in the future: without any doubt, this book is a significant step in that direction.

Marc Ribière
Manager, Operational Center for Production and Markets
Electricité De France (EDF)
September 2009

LA VISION D'UN UTILISATEUR

Tant du côté demande que du côté offre, l'électricité est une commodité fortement impactée par les aléas climatiques ce qui depuis toujours a conduit EDF à développer avec la Communauté scientifique des collaborations poussées pour être en capacité d'anticiper au mieux les conditions climatiques futures.

Jusqu'au début des années soixante, la production d 'électricité était à 50% d'origine hydraulique, la capacité à prévoir plusieurs semaines, voire plusieurs mois à l'avance les apports aux ouvrages était un enjeu majeur pour EDF, c'est autour de ces thèmes que s'organisaient les travaux et les collaborations.

A partir des années quatre-vingt, la sensibilité de la demande d'électricité à la rigueur du climat augmentant fortement, la prévision de température est devenue prioritaire pour EDF. A court terme (de quelques heures à une dizaine de jours), la bonne prévision de la température au niveau de toute la France est essentielle pour anticiper correctement le démarrage des installations et les achats nécessaires à la satisfaction de la consommation des clients d'EDF. En hiver, une erreur de 1°C sur la température génère un écart de prévision de demande à satisfaire équivalent à la somme des consommations des villes de Marseille et de Lyon. Avec de tels enjeux, l'exigence de qualité attendue par EDF de son fournisseur de données météo est très forte tant sur le respect des délais que sur la qualité de l'information fournie.

Une bonne prévision à court terme n'est toutefois pas suffisante. Compte tenu des constantes de temps qui sont celles de son outil industriel, EDF se doit d'avoir une vision prévisionnelle à plusieurs mois pour placer au mieux l'entretien de ses équipements, approvisionner le combustible nécessaire au fonctionnement de ses centrales, gérer ses stocks d'énergie, anticiper des évènements climatiques extrêmes (vague de froid exceptionnelle mais aussi épisodes caniculaires). EDF attend beaucoup et est partenaire des travaux en cours autour des prévisions saisonnières pour enrichir ses approches prévisionnelles aujourd'hui essentiellement basées sur des chroniques historiques de température.

Avec le développement massif de la production éolienne attendu sur les prochaines années, le système électrique sera soumis à des variations de plusieurs milliers de MW en fonction de l'intensité des vents. La capacité à anticiper avec une bonne précision ces variations rapides est donc essentielle pour l'économie du système électrique, elle repose sur une bonne prévision des vents et de leur répartition par zone géographique.

Pour le long terme et les choix des équipements futurs, EDF est très attentif à tous les travaux sur le changement climatique. Les étés 2003 et 2006 ont montré que les températures des fleuves pouvaient atteindre, à l'amont de nos installations, des températures très élevées, la probabilité d'occurrence de tels évènements va-t-elle augmenter? Plus généralement les décisions long terme sur la base des chroniques historiques sont elles encore justifiées? Les hivers seront-ils toujours aussi froids?…

Le rapide panorama précédent montre qu'à l'évidence le système électrique attend beaucoup des prévisions climatiques. Du court terme au long terme, du local au global, les collaborations à mener doivent permettre de maintenir voire d'augmenter la performance dans la durée : assurément le livre ici présent y contribue.

Marc Ribière
Directeur du Centre Opérationnel Production Marchés
Electricité De France (EDF)
Septembre 2009

PREFACE

There is little doubt that weather/climate considerations are becoming a very important element in policy/decision making relevant for the energy sector, both within the context of climate change adaptation and climate change mitigation. For instance, information from weather forecasts is currently routinely employed in the energy sector – from energy producers to suppliers, and from financial analysts to national regulators – to assist in decision-making. Given the diversity of the energy sector, this information is used for several purposes such as for pricing the cost of energy or that of financial instruments. Other climate information, such as that from seasonal and decadal forecasts, is also starting to be included in the decision processes in the energy sector. This weather/climate information, especially when severe weather events are expected, will likely become a regular factor in climate change adaptation contingent strategies, including in the formulation of climate change adaptation regulations. In addition, weather/climate information is, naturally, a key element in the development and use of renewable energy resources such as wind, solar and hydropower.

A better understanding of what climate information can and can not provide, how it might be used in context, and an improvement in communication channels, certainly helps the interaction and flow of information between climate scientists and energy experts. The NATO Advanced Research Workshop (ARW) *Weather/Climate Risk Management for the Energy Sector* was an excellent opportunity to bring the communities involved in the exchange of weather/climate information together. The 28 workshop participants including weather/climate scientists, energy experts, institutional specialists, and economists engaged in lively and constructive discussions on ways to progress the above mentioned issues and eventually formulated recommendations aimed at improving collaborative use of information by climate scientists and the energy industry.

About 20 papers were presented at the workshop and these set the scene for the discussions of the three working groups (see below). The papers themselves constitute the backbone of this book, which has been subdivided into three parts:

1. Weather & Climate Fundamentals for the Energy sector
2. Policies for the transfer between Weather/Climate and Energy sectors
3. Energy sector practices, needs, impediments including Current Weather/Climate information transfer to the Energy sector

The three working groups (WGs) were formed to address the five objectives of the Workshop. These objectives were:

A) To identify vulnerabilities of energy sector to extreme weather events in the context of climate change adaptation

B) To identify impediments to the use of weather/climate information for the energy sector in the context of climate change adaptation

C) To suggest ways to improve and/or facilitate the transfer of knowledge between weather/climate scientists and the energy experts to allow an optimal use of climate risk management

D) To outline proposals to improve the way in which weather/climate information is used for modelling demand and to provide warnings for potential disruptions on energy operations and infrastructure

E) To discuss possible contributions of the weather/climate scientists and the energy experts to climate change adaptation policies for energy security

The recommendations are presented in the last chapter and references therein.

This NATO ARW was held in the beautiful setting of Santa Maria di Leuca (Italy) between 6 and 10 October 2008 and was attended by leading academic scientists, industry experts in the various energy specialities (oil, gas, renewable, finance), policy makers and non-governmental organisation practitioners. It has been a privilege to have so many worldwide experts in the field of *weather/climate and energy* as participants at the ARW. Their enthusiastic participation and their contributions to this book can not be overstated[1]. All participants provided very positive feedbacks at the end of the Workshop on what had been achieved during the week. Several new links were created and many ideas for future collaborations were discussed. Indeed, some of the participants have already established new collaborations.

It would have not been possible to organise this ARW without the collaboration and support of many people: the team at the NATO Environmental and Earth Science & Technology (EST) Programme with *Mrs Alison Trapp* (Secretary) and *Dr Fausto Pedrazzini* (Programme Director), who assisted in securing a smooth development of the ARW; *Mrs Elena Bertocco* (ARW Secretary) assisted with the copious queries from participants while keeping at bay lovely little Edward and Jacqueline; the members of the Organising Committee, *Mr Mohammed Sadeck Boulahya (ARW Co-Director),*

[1] For more information on the ARW, see: http://www.climate-development.org/atroccoli/nato_arw/index.html

Prof. Robert Gurney, Dr Mike Harrison, Dr Pascal Mailier and *Prof. Oleg Pokrovsky*; *Mr Jonathan Saunders* and *Ms Kathryn Needham* (graphic creators) for producing high quality promotional material; *Mrs Annamaria Caputo* and all the staff at the Hotel Terminal (S. Maria di Leuca) for their warm and professional hospitality and for the extremely well planned and thoroughly enjoyable social and cultural programme. I am particularly grateful to the organisations that supported this ARW financially: NATO and the Environmental Systems Science Centre of the University of Reading.

I hope this book will provide a useful reference for all those keen to venture in the fascinating interaction and communication between the weather/climate science and the energy industry.

Alberto Troccoli
August 2009

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WEATHER, CLIMATE, AND THE ENERGY INDUSTRY

A Story of Sunlight—Some Old, Some New

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Abstract. Some of the key interactions between the atmosphere and the energy industry are considered, with a special focus on concepts and forecasts through which atmospheric science assists the industry and its support for society. Probabilistic weather and seasonal forecasts take advantage of contemporary understanding and computer power to clarify the envelope of expectation for risk and opportunity in the industry on the scale of days and seasons. The quality of seasonal forecasts is examined with two statistical verification schemes. Climate change, regardless of cause, poses potential challenges for the energy industry, perhaps the most significant arising from political and economic pressures. A formal analysis scheme is outlined that may assist energy companies to foresee and manage the implications and consequences of climate change for their business.

Keywords: Energy; weather; climate change; fossil fuel; renewable energy; uncertainty

1. Interaction Between the Energy Industry and the Atmosphere

Energy management, weather, and human activities have been intertwined since prehistoric camp fires provided nighttime light and warmth against the winter chill. Largely derived from combustion of fossil fuel, energy is a key component of contemporary daily life and industrial might, but the evidence

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grows that the increasing human appetite for energy is the likely cause of a slow but detectable change in the Earth's climate.

A significant fraction of the energy consumed in developed nations is still used to provide protection against atmospheric cold and heat. Atmospheric processes are important in generating renewable energy, but adverse weather or unfavorable seasonal conditions can impede the production and transportation of energy. A changing climate, regardless of cause, may intensify some adverse weather effects, change energy consumption patterns, and generate new economic and policy pressures that will mandate new thinking and new approaches in the energy industry.

The extent to which contemporary civilization is dependent on readily available energy is demonstrated dramatically by the stunning mosaic of satellite images in Figure 1 showing the Earth illuminated by nighttime lighting. As this dependence accelerates with increasing demand for energy across the globe, the urgency of understanding and managing the risk posed by weather and climate to the production, transport, and use of energy accelerates as well.

This chapter will review some of the fundamental aspects of atmospheric processes relevant to the energy industry and its support of society. Table 1 summarizes some of those interactions.

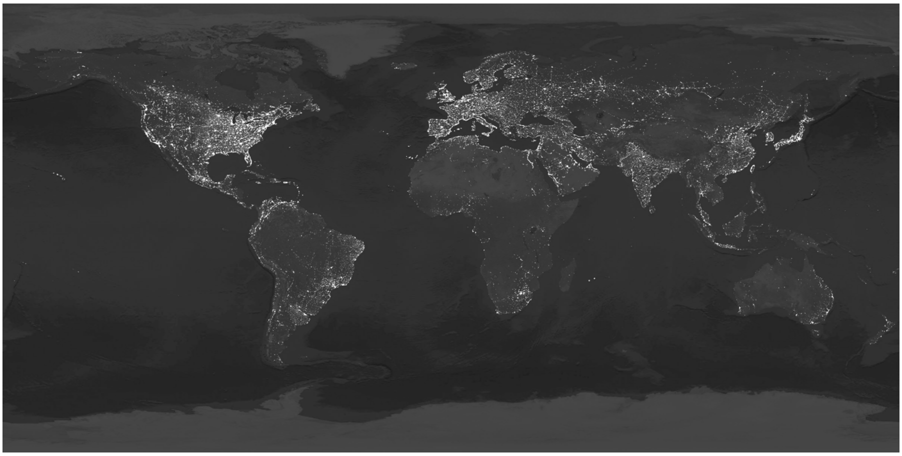

Figure 1. A mosaic of nighttime lighting compiled from satellite images by the U.S. National Aeronautics and Space Administration (NASA): C. Mayhew and R. Simmon at Goddard Space Flight Center.

TABLE 1. Weather and climate impacts on the sources, use, and transport of energy.

Activity	Weather, climate & environmental variable
Energy sources	
Fossil sunlight (coal, oil, gas)	Severe weather impacts on drilling and production platforms and facilities, heavy precipitation and floods on mines
Solar power	Insolation as affected by latitude and clouds
Wind power	Wind speed (V^3), icing
Hydropower	Precipitation, evaporation, surface slope
Biomass power	Temperature, precipitation, insolation
Wave and tidal power	Wind
Nuclear power	Earthquakes, severe weather
Energy uses	
Heating	Temperature (HDD), wind speed, insolation, clouds
Cooling	Temperature (CDD), wind speed, insolation, clouds
Illumination	Insolation, clouds
Transportation	Weather related delays and cancellations
Industrial processes	Severe weather, industry dependent effects
Energy transport	
Electrical transmission wires	Wind, icing, lightning, local ground movements, precipitation
Trucks and trains	Severe weather, icing
Ships and barges	Wind and waves, severe weather

2. Energy and Power in the Atmosphere and the World Energy Industry

Almost all of the world's energy is sunlight, some from today, some from yesteryear. Indeed, the energy obtained from coal, petroleum, and natural gas is all fossil sunlight, and the energy in sunlight is responsible for all renewable sources of energy. Only the energy generated in nuclear plants is independent of sunlight.

The power of the sunlight impinging on the top of the atmosphere is approximately 1,364 $\mathrm{W/m^2}$. That sunlight appears to fall on a disc with the Earth's radius of 6,370 km and thus an area of $1.275\,10^{14}$ $\mathrm{m^2}$. Therefore the total solar power intercepted by the Earth is $1.74\,10^{17}$ W$=1.74\,10^{5}$ TW or 174 PW where TW denotes terawatt (10^{12}) and PW denotes petawatt (10^{15})[1]. About one-third of this is reflected back to space by clouds and the

[1] One Watt equals 1 J/s and 3.412 BTU/h. Raising a mass of 1 kg 1 m against the force of gravity requires approximately 10 J of energy. Thus it requires 1 W to accomplish the task in 10 s and 100 W to accomplish it in 0.10 s.

Earth's surface and so the solar power fluxing into the Earth system is about 116 PW.

By comparison the worldwide human consumption of energy in 2008 is estimated by the Energy Information Administration (2008) to be 493 quadrillion $\text{BTU} = 144\,10^{15}$ W-hr $= 5.2\,10^{20}$ J; on taking account of 8,760 h per year, we find that the corresponding power is $1.64\,10^{13}$ W or about 16 TW – approximately 1/7,200 of the solar power absorbed by the Earth. Dividing by the area of Earth gives an average human power consumption of $0.129\ \text{W/m}^2$.

The energy in the atmosphere includes the static forms of thermal, potential, and latent heat amounting to $2.56\,10^{9}\ \text{J/m}^2$ along with $K = 1.23\,10^{6}\ \text{J/m}^2$ of kinetic energy (Peixoto and Oort, 1992). The dissipation of kinetic energy represents the net mechanical power of atmospheric motion; it cannot be measured directly and hence there is controversy over the amount. Here we use $D = 4.32\ \text{W/m}^2$ (Dutton, 1986; Kung, 1969). The ratio $K/D = 3.3$ days provides a time scale for the dissipation of kinetic energy should the solar forcing cease.

This discussion is summarized in Table 2. There are significant implications. Although the world use of energy by humans is critical to contemporary society, the power involved is quite small compared to that in the Earth's environment. This implies that a larger fraction of world energy might be obtained from systems designed to capture some of that energy – although the consequences for the environment of extracting it are not known. If use of fossil power at rates small compared to atmospheric power can actually be detectable as a changing climate, then there must be feedback processes that amplify small causes into large consequences. Indeed, we may discover now unknown feedbacks that would create adverse results from a global commitment to wind power as a source of energy. The possible consequences of significantly increased use of alternative energy should be a key issue in exploring options for mitigation of climate change. We will return to climate change in Section 5.

TABLE 2. Ratio of world energy to atmospheric energy and to solar power.

	World consumption	Atmosphere	Solar
Energy	$4.1\,10^{6}\ \text{J/m}^2$	$2.56\,10^{9}\ \text{J/m}^2$	
Power	$1.29\,10^{-1}\ \text{W/m}^2$	$4.32\ \text{W/m}^2$	$342\ \text{W/m}^2$
	Ratio of energy	$1.59\,10^{-3}$	
	Ratio of power	$2.99\,10^{-2}$	$3.77\,10^{-4}$

3. Atmospheric Motion and Atmospheric Systems

The intensity of the clear-sky sunlight falling on the Earth's surface depends on latitude, decreasing from an annual maximum intensity at the equator to only a small amount at the poles. Thus on the spherical Earth, the equatorial regions are warm and the polar regions cold. This creates a thermodynamic imperative to transfer heat from the equator to the poles.

As this transfer begins, it encounters a second critical fact about the Earth: the planet rotates on its axis and thus we live in a coordinate system that is accelerated with respect to space. The effect (known as the Coriolis force) of this rotation is to change the direction of moving air or ocean water, always to the right in the Northern Hemisphere. The rotation of the Earth thus reappears in the rotation of atmospheric systems such as cyclones or anticyclones and, along with the latitudinal thermal gradient, leads to the high-speed jet streams circling the Earth in the mid-latitudes.

The thermodynamic imperative to reduce the latitudinal temperature gradient sets both atmosphere and ocean into constant motion, seeking a thermodynamic equilibrium they can never reach. Because of the Earth's rotation and the Coriolis force, the required transfer of heat is an inefficient process accomplished by quasi-horizontal mixing in waves and storms, rather than through a direct flow of warm air to cold.

The complexity of atmospheric and oceanic motion arises in the transfers of energy from one wavelength of flow to another. Indeed, the nonlinear aspects of fluid dynamics mandate that energy injected at one wavelength be transferred to both smaller and larger wavelengths. The fact that small causes can have large effects leads to the phenomenon known as chaos – everything depends on everything else and predictability will always be limited because of variations too small for us to observe.

These transfers of energy, both thermodynamically and mechanically, lead to a broad spectrum of atmospheric phenomena and processes, as illustrated schematically in Figure 2. Stratifying the effects of weather and climate on the energy industry on the basis of these temporal and spatial scales helps us to understand the risk and foster appropriate management strategies. Thunderstorms and severe weather obviously have implications very different from those of climate change.

The traditional interest in atmospheric science focused on weather systems and storms with the accompanying severe weather that has immediate consequences for human activity. Now rapidly increasing capabilities in observation and measurement have stimulated significant progress in understanding and modeling the small-scale processes on the left side of Figure 2 as well as atmospheric structure and evolution on larger scales.

This new understanding and the increase of computational power available to both researchers and operational forecast centers has improved the accuracy of forecasts in the range of a week or two and made possible both seasonal outlooks and projections of climate variability on the scale of decades to centuries.

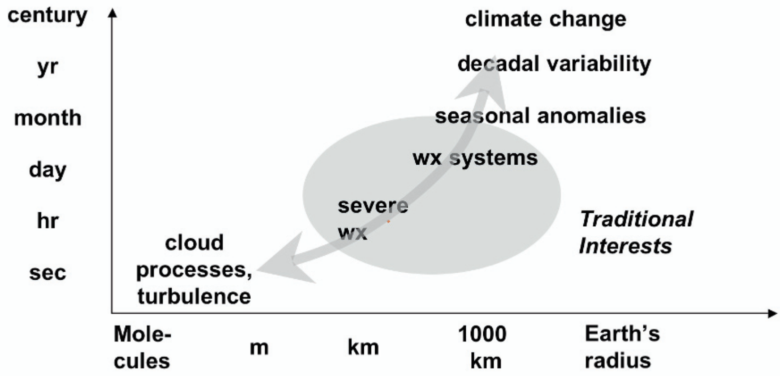

Figure 2. The spectrum of atmospheric processes and scales (*wx* is an abbreviation for *weather* from the teletype era).

Thus much of the work of the atmospheric sciences focuses on creating mathematical models to describe physical processes across the scales shown in Figure 2. The equations for the larger-scale features have been known since early in the twentieth century (see, for example, Dutton, 1986), but the task of accurately modeling smaller scale processes, especially those associated with water and the atmospheric boundary layer, is a continuing challenge. As shown in Figure 2, some of the focus of the atmospheric sciences is shifting from the center of the spectrum to both the smaller and larger scales.

The theoretical equations derived from basic physical principles are predictive in nature: they specify rates of change as a function of the present state of the atmosphere and thus can be used in a repetitive cycle to move forward in time. For this purpose, the theoretical equations are converted into algorithms suitable for numerical computation and then predictions or simulations are computed by national and international forecast centers using some of the most powerful computers in the world.

The forecasts take many forms of interest to the energy industry, ranging from warnings of severe weather and possible disruptions of power supplies to the simulations of how global and regional climate may change over the next century. The predicted climate-change patterns of temperature, precipitation, and other environmental variables will have implications for power demand and use and for the policy environment in which the industry must operate. Prospects for improved prediction with petascale computers are described by the National Research Council (2008). Additional information on weather and climate prediction may be found in the article by Troccoli (2009) in this volume.

The nations of the world expend the equivalent of tens of billions of dollars annually to acquire surface, airborne, and satellite observations, to analyze them, and then to turn them into a steady stream of forecasts with supercomputers. In the United States, all the observations and forecasts obtained with government support are freely available to all – including the citizens of other nations. In some other countries, the governments assess charges for observations and forecasts on the very taxpayers who have already paid for them.

4. Probabilities for Quantifying Opportunity, Risk, and Uncertainty

Weather and climate events pose both opportunity and risk for the energy industry. The contemporary technological society is increasingly dependent on energy and thus the demand for reliable power is intensifying. The technologies required to take advantage of the wind, the sun, and sea for power are advancing and may soon be economically and politically competitive with fossil sunlight and become a more significant opportunity for the industry.

But risk is undoubtedly increasing more rapidly than opportunity. As activities become more sophisticated and more dependent on power, less margin is available, and so weather and climate risk or uncertainty become increasingly significant to the energy industry and its customers – to all of us.

Thus reliable information about the statistics of weather and climate and about the range of conditions expected in the future is essential to plan wisely, to prevent loss and otherwise minimize the consequences of adverse weather or seasonal climate variations, to hedge financial risk, and to develop strategies to secure the future of the business as climate change reshapes both the physical and societal environment in which the industry operates.

Effective decisions about opportunity and risk related to weather and climate require reliable, quantitative information about the probability of success in specific activities on both the short and long term. Once the metrics that describe success are clearly formulated, we can say that the probability of success in operating an energy supply system composed of both technological and economic components depends in part on

- The response of the system to atmospheric events
- The probability of those events occurring

To combine these two, we must have a quantitative model of the system and its implications for the business and we must have atmospheric probabilities: probabilistic forecasts on the scale of days and months for operational decisions and probabilistic climatologies and long-term simulations for strategic planning on the scale of decades.

4.1. PROBABILITIES OF ENVIRONMENTAL AND ENERGY VARIABLES

The empirical view of probability is based on frequency of occurrence: the probability of a tossed coin landing heads up is one-half. When we say the probability of rain tomorrow is one-third we mean that we expect rain on one-third of the days with conditions similar to those we expect for tomorrow. When we assess the reliability of such forecasts, we would say the probability forecast were very reliable (or even perfect) if it rained on exactly one-third of the days on which we said the probability of rain was one third. In other words, we predict the probability of an outcome and verify with the frequency of occurrence.

For various reasons, including the vagaries of chaos, it is impossible to make precise quantitative forecasts of atmospheric variables. A forecast that the average temperature tomorrow will be 15.0°C is almost certain to be in error. But a forecast that the average temperature is likely to be between 14 and 17 degrees may be more useful and assist us to make decisions about appropriate actions. Probabilities allow us to be specific about what 'likely' means in such a statement.

Figure 3 shows two probability functions for a statistical variable x. The *probability distribution function*, shown on the left, tells us the probability $P_x(X)$ that the variable x in which we are interested will be less than X. The *probability density function*, shown on the right, describes the relative frequency of occurrence $p_x(X)$ of values X of x. Mathematically, these two are related by the reciprocal expressions (given various technical restrictions):

$$\text{Prob}[\mathrm{x} \le \mathrm{X}] = P_x(X) = \int_{-\infty}^{X} p_x(\xi)\,d\xi \qquad p_x(X) = \frac{\partial}{\partial X} P_x(X) \tag{1}$$

The probability distribution function provides the information we need for most of the assessments with which we are concerned here. It defines the envelope of expectations in which we will operate, and with it we can attempt to calculate the probability of success given certain actions or decisions on our part.

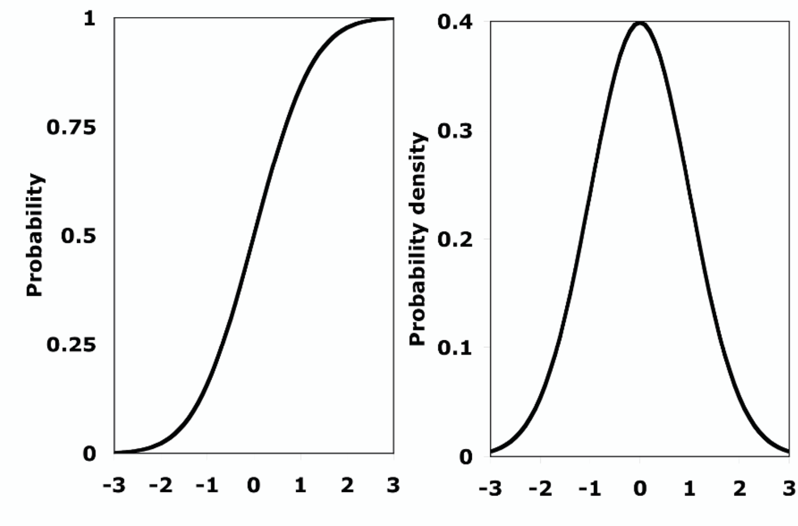

Figure 3. A probability distribution function P and the probability density function p for a variable x with values on the lower axis.

To illustrate this point, Figure 4 shows the daily average generation load of two utilities as a function of the average daily temperature, clearly indicating that load increases on either side of a basis temperature near 65°F used to define degree days in the heating and cooling industry. While these are actual data from federal filings and official weather records, here we shall denote these two utilities as Cougar Power and ErieEnergy. Cougar Power serves an area along the Atlantic seaboard while ErieEnergy serves an industrial region along the southern shore of Lake Erie.

The data in Figure 4 allow us to develop a method for estimating probabilities of load L given a predicted probability distribution for the daily average temperature. Transforming probabilities mathematically for a change of variables requires strictly monotonic relationships and so we illustrate with linear fits to the heating and cooling branches of the Cougar Power data. As depicted in Figure 5, we obtain:

$$L = a + bT \quad (T > T_0 \text{ for heating, } T < T_0 \text{ for cooling}) \tag{2}$$

for each branch and then in the appropriate T-domain we have

$$\text{Prob}[L \le M] = \text{Prob}[T \le (M - a)/b] \tag{3}$$

The probability of the load being between in a range (M_1, M_2) can be obtained from (3) as the difference of the probabilities $\text{Prob}[L \le M_2] - \text{Prob}[L \le M_1]$.

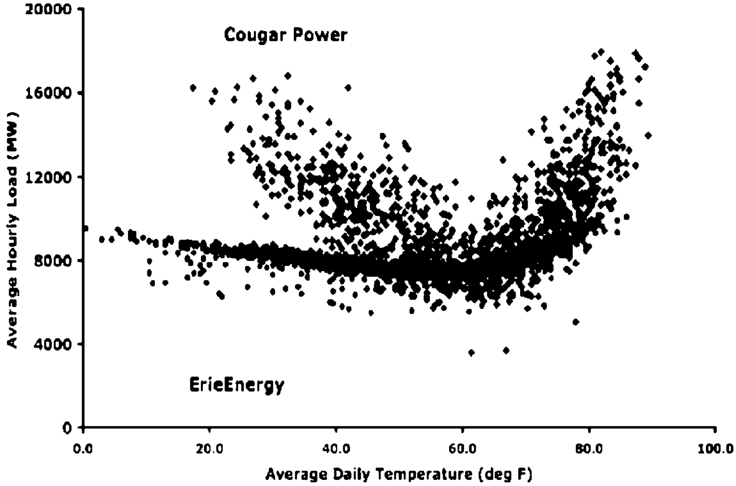

Figure 4. Dependence of average load on average daily temperature for two U.S. utilities.

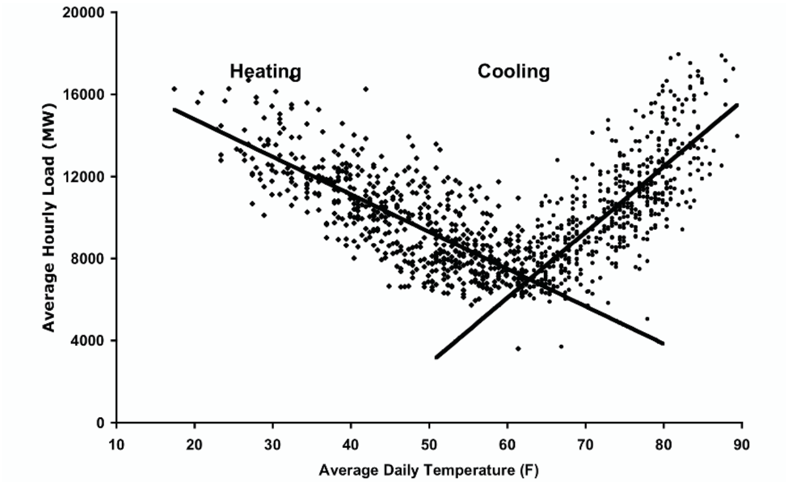

Figure 5. Linear fits to the heating and cooling branches of the Cougar Power load *vs*. temperature diagram.

If the daily average temperature were predicted to be normally distributed with mean 72°F and standard deviation 4°F, then the probabilities of load at Cougar Power would be described by the probability curve in Figure 6. The dashed line shows the probability distribution for load should the standard deviation be 2°F rather than 4°F. Forecasts that reflected such differences would be of evident advantage. Teisberg et al. (2005) have analyzed the economic value of improved temperature forecasts in electricity generation.

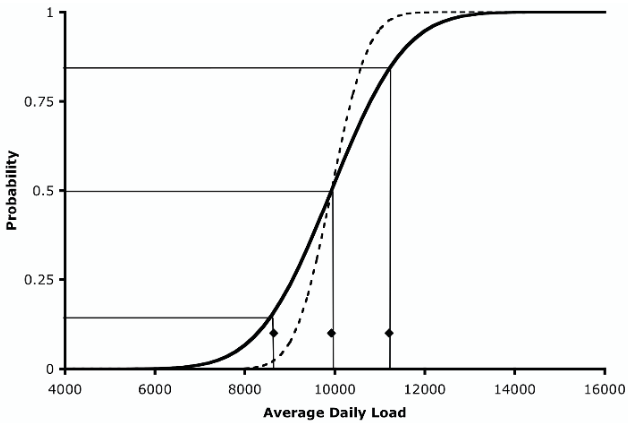

Figure 6. Probability distribution function for Cougar Power load computed from a predicted temperature distribution. The three lines indicate the mean less one standard deviation, the mean, and the mean plus one standard deviation. The dashed curve shows the predicted load distribution for a standard deviation half as large.

4.2. PREDICTING PROBABILITIES

The power of contemporary supercomputers makes it possible for the major national and international atmospheric forecast centers to produce predicted probabilities of occurrence for atmospheric variables. This is done, quite simply in concept, by running many forecasts instead of one. The major sources of uncertainty in numerical forecasts include:

- Depiction of the initial state of the atmosphere as obtained from surface, airborne, and satellite observations (the initial conditions)
- Depiction of the conditions at the surface of the land, the sea, and the polar ice caps and ice sheets (the boundary conditions)
- Mathematical representation of interactions among large-scale flow patterns and the smaller scale processes involved with transfers and transformations of energy and momentum, with changes of phase and transport of water, and with the chemical processes that affect the radiation streams in the atmosphere (internal physics)

The current strategy is to describe these uncertainties with probability distributions and to compute forecasts for each set of representative conditions, leading to an ensemble of forecasts with tens of members. This ensemble of predicted conditions then provides the probability of expected outcomes, with the high-probability events described by ensemble members clustering near an average value and the low-probability events by the ensemble members with relatively extreme values. The process is illustrated in Figure 7.

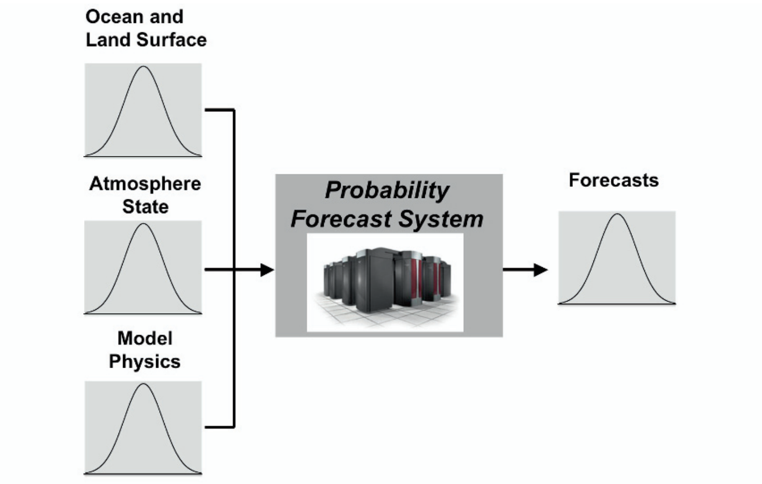

Figure 7. An ensemble forecast system converts input probabilities into predicted probabilities.

But even with these probability forecasts, there is more to do to produce information useful to the energy industry and other applications. First, we recognize that the numerical models may have systematic errors that can be detected and corrected by comparing forecasts with verification observations. Seasonal forecast models, for example, are found to predict temperatures too warm in some parts of the world and too cool in others, perhaps as a function of season. These bias errors can be corrected by comparing forecasts made retrospectively for the past 25 years, say, with the equivalent observations to determine the statistical basis of the system. Similar steps can be taken to adjust the variance of the ensemble of forecasts. Second, we need to convert predicted probabilities of atmospheric variables into probabilities of response of the industrial or business system with which we are concerned, as we did above for Cougar Power. This can be accomplished by various means, including mathematical transformations or direct numerical simulation of the response of the system as forced by the members of the atmospheric ensemble. Figure 8 shows how such a system might be assembled to produce action recommendations and estimate the concomitant probabilities of success.

The value of this process in the industrial setting depends on the reliability of the probability forecasts and on the accuracy of the quantitative representation of the response of the system. The skill of atmospheric prediction increases to a large extent with increasing spatial scale and with the smoothness of the variables. Thus upper-air fields are predicted better than variables near the surface where local effects can be strong. Temperature predictions near the surface are usually better than forecasts for precipitation or wind speed.

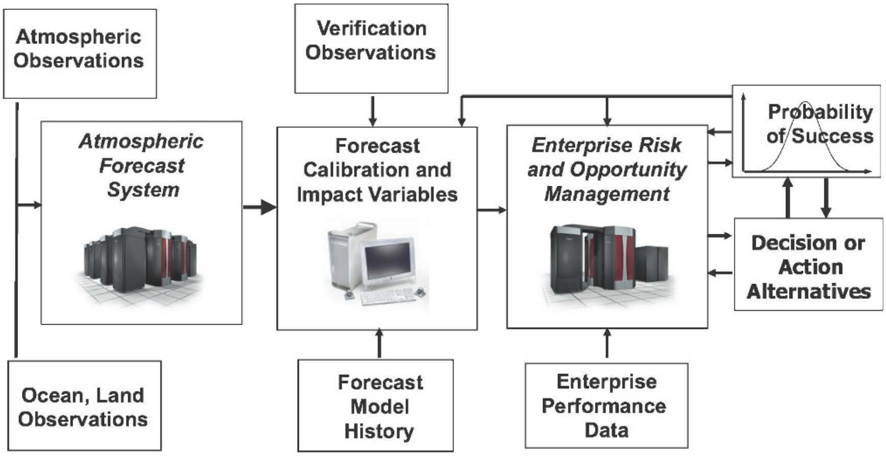

Figure 8. Calibrated forecasts are linked with the enterprise risk and opportunity management system to recommend actions and estimate the probability of success. The process terminates when the decision-maker accepts a recommendation and approves an action.

A qualitative assessment of predictive skill is provided in Table 3 for the variables required for assessment of risk and opportunity with both conventional and renewable energy sources. In the table, *Observations* refers to direct measurements obtained from surface, airborne, or satellite instruments. *Re-analysis Data* refers to local or world-wide data sets prepared by combining observations and numerical prediction models to obtain a dynamically consistent climatology extending over several decades. The reanalysis datasets are rapidly increasing in importance, both for calibration of the prediction models in the retrospective forecast process described above, and for providing climatologies of variables such as insolation or evaporation that are only rarely measured. Finally, the *Ensemble Models* are the probability predictions described earlier in this section.

TABLE 3. Subjective assessment of the relative value of information about atmospheric variables. For ensemble temperature forecasts (Good/Fair), implies Good for 1–10 days, Fair for 1–3 months.

	Climatology		Forecasts
	Observations	Re-analysis	Ensemble models
Temperature T	Very good	Good	Good/fair
Cooling and heating degree days	Very good	Good	Good/fair
Precipitation	Spatially complex, difficult to observe and predict		
Wind (u,v), wind power (V^3)	Varies greatly with height and averaging interval		
Insolation	Rare	Few observations for verification	
Soil moisture, evaporation, runoff	Rare	Few observations for verification	

4.3. ASSESSING THE QUALITY OF SEASONAL FORECASTS

There is a wide range of methods for comparing forecasts with the observations at the verification time (Wilks, 2005; von Storch and Zwiers, 2001). Here we consider two methods for evaluating the numerical seasonal forecast products of the Prescient Weather World Climate Service (WCS). In both examples, we focus on the predicted probabilities for the atmospheric variables being below normal, normal, and above normal, with normal derived from the climatology at observation stations. In a stable climate, each of the three possibilities has a probability of one-third of occurring in a sufficiently long record. Seasonal forecasts attempt to foresee and assign probabilities to the situations when the probabilities depart from those of climatology.

The first measure is modeled on the weather derivative contracts traded, for example, on the Chicago Mercantile Exchange, but here we consider what we will term a plain vanilla option. The cost of an option on below, normal, or above normal conditions is set at 1. The payoff for the case that occurs is 3. Thus the return on the successful option is $R = 3 - 1 = 2$. Obviously, this model ignores transaction costs or dealer profit in an over-the-counter mode. Moreover, the model takes no account of the fact that the counterparty offering the contract will be setting the price on the basis of its own forecast, which may be more or less skillful than ours.

The forecast performance is scored with a contingency matrix as shown in Table 4, in which forecasts are binned according to the category in which the verification occurred. The correct forecasts fall along the diagonal and total $H = H_b + H_n + H_a$ in number. Thus for N forecasts the return is $R = 3H - N$ and the virtual return $V = R / N$ for a sequence of N options each acquired at a cost of one unit is $V = 3(H / N) - 1$. For perfect forecasts, $H = N$ and so $V = 2$; for random forecasts, $H = N/3$ and thus $V = 0$.

The virtual return for seasonal probability forecasts computed for nearly 1,600 locations in North America and Europe for 1997–2006 is shown in Table 5 with V in percent. In the table, ECMWF denotes the WCS version of the forecasts of the European Centre for Medium-Range Weather Forecasts, CFS denotes the WCS version of the Climate Forecast System of the U.S. National Weather Service, and Multi denotes a combination of the two forecasts into one set of probabilities.

TABLE 4. Contingency table for computing virtual return.

		Observations		
		Below	Normal	Above
Forecasts	Below	Hb	Bn	Ba
	Normal	Nb	Hn	Na
	Above	Ab	An	Ha

TABLE 5. Virtual return in percent for three seasonal forecast models. The statistics are aggregated over forecasts for North America and Europe, for leads of 1–5 months.

	Temperature		Precipitation	
	10-year history	Full history	10-year history	Full history
ECMWF	21	19	17	12
CFS	17	11	17	9
Multi	21	18	16	11

The results for bias removal over both 10-year histories and the entire history to 1981 are compared. No adjustments to the variance were made in these forecasts. A WCS version of these forecasts with variance adjustments made by a maximum expectation retrospective forecast process shows improvement in some cases.

The reliability diagram provides another way to examine the value of seasonal forecasts. We divide the predicted probabilities into, say, ten bins between 0 and 1. For each of these bins we compute the average frequency of occurrence in the verifying observations and plot that average as a function of the probabilities. For perfect forecasts, we would find that the frequency of occurrence equals the probability and plot a diagonal line on the diagram. For probability forecasts with no skill, the climatological probability of one third will prevail and the ratio of frequency to probability will be one third for every probability bin. A reliability diagram for the WCS probability forecasts for Northern Europe computed from the ECMWF ensemble model is shown in Figure 9, again combining the probability forecasts for below, normal, and above normal temperatures and combining monthly forecasts for the four seasons (March, April, May; June, July, August; September, October, and November, December, January, February). The lighter lines are the original reliability curves; the heavier lines show the increase in reliability that would be obtained by a linear transformation of the forecasts so that the reliability curves rotate to the diagonal. Thus large probabilities are reduced in the calibrated forecasts, small probabilities are increased.

The seasonal forecasts issued by the major national and international centers, Prescient Weather World Climate Service, and other vendors do not rely exclusively on the numerical forecasts evaluated here. There are a number of long-term oscillations in large-scale patterns that provide advantage to skilled and experienced forecasters. The best known is the El Niño-Southern Oscillation (ENSO) that involves warm and cool anomalies of surface temperatures in the tropical Pacific Ocean. Strong patterns of the warm El Niño and cool La Niña conditions are often accompanied by characteristic seasonal anomalies in the tropics and in North America. The numerical forecast models demonstrate some skill in predicting these events, especially the onset of a new phase. In an evaluation of the first decade of long-lead seasonal forecasts by the U.S. National Weather Service, Livezey and Timofeyeva (2008) point out that ENSO is a first important source of skill and that the trends created by climate change in the U.S. provide a second. The evaluations of the seasonal forecasts presented above mask the climate change effect through aggregation, but it is actually present because forecasts of warmer than normal conditions are the most successful category.

4.4. FORESEEING THE FUTURE OF FORECASTING

As a general qualitative summary of forecasts of weather and climate conditions for the energy industry, we can say that the forecasts for a week ahead are very good and that forecasts for a season or two in advance are improving. Forecasts for lead times of 2–4 weeks are very difficult, and progress is slow. The major national forecast centers are beginning to turn some attention to forecasts for a decade or so. We know today that the methods used to simulate climate change as forced by various scenarios of emissions in the decades ahead perform well in some respects when tested on the twentieth century, but only time will tell whether today's simulations are correct for the years to come in the twenty-first century.

But before then, we can expect dramatic progress over the next 20 years with a new generation of vastly more capable meteorological satellites and

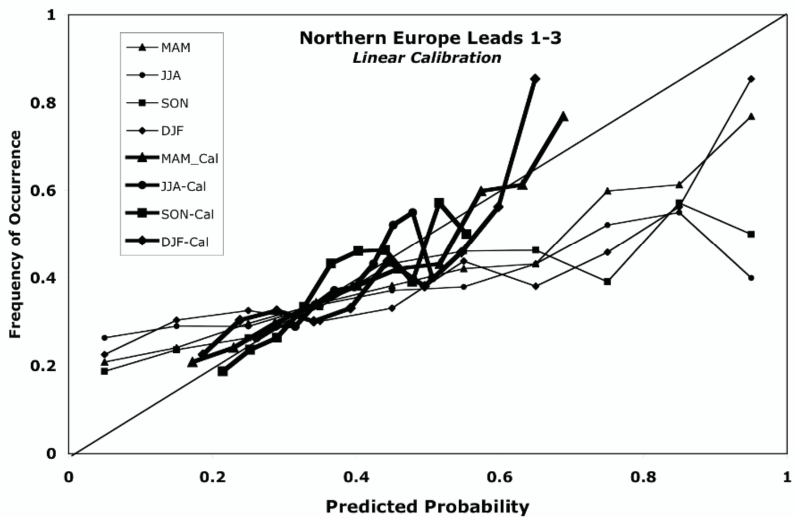

Figure 9. Reliability diagram for the WCS version of the ECMWF forecasts for the next season in Northern Europe (lighter lines), showing the result of linear calibration (heavier lines). Forecasts for below normal, normal, and above normal temperatures are combined to give more stable statistics.

dramatic increases in computing power. Indeed, the National Research Council (2008) foresees the development of a Virtual Earth System (VES) running on linked petascale machines, assimilating data from tens of satellites, and maintaining "a continuous, dynamically consistent portrait of the atmosphere, oceans, and land…a digital mirror reflecting events all over the planet". By extension, a companion of the VES could be a Future Earth System (FES), similarly taking advantage of an Internet cloud of powerful computers to maintain a continuous simulation of the Earth System expected in the decades ahead, incorporating advances in understanding of Earth System dynamics as they develop. The VES would be the foundation for sharper, more reliable high resolution forecasts of weather events and seasonal evolution. The FES simulations could be the driver for numerical models of the energy enterprise and its interaction with society, providing a continuous outlook on opportunity and risk as the industry develops strategies to adapt to the new realities created by climate change.

5. A First Look at Climate Change and the Energy Industry

A substantial international effort in the atmospheric and related sciences over the past two decades has sought to understand, and perhaps foresee, the consequences of what appears to be accelerating change of the global climate. The average surface temperature is increasing slowly, sea level is rising as a consequence of thermal expansion and increased melt-water, glaciers are retreating, the Arctic permafrost is thawing, and the Arctic ice cover has diminished markedly in recent summers. The assessment reports of the International Panel on Climate Change (IPCC, 2007) chronicle the growing scientific confidence that the climate is changing in response to increasing concentrations of gases with significant consequences for radiative transfer in the atmosphere.

Climate change, while neither good nor bad in any scientific sense, provides opportunity and poses risk for the energy industry and many other activities, regardless of its cause. The per capita rate of carbon dioxide emission is to a large extent proportional to standard of living, making meaningful reductions very difficult in the absence of a much greater global commitment to energy efficiency and renewable energy, both assisted by significant technological advance. The extent of this challenge was examined in detail in an essay by Dutton (1994) and is considered more comprehensively in the series of IPCC reports. It seems likely that the most important impacts on the energy industry will arise from economic and political forces as governments and customers seek to mitigate and adapt to climate change.

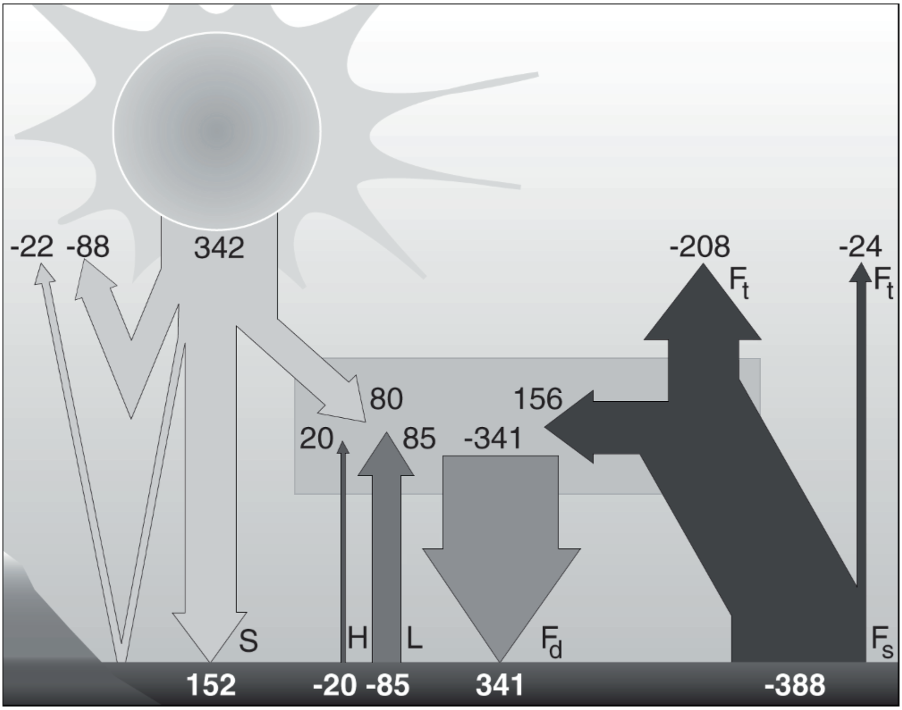

Figure 10. The average global energy balance of the Earth with all fluxes in W/m^2. Here *S* denotes solar energy absorbed at the surface, *H* sensible heat flux, *L* latent heat flux, F_s flux of infrared radiation from the surface, F_d flux of infrared radiation downward to the surface, and F_t the outward flux of infrared radiation at the top of the atmosphere. Adapted from *Science, Technology, and the Environment* edited by James Rodger Fleming and Henry A. Gemery. Copyright © 1994 The University of Akron Press. Reprinted by permission. Unauthorized duplication is prohibited.

The forcing for climate change is believed to arise in the energy balance of the atmosphere and the planet, as illustrated in Figure 10. As shown, the long-wave radiation emitted from the surface of the Earth is partially absorbed by radiatively sensitive gases in the atmosphere and re-radiated toward the surface, thus warming the planet, in a process called the green-house effect. Were it not for this warming, Earth would be ice-covered. Thus the greenhouse effect is critical to life on Earth; the question now is to what extent human activities are intensifying it and thereby altering the climate.

The scientific analysis focuses on feedback and gain. The direct effect of significant increases in the concentration of a greenhouse gas such as carbon dioxide in the atmosphere may be small, but the small change may amplify through positive feedback processes to intensify the effects of water vapor, the major greenhouse gas. The extensive computer simulations of the

IPCC investigate this feedback process through an integrated numerical exploration of the interactions between all the components of the Earth system. On the basis of these simulations and estimates based on empirical evidence (e.g., Dutton, 1995), the direct effect of a doubling of carbon dioxide concentration is amplified about seven times by the positive feedback in the system.

The IPCC computer simulations imply that surface temperature will be warmer in the coming decades, especially at high latitudes, and that precipitation will increase in higher latitudes but decrease in lower latitudes. Sea level will continue to rise, perhaps dramatically, if major ice sheets collapse. And finally, it is likely that volatility will increase as extremes become more pronounced relative to the recent and present climate.

The direct implications for the energy industry include changing emphasis on heating and cooling in developed countries (as illustrated for the U.S. in Figure 11), changes in water available for hydropower as melt water flows decrease, and an increasing interest in renewable energy as an alternative to releasing fossil sunlight through combustion. The development of renewable energy will be intensified by efforts of some nations to decrease their dependence on imported fossil fuel, including the recent speculation in the U.S. about a national commitment to electric automobiles recharged with wind-generated electricity.

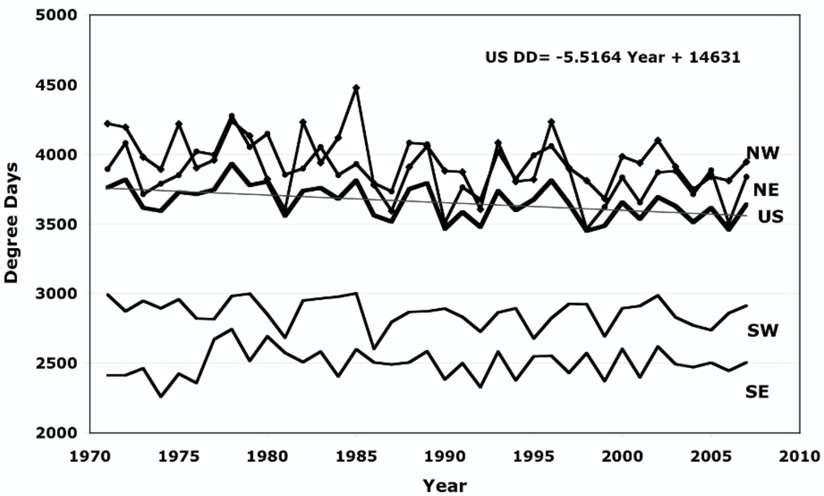

Figure 11. Annual degree-days (sum of cooling and heating degree days) for the U.S (heavy line) and for the northeast, southeast, northwest, and southwest quadrants (light lines). Overall, warmer winters in northern states lead to a long-term decrease of 5.5 heating degree days per year.

The indirect implications will arise in a wide range of policy initiatives related to limitation of carbon dioxide emissions, enhanced energy efficiency, development of more flexible electrical distribution grids, and to regulation of environmental impacts of power generation, including the temperature of cooling water discharge, disposal of ash and particulate materials, and perhaps carbon sequestration.

Proceeding systematically to assess implications of accelerating global change may help to identify the main opportunities and risks for the energy industry. Such a process might be developed along the following lines:

- **Identify and model links between business variables and environmental variables** (such as temperature, precipitation, or wind). How would change in the environment affect business outcomes?
- **Estimate the likelihood of change in environmental variables**. Describe the boundaries of the envelope of possibilities during the next few decades.
- **Estimate the likelihood of changes in the economic, policy, regulatory, and technology frameworks**. What will government do as it tries to mitigate and adapt to global change. How might customer needs and expectations evolve? What technological innovation could be significant or change the business dramatically? Describe the boundaries of the envelope of possibilities during the next few decades.
- **Assess the risks and opportunities quantitatively**. Make quantitative estimates of how change in the physical environment and the societal framework will affect the business. Consider both the most likely changes and examples of potential extremes. What metrics will prove effective in assessing change and business results?
- **Create business scenarios**. Develop realistic, long-term scenarios describing how a business could respond successfully to both the likely and extreme opportunities and risk analyzed in the previous step.
- **Determine key business decisions on the path to the future**. Which of the scenarios should be adopted as the basis for a strategic plan? What are the key uncertainties? What must be known to act? What investments will be required with what lead time? What should be the key metrics of business success and how should they be monitored? What would mandate a switch to another scenario, a new plan?

The evidence that significant climate change is underway is clear enough that companies in the energy industry should proceed with a deliberate consideration of the opportunity and risk ahead, giving careful attention to key business decisions and uncertainties. The climate, society, and the energy industry are sufficiently entwined that climate change will drive further change, first in society, and then in the energy industry. Starting now to manage that change would seem to be prudent and may avoid unfortunate surprise in the years ahead.

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WEATHER AND CLIMATE PREDICTIONS FOR THE ENERGY SECTOR

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Abstract. Weather and climate forecasts are potentially valuable sources of information for use in risk management tools. It is important however to be aware of their limitations (several approximations go into a forecasting model) as well as of opportunities to enhance their information content (e.g. through understanding the underlying physical processes which lead to a given forecast). This chapter explores, at a rather high level, the physical basis of forecasts, the tools used for producing them and the importance of assessing their skill. An interesting case of a seasonal forecast and its impact on the energy market is also discussed.

Keywords: Weather; climate information; climate predictions; forecast skill; energy management

1. Introduction

Weather and climate predictions are worthwhile scientific endeavors in their own right. What makes them really useful however is the application or transfer of this information to specific sectoral activities of societal relevance. There are numerous sectors for which this information is critical, prominent amongst which is energy. Energy exploration, extraction, transportation, refining, generation, transmission and demand are all critically exposed to weather and climate events in one way or another. Energy generation, to pick one, is sensitive to wind, rain, hail, ice, cloudiness, radiation, storms, droughts, water in rivers, unseasonable demands, amongst others. The potential for improving these energy operations by using quality weather and climate information is therefore apparent.

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Clearly to say that forecasts are valuable tools for a certain sector is just the beginning of a long path. One needs to assess which aspects of the predictions are really useful for energy applications – numerical models used for predictions churn out millions of variables and therefore one needs to be clear on what aspects of the forecasts are the most relevant for the problem at hand. Then there is the "presentational" aspect of the prediction. Getting the message across to recipients is what really matters: there is little benefit, apart from leaving scientists a feeling of accomplishment, to achieving the 'perfect' forecast if it is not used. Even when the useful variables have been identified and the message effectively communicated the road ahead is still rough. How does well-communicated weather/climate information get considered in the mix of information by the decision taker in the energy sector? In other words, how can you convey the fact that there is a high probability that a temperature anomaly of 2 degrees may occur for the next season over a certain region and such anomaly may affect the way gas is stored, for instance?

After an overview of the types of predictions available (Section 2), a discussion of how these forecasts are actually produced is given (Section 3). It is also important to acquire confidence in these forecasts and thus a discussion on the quality of these forecasts is provided (Section 4). The chapter concludes with a case study of the way a seasonal forecast was communicated in the UK for the European winter of 2005/06 (Section 5). Complementary discussion on weather and climate predictions can be found in Dutton (2009) and Buontempo et al. (2009) in this volume.

2. Rationale for Weather and Climate Forecasting

Weather forecasting has been around for many decades. Beginning from the first hand written charts of the 1940s the technology has expanded enormously. Forecasts are now performed using the most powerful supercomputers available that churn out millions of pieces of information coming from a combination of measurements of the earth system and the mathematical representation of the atmosphere, ocean, land and ice. These forecasts, available on horizontal grids of as low as 20 km on the global scale, have reached such a high quality that people can now consider sensibly, say, the predicted probability distribution of temperatures for a specific location at a 10-day lead time. Precipitation forecasts are not of the same quality as those for temperature as yet since, by its very nature, rainfall is highly variable both spatially and temporally and this makes it more difficult to predict. Overall, the chaotic nature of the climate system is such that we will always be limited in our ability to predict weather beyond a theoretical threshold (currently thought to be about 2 weeks but dependent on numerical model features, including resolution, used to test the predictability assumptions).

However, there are parts of the geophysical system, like the oceans, which evolve more slowly than the atmosphere and this slower motion allows us to extend the time horizon of predictions to well beyond this theoretical limit. That is why we can talk about seasonal to interannual forecasts, though the way in which results are looked at has to be modified (see discussion later). The ocean has a large heat capacity and slow adjustment times relative to the atmosphere. In addition, ocean variability can give rise to enhanced atmospheric predictability in the case of processes that depend on both media interacting. The coupling between the atmosphere and ocean is known to be relatively strong in the equatorial region, viz. El Niño/Southern Oscillation (ENSO). By including other external (to the natural earth system) factors such as human-induced gas concentrations in the atmosphere and oceans we can extend the prediction time horizon, also called *lead time*, even further and therefore produce climate change scenarios.

The extension of the predictions/scenarios lead time from a few days to decades needs careful consideration however. It is entirely reasonable that a prediction for a specific date 10 years from now may not be of the same quality as a prediction for the day after tomorrow, say. In other words, what is considered a meaningful feature, according to some metric, varies considerably according to lead time. So, looking at the predicted temperature probability distribution at a specific location for a certain day several months in the future, although do-able, has limited scientific validity. A practical approach to interpret predictions at different lead times is to increase the averaging spatial and temporal intervals with increasing lead times[1]. What this means is that instead of trying to extract information from a probability distribution at a specific location (e.g. Lecce) and a specific date several months from now it is more useful to consider how the climate is going to differ from a certain reference period for the Mediterranean region over the period of a month, say. More simply, the trick is in the averaging. By taking a larger area and a longer averaging period, the signal from the forecasts starts to emerge (whether it is the correct signal or not is a different matter: more on this in Section 4). Going even further into the future in terms of lead times (decades and beyond), one needs to consider even larger regions (e.g. North America) and longer averaging time periods (typically 20–30 years).

[1]Mathematically, this equates to saying $\bar{x} = \bar{x}(leadtime)$ and $\bar{t} = \bar{t}(leadtime)$.

In summary, in order to be able to extract potentially useful information, the longer the lead time the larger the averaging time and the larger the spatial area need to be. The schematic in Figure 1 shows how this can be done in practice for the time averaging case. Therefore the extent to which one can define medium-range, seasonal and decadal predictions/scenarios – along with the levels of their skill – will depend on the time and space scales considered. Note that the level of skill is an important qualifier because users would like to know about the quality of the forecasts before using them. An implication is that the longer the lead time the longer the observed record needs to be in order to assess the quality of a forecast/scenario. This is why, for instance, it is essentially impossible, at present, to define the level of skill of climate change scenarios.

It is worth noting that while the focus here is on weather and climate predictions, these are just a subset of all the available weather and climate information. For example direct observations and re-analyses (i.e. the 'best' reconstruction of the past) also provide extremely useful information for the decision making process (see Harrison and Troccoli, 2009, Chapter 9, this volume).

3. How Are Weather and Climate Forecasts Produced?

Different components or attributes of the earth system affect in specific ways physical processes relevant to weather and climate. By isolating certain aspects of the earth system predictions of weather and climate at different lead times become a more tractable problem. Generally speaking physical processes can be divided into fast ones (e.g. atmospheric convection) and slow ones (e.g. circulation of the deep ocean), with an essentially continuous spectrum of processes in between. Given the presence of this wide spectrum, choices about which process is more relevant for a particular purpose have to be made. Thus for instance it would be of little use to run a complex sea ice component to produce forecasts for tomorrow's weather as the sea ice response is much longer than a day. Likewise for a climate forecast several years hence, the precise details of today's weather are less relevant than for forecasts for the next few days/weeks. So, although in principle a single system for all lead times would be desirable (and this is what some prediction centres are attempting to achieve), in practice predictions are made with built-for-purpose model configurations.

As a rule of thumb, atmospheric initial conditions are essential for weather forecasts on lead times up to a few weeks, land surface initial conditions are important on lead times up to a few months, ocean initial conditions are critical for climate predictions on lead times from months to decades, and sea ice is relevant on time scales from years to centuries (unless it disappears in the meantime!). This time scale classification indirectly tells us also which component of the earth system needs the most attention by modellers at the various lead times. Typical current configurations of forecasting systems are illustrated in the schematic of Figure 2.

There are three essential elements in a forecasting system:

1. A numerical model for which various complexities are available (e.g. an atmospheric model)
2. Observations of the earth system (e.g. sea surface temperatures, greenhouse gas concentrations)
3. A strategy for combining numerical models with observations in a consistent way (e.g. using a variational assimilation approach)

These elements are discussed in more detail in the following subsections.

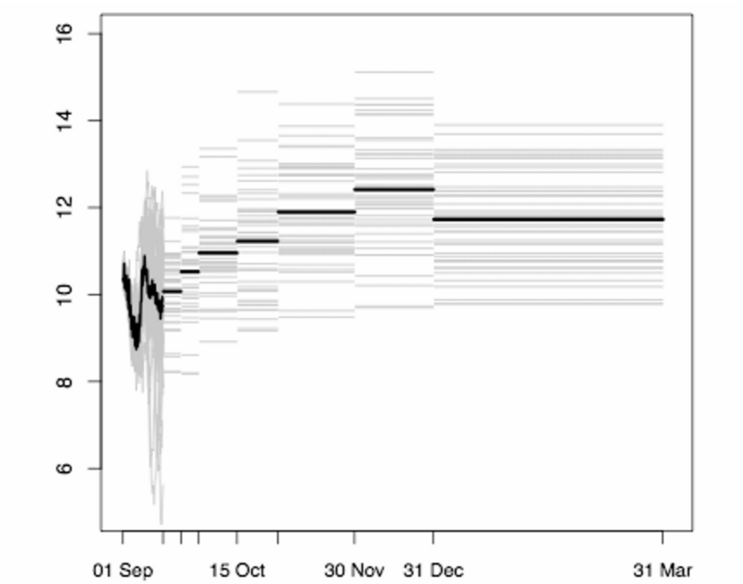

Figure 1. Example of time averaging for a generic forecast started on a 1st September. The time averaging has been applied here to an ensemble of forecasts (i.e. different representations of the same event) but the approach is valid even with one model realization only. The grey lines represent individual ensemble members and the black line is their mean. No time averaging is carried out for the first 2 weeks (the direct model output is plotted). This first period is followed by increasing time-window averages: two weekly averages, two bi-weekly averages, two monthly averages and a 3-month average. A similar approach can be applied to spatial averages. Plot adapted from Rodwell and Doblas-Reyes (2006).

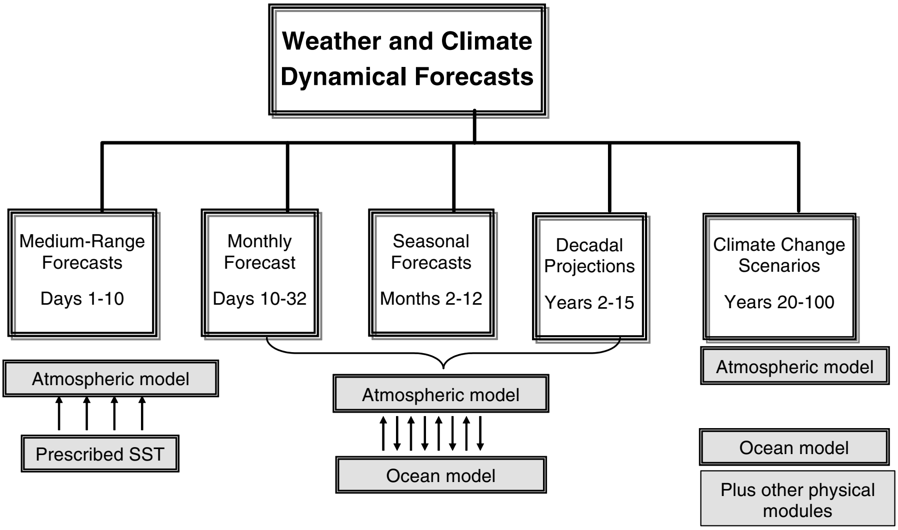

Figure 2. Schematic of lead time classification (from Medium-Range Forecasts on the left to Climate Change scenarios on the right) based on the forecast systems currently in use. For instance, Medium-Range Forecasts are carried out with an atmospheric model whereas at longer lead times an ocean model, possibly with a sea-ice component, needs to be used. Atmospheric models normally include a land surface model too.

3.1. NUMERICAL MODELS

A numerical model is a computerized version of mathematical relationships that describe the earth system. The earth system in these models is typically subdivided into cells of sizes varying by model (e.g. 100 by 100 km in the horizontal and 50 m in the vertical for the atmosphere). Dynamic and thermodynamic relationships are solved for each cell as well as for the interactions amongst cells.

All components of the earth systems could in principle be included in forecasting systems for each lead time. Practical considerations, however, limit the complexity of such systems. For instance, a weather forecasting system is normally constituted of an atmospheric model with a land surface component (left-hand-side in Figure 2). In such a system, the ocean model is often replaced by best estimates of sea surface temperatures at the start of the forecast. However, at longer lead times, say from several days onward, an ocean model becomes essential, even if its impact will differ according to which part of the earth system is considered. Thus, an ocean model is clearly more useful in places where ocean dynamics evolves faster. For instance tropical cyclones, phenomena which show a strong interaction between the atmosphere and ocean on time scales of hours/days may be better predicted when an ocean model is used (see Troccoli et al., 2008, for a case study of the impact of an ocean model on predictions of a tropical cyclone). It is also to be expected that deeper parts of the oceans become increasingly relevant at longer lead times. The details of the north-south deep ocean circulation in the North Atlantic, for instance, are unnecessary for weather forecasts but are important if a prediction a decade hence is attempted. Analogous considerations apply to ice models, biological models, carbon cycle models, and so on.

3.2. OBSERVATIONS OF THE EARTH SYSTEM

Observations are essential to ensure the model starts from a point as close as possible to reality. Observations can be segregated into two types:

1. *In situ* measurements, which require sensors to be collocated with the quantity to be measured
2. Remotely sensed measurements, which rely on inferring physical variables from afar through the inversion of a radiated signal

Radiosonde temperature measurements and satellite temperature retrievals are prototypical examples of in situ and remotely sensed data respectively. Prior to the advent of satellites in the 1980s, the majority of data were collected through in situ measurements. Since then an exponential growth in volumes of remotely sensed data from satellites has been achieved. To give an idea of this growth, about 100,000 observations were used for weather forecasting in the early 1990s. Now, about 15 years later, this number is about ten million, i.e. 100 times larger. The spatial data coverage has also become more uniform. Whereas before satellites the southern hemisphere was relatively poorly observed, now the quality of forecasts for the north and south hemispheres is basically the same mainly as a reflection of the more uniform global data coverage.

3.3. STRATEGIES FOR COMBINING MODELS WITH OBSERVATIONS

In order for a model to be able to produce reasonable forecasts, appropriate knowledge of the real world must be inserted into the model. The merging of observations and models is achieved through an approach called data assimilation. Data assimilation is therefore a combination of observations and model data, performed with the aim of achieving the ‘best’ initial state for the model. Ideally all available information should be used for this purpose. However practical considerations such as the inter-dependency of different observations, the need for models to be ‘in balance’ with observations (a technical requirement to ensure the model moves forward smoothly, rather than jumps, from its initial state) and many others put constraints in the way data assimilation is actually implemented.

We will not discuss the details of data assimilation, but it is worth noting that data assimilation is not a specific technique for the earth system only. Rather, it is utilized in a wide variety of disciplines, e.g. in satellite orbit determination, in any application that requires an optimal way to combine a model with observations. For a more detailed discussion see e.g. Tribbia and Troccoli (2008).

4. How Trustworthy Are Weather and Climate Forecasts?

A valid skill assessment of forecasts may only be carried out on past performance. As mentioned above, the longer the lead time the longer the period of assessment must be. This is perfectly understandable since skill assessment requires a minimum number of cases in order for its statistics to become robust. Weather forecasts are typically assessed over a few seasons, assuming the forecasts are run every day, i.e. the sample is of order of hundreds of cases. Seasonal forecasts are normally assessed over 2–3 decades, with the system run every month, i.e. again of order hundreds of cases. Very different is the case for climate change scenarios for which no assessment can be made except by using the model to ‘predict’ over a past known period.

By carrying out these assessments one finds that skill varies markedly depending on the region considered, on the state of the earth system components when the prediction starts and on the lead time. So for instance it is easier to predict when an El Niño is likely to occur than to predict its termination once it has started. This is because we understand relatively well the dynamics of the ocean-atmosphere interaction subsequent to the start of an El Niño (e.g. see Anderson, 2008). Moreover, location dependent skill is easily explained if one takes into account local features (e.g. a mountainous region versus a desert) or the presence of remote atmospheric connections (also known as tele-connections) during, for example, an El Niño. More specifically, because of the relatively large climate anomalies accompanying an El Niño, several global tele-connections are manifest, for instance, over North America. Thus, although predictions are generally more skillful in tropical areas than at higher latitudes during an El Niño, predictable features can be seen at higher latitudes. A map of skill for near surface temperature of a seasonal forecasting system as given by the anomaly correlation for forecasts started in February is shown in Figure 3. This plot confirms that the tropics display a higher degree of skill but higher latitudes also have some potentially useful skill, where correlations are larger than 0.4. Somewhat different considerations apply to another important physical variable, precipitation. Although the analogous map for precipitation displays also a maximum in the equatorial Pacific, though with lower values, elsewhere correlation values are close to zero (not shown).

Maps such as that in Figure 3 provide useful indications about the quality of predictions. As one can imagine, a much more extensive assessment than just correlation maps is normally carried out in operational forecasting centres in order to examine how a forecasting system is performing. This is because (a) there are many ways skill can be measured, correlation being just one of them (see e.g. Mason and Stephenson, 2008); (b) skill depends on time and location and (c) several other physical variables need to be assessed aside from the most common two, surface temperature and precipitation (e.g. pressure, wind). As a result of such evaluations a wealth of statistics is usually produced which can then be used to calibrate subsequent specific forecasts either objectively or subjectively.

Statistics are fundamental to gaining confidence on the quality of a forecasting system: clearly it is desirable to learn as much as possible about past performance before diving into the unexplored territories of the future. However, one needs to be careful about over-interpreting statistics. By definition, statistics provide a summary of behavior of a system and as a consequence they may gloss over important details.

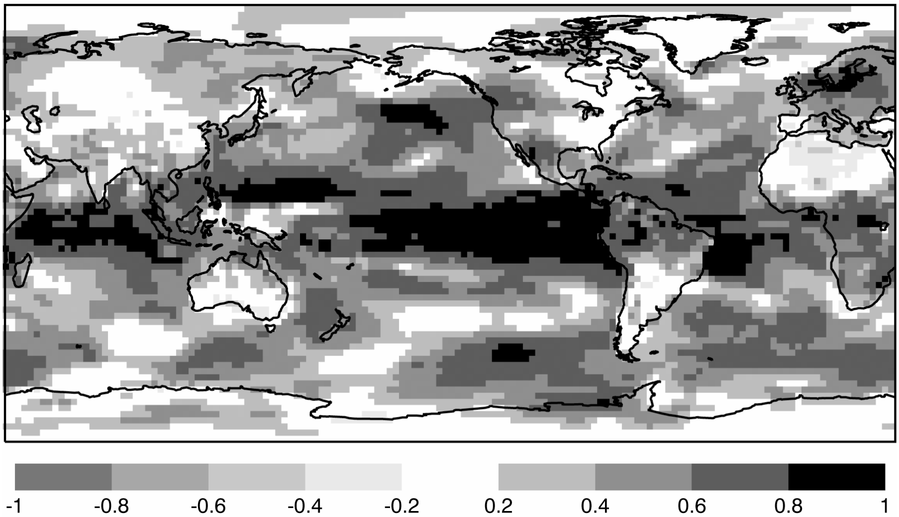

Figure 3. Skill of a seasonal forecasting skill as measured by anomaly correlation for near surface temperature. Results will vary depending on the season being predicted. In general skill is higher in the tropics than at higher latitudes and for this particular season (March-April-May) the temperature signal over northern Europe is real (From Anderson, 2008).

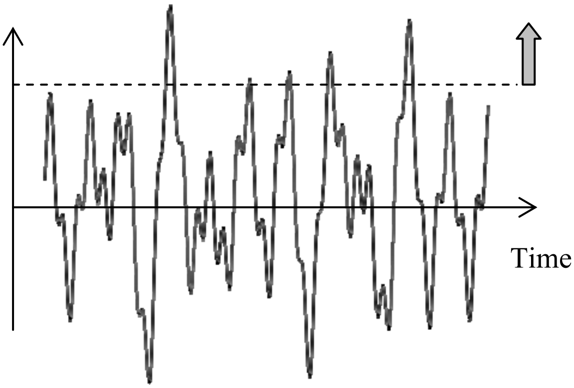

Figure 4. Schematic of temporal evolution of a generic skill measure with zero mean. Values above a chosen threshold (dashed line) may provide potentially useful predictions (the so-called "Windows of Opportunity").

Imagine a particular skill measure that behaved like the curve in Figure 4 with periods of both negative and positive values, but with a zero mean (this could be a white area within Figure 3). It is apparent that, based on this skill measure, there are instances on which this forecasting system performed particularly well. This may be the case, for instance, for forecasts produced while an El Niño is underway: models are often sensitive to stronger anomalies such as those provided by an El Niño and hence their response may emerge from the noise during such events and may then provide a good forecast. Periods of higher positive skill in such circumstances are normally referred to as "windows of opportunity" as potentially beneficial forecasts may be attainable during such periods.

Being able to exploit windows of opportunity would therefore equate to achieving a higher skill than that yielded by assessing the system purely from a statistical basis. Critical to the exploitation of these windows is the understanding of how the physical system works. The forecast provided by the model then becomes just one, though an important, piece in the jigsaw of the final forecast. This was the case with the seasonal forecast issued by the UK Met Office in the winter 2005–2006 discussed in the next section.

5. Prediction for a Cold Winter: Impact on the Energy Sector

In August 2005 and in updates during the subsequent autumn, the UK Met Office issued a forecast for the UK and the rest of Europe for the boreal winter 2005–2006. Public seasonal forecasts had routinely been issued for about a decade, but this was the first time the forecast was specifically targeted to a high latitude region such as UK/Europe. Judging by the overall skill of the UK Met Office (and others) dynamical seasonal forecasting system this forecast looked hazardous: the skill of temperature predictions over the region was in fact negative on average. However, the dynamical forecast constituted only part of the forecast preparation process. The final forecast was prepared by considering also information from a statistical model, from observed subsurface ocean conditions and their evolution, as well as from interpretation by operational forecasters (Graham et al., 2006). Based on these various inputs the issued forecast read:

> Our predictions continue to indicate a colder than average winter for much of Europe. The balance of probability is for a winter colder than those experienced since 1995/6. There is also an indication for a drier-than-average winter over much of the UK.

In spite of the impossibility to state after the event whether an individual probabilistic forecast of this type was correct, most of Europe did experience the colder-than-average temperatures stated as a 66% probability in the forecast (Folland et al., 2006). Southern regions of the UK were indeed affected, though northern UK had a relatively mild winter. The UK also had a drier-than-normal winter, as suggested as more probable by the forecast – as did much of the European region. Thus, on this occasion, the observed European conditions for winter 2005/06 matched very closely the most likely outcome that had been predicted.

5.1. IMPACT OF WINTER FORECAST ON ENERGY MARKETS

As it may be expected in a colder-than-normal winters, energy markets have to be prepared to face marked changes in offer-demand balances. Especially when energy availability is low, cold spells, and therefore increased demand for energy, may trigger disproportionate market reactions. As it turned out, towards the end of 2005 the UK was turning from a net exporter of gas to a net importer. Moreover, there was a high demand for energy in other parts of Europe too. Ahead of the winter 2005/06, there was no impact on the markets at the time of the Met Office winter forecast press release in September. The markets did however react significantly when the first anomalously cold weather hit London in November (e.g. Oil & Gas UK, 2007), so it is possible that the winter forecast primed the markets and made them more sensitive (Troccoli and Huddleston, 2006). Overall wholesale gas prices for the UK remained well above the long term average for the whole winter 2005/06, reaching another peak in mid-March 2006, reflecting the fact that demand was anomalously high.

A question often asked by stakeholders when they were told about the prediction for a cold winter was: "How cold is cold? You're the experts - what's your best guess?" Indeed many people naturally needed context for their planning: was it going to be another 1962–1963 British winter, the coldest over England and Wales for more than two centuries? Not properly quantifying the context led to a lot of invention about how extreme it would be in 2005/06. And although climate information, as often is the case, was only one of the components in the decision making process (e.g. Harrison et al., 2008), better communication could have possibly avoided over-reactions by the energy markets.

All in all, important lessons were learned by the scientific community in the UK following the 2005/06 winter forecast exposed, as it was, to public reaction to a long-range (seasonal) forecast. One such lesson was that it is crucial to engage with a wide range of stakeholders to ensure they understand the forecast and that they do not base their decisions on, say, newspaper headlines, as happened in some cases. It is probably fair to say that one critical aspect of communicating forecasts, deterministic and probabilistic, yet to be resolved adequately is the proper communication of uncertainty to all. For less specialised audiences "likely" might be more readily understood than "a 60% chance", yet might lead readily to misinterpretation. Precise communication (e.g. a 60% chance) unfortunately might confuse, or even repel, some. Answers on a postcard, please.

6. Conclusion

In this chapter the different types of predictions available have been presented along with a discussion of how these forecasts are produced and assessed. A case study of the prediction of the European winter of 2005/06 and its impact on the energy market in the UK has also been presented. The main messages are: (1) the quality of forecasts is dependent on the time and space scales considered; (2) although average skill may be low, there may still be windows of opportunity to be exploited: it is important to get to know the system and not to consider just overall statistics (forecasting, especially at time scales longer than 2 weeks, is a recent endeavor and as such is still a mixture of science and art: the role of the forecasters, the people who understand the physical aspects of the system being forecasted, is therefore vital); (3) when communicating forecast it is important to quantify the context e.g. by referring to recent periods or major events.

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MULTI-SCALE PROJECTIONS OF WEATHER AND CLIMATE AT THE UK MET OFFICE

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Abstract. Due to the availability of unprecedented computational power, national meteorological and hydrological services have had the opportunity to push the limit of predictability beyond the 2 weeks Lorenz suggested in 1963. This has been largely possible through the use of ensemble modelling. The adoption of such a technique has had a twofold effect: by averaging out the most unpredictable scales an ensemble average could directly increase forecast skill; ensembles also provide an estimate of uncertainty. This paper analyses the sources of predictability at different time scales and shows how the ensemble technique has been successfully used to inform decisions on time scales ranging from days to centuries.

Keywords: Weather forecast; ensemble; seasonal prediction; climate projection; uncertainty; predictability; decadal prediction

1. Uncertainty and Prediction: From Initial Condition Sensitivity to the Effects of Radiative Forcing

Weather predictability, as Lorenz discovered almost 50 years ago (Lorenz, 1963), depends on the accuracy of the initial conditions and generally on the specific state of the atmosphere[1]; it also depends on the realism of the model. Since then numerical models have increased in complexity and resolution and now are routinely used to provide not only weather predictions but also seasonal forecasts and centennial climate projections.

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[1] More generally predictability depends on the specific state of the dynamical system (ocean, troposphere, stratosphere, etc.).

Figure 1. Schematic process of an ensemble prediction system. This is a procedure which maps a small subset of climatology, the analysis uncertainty (dark grey on left-hand side), into a generally larger subset of climatology, the forecast uncertainty (light grey on right-hand side). F may, in fact, include unphysical states.

Despite the similarities in the models used for these purposes there are some important differences between different time scales. While on the weather time scale overall uncertainty tends to be dominated by the uncertainty in the initial conditions, on longer time scales other processes become relevant. Climate projections, for example, tend to be dominated by the uncertainty in driving conditions (e.g. greenhouse gas emission scenario, volcanic eruptions) and by the structural uncertainty associated with model formulation. In this section we analyse the uncertainties operating on the different time scales and describe how the different flavours of the ensemble approach can be used to increase reliability of predictions and to estimate associated uncertainties.

1.1. WEATHER PREDICTIONS

Predictability in weather forecasting is limited by the chaotic nature of weather. As Lorenz first noticed in the 1960s "*even with perfect models and perfect observations, the chaotic nature of the atmosphere would impose a finite limit of about two weeks to the predictability of the weather*" (Lorenz, 1963). This sensitivity to the initial condition gives rise to the so-called predictability of the first kind (Kalnay, 2003): two very similar initial conditions can develop into very different futures.

Building on an original idea of Epstein (1969) and Leith (1974), the National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) started developing operational ensemble prediction systems (EPS) in the early 1990s (Kalnay, 2003). The idea behind this approach is to run several model forecasts starting from different perturbations ***I*** of the initial conditions. The size of ***I*** (dark grey in Figure 1) reflects our ignorance on the actual state of the atmosphere. This cloud of initial states is expected to surround the "true" state of the atmosphere at the start of the simulation. For this forecast process to be meaningful we should expect that $\boldsymbol{I} \subset \boldsymbol{C}$ where $\boldsymbol{C}$ represents the total phase space accessible to the system. The prediction consists of integrating numerically the equations of motion starting from these different initial conditions. Because of the variety of starting points each forecast will follow a different trajectory in the phase space. Assuming we had infinite time to wait, and assuming a steady climate and a perfect model we should expect the forecast process to explore the entire phase space. The fact that even after infinite time certain parts of the phase space will never be reached (or that physically impossible states can be predicted) indicates that the models are normally structurally biased[2].

To address a source of uncertainty which is likely to dominate on longer time-scales, namely the structural uncertainty associated with the model formulation, in the current implementation of the Met Office weather ensemble prediction system, similarly to what happens in other centres, the difference between different trajectories is also enhanced through the adoption of a stochastic physics approach (Bowler et al., 2008).

Most weather forecasts are now based on ensemble prediction systems. These systems are able to provide skilful predictions for up to 2 weeks into the future.

1.2. SEASONAL PREDICTIONS

The 2 weeks Lorenz identified as an upper limit to weather predictability, despite representing a serious constraint for weather forecasts, are relevant only to atmospheric processes. Seasonal anomalies and longer-term climate anomalies tend to be controlled by other processes whose predictability is not necessarily limited to 2 weeks. We are now aware of several processes operating on time scales of months or years. This is, for instance, the case of the Madden Julian Oscillation (MJO), El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Southern Annular Mode (SAM), or the Quasi Biannual Oscillation (QBO). This long-term variability of the climate system can be used to predict the climate on time scales exceeding those associated with the daily weather.

On time scales longer than 2 weeks – when atmospheric models with prescribed boundary conditions lose skill – slow-varying processes can

[2] The envelope of all the predicted states after infinite time F does not normally coincide with the accessible phase space $\boldsymbol{C} \cap \boldsymbol{F} \subseteq \boldsymbol{C}$.

make it possible to predict the probability of occurrence of specific weather-related events. The anomalies in the ocean heat-content and the changes in the soil properties (snow cover, humidity, vegetation) are two of the most important processes responsible for climate anomalies on the seasonal to decadal time scale. Unlike the weather forecasting ensembles, the seasonal prediction systems include interactive ocean and sea-ice models and thus are able to resolve the internal dynamics of the oceans and their interactions with the atmosphere. The UK Met Office, for instance, uses the coupled model GloSea3 for its seasonal predictions (Graham et al., 2006, and references therein). GloSea3 and its successor GloSea4 are basically identical to the model used for climate projections (Ringer et al., 2006a, b). Compared to the climate model the seasonal model has a higher-resolution ocean which is initialised to take into consideration the most recent observations.

Research has shown that even on seasonal time scales predictability is mainly limited by knowledge of the initial state of the system. The dynamics of the ocean, generally slower than the dynamics of the atmosphere, allow predictions beyond the 2-week limit. The fact that uncertainty in seasonal predictions is generally larger than that associated with weather forecasting (Figure 2) has to do with both the limited number of suitable observations in the ocean and the relatively weak forcing which the ocean and other slow processes exert on the atmospheric variability.

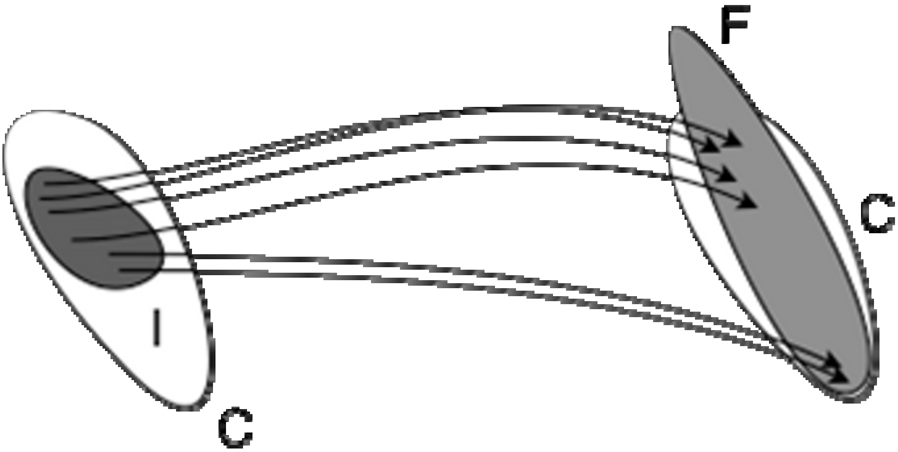

Figure 2. Schematic description of a seasonal prediction system. The uncertainty in the predicted state is larger than in a weather forecast. The predicted area is a subset of the accessible phase space. In the example four forecasts are predicting one outcome while two others are suggesting a completely different outcome. This information can be translated into a probability of occurrence for the two different outcomes.

1.3. CLIMATE PROJECTIONS

The memory of the initial conditions of the atmosphere (ocean) used in prediction models is believed to be lost within months (years). This implies that in a stationary climate there should be no predictability on very long time scales. A stationary climate requires ‘constant’ boundary forcings; it is now commonly accepted (IPCC AR4) that it is very likely that increases in concentration of greenhouse gases (chief among them carbon dioxide) have caused unprecedented changes in the climate. Knowledge of how man’s activities alter the atmospheric composition and land use and assumptions on how these will evolve in the future effectively offer predictability on a centennial time scale. By modelling the interaction of greenhouse gases with the climate system it is possible to describe what the average “weather” conditions will be like in a few years’ time given projected changes in their concentrations. It is important to highlight that this is a completely different form of predictability from the one which underpins predictability on a shorter time scales (Figure 3). Unlike predictions on shorter time scales, climate projections on multi-decadal time scales are based on accurate modelling of energy balances and fluxes, primarily the effects of radiative forcing. By detailed modelling of these effects it is possible to provide realistic long-term projections.

1.4. FILLING THE DECADAL GAP

In the previous sections we have seen how predictability on different time scales is limited by different factors: initial condition and chaos for relatively short time scales, “boundary conditions” and chaos in the climate-change range. This distinction would seem at first to suggest the possibility of a predictability gap. The time scales which are not long enough to experience a significant change in radiative forcing and which, at the same time, are long compared to a seasonal-prediction horizon are the most difficult to tackle. From a climate modelling point of view decadal prediction is neither a pure initial value problem nor a pure boundary conditions problem: both factors play a limiting role in predictability on this time scale (Cox and Stephenson, 2007).

However, there are known modes of climate variability which operate on decadal and multi-decadal times cales. To investigate their predictability, recently several climate centres have started producing short-lead climate projections initialized with observed ocean and atmosphere conditions. Unlike some seasonal predictions (where the effect of changes in radiative forcing is considered negligible on intra-annual time scales), these projections include the effect of radiative-forcing changes. Unlike climate projections, where specification of the initial state is believed to be relatively unimportant on very long time scales (especially in the context of the expense of initialising predictions with observations), decadal systems start predictions from observations, in an attempt to represent the influence on the forecast of the internal variability of the system. As with the other time scales where the initial conditions (and therefore natural variability) are considered important, decadal predictions are generated from initial-condition ensembles. Uncertainty due to variations in the projected radiative forcing (believed to be small) has not yet been quantified.

Decadal projections have shown skill in temperature predictions which exceeds both that achievable through usual climate projections and those based on present-day climatology (Smith et al., 2007).

The decadal time scale is very relevant for investment decisions. An example of the interest the private sector has in such projections is represented by the UK energy project Energy Phase 2 (EP2). In 2007 the UK Met Office was asked to provide energy companies with information on how to modify their investments to take into consideration the most likely climate conditions for the next 10 years. These experimental projections were based on a decadal prediction system.

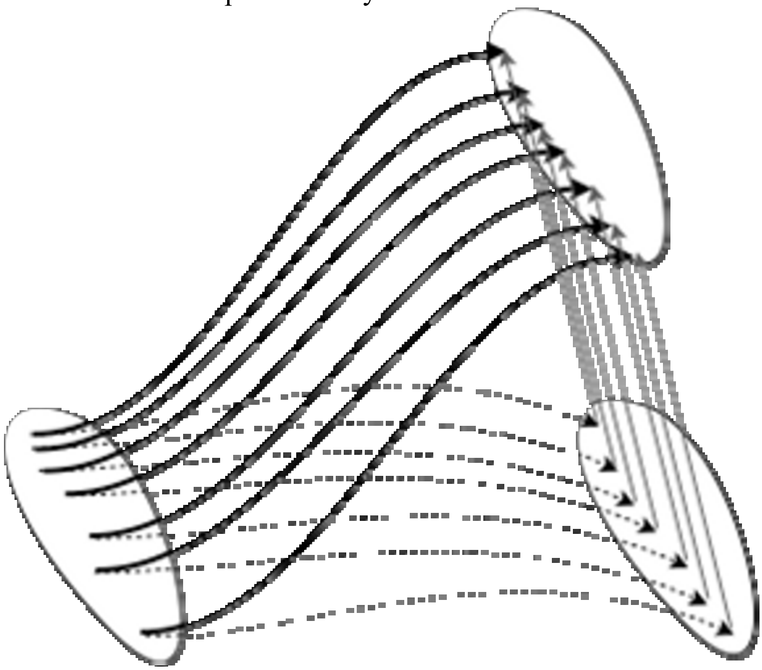

Figure 3. Schematic description of a climate projection. In a very simplistic view it can be said that predictability mainly comes from the ability to predict a shift in the climatology rather than from the ability to reproduce a specific climate state.

2. Useful and Accessible Predictions

2.1. TOOLS FOR IDENTIFYING SYNOPTIC FEATURES

Communicating probabilities and uncertainties is a difficult task. The first step to make a forecast more accessible to the final user is to make it more accessible to the weather forecasters. The Met Office Regional Ensemble Prediction System (MOGREPS), which addresses short-range time scales, is used by forecasters to analyse the development of significant synoptic features over the next 2 days. In the example shown in Figure 4, the click-able synoptic map is used to follow the development of a relatively small but important feature present in the analysed field. Clicking on a feature of interest brings up the forecast ensemble for the variables involved. Here, a low-pressure system in the north Atlantic is predicted by part of the ensemble members to evolve into a very intense wind storm over Scotland. In the event – on New Year's Eve 2006 – the wind reached 100 mph, leading to the high-profile cancellation of New Year's Eve celebrations and loss of power to thousands of homes.

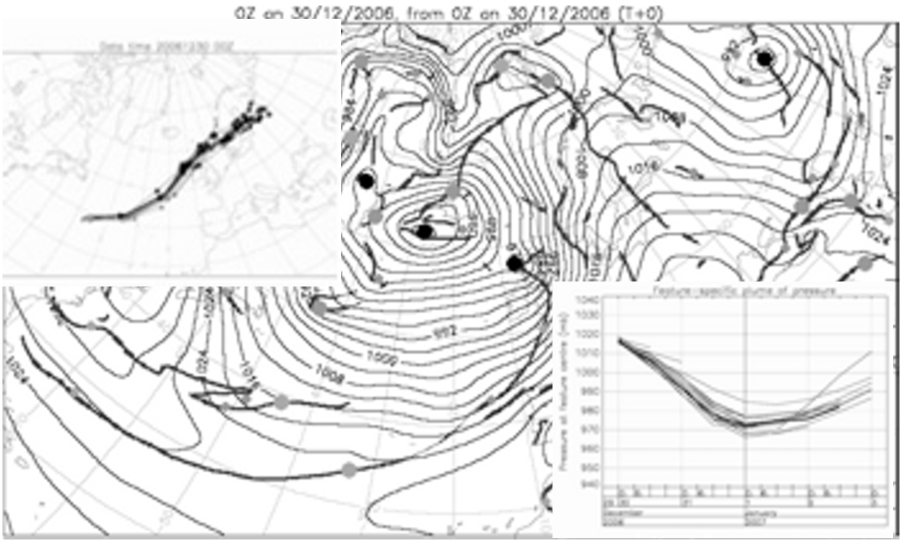

Figure 4. The 2006 New Year's Eve wind storm: the two boxes represent, respectively, the predicted storm tracks (top left) and the pressure at the centre of the storm (bottom right) for different members of MOGREPS.

The tool is aimed at an educated audience interested in following the development of a weather system, rather than the general public. Generally speaking weather and climate information is relevant to the final user if it offers local information about parameters of relevance. The first step in the process of making weather information more useable is to make it geographically relevant. On all time scales local predictions are more likely to trigger action than large-scale forecasts. Local weather predictions based on the ensemble approach are now part of the routine products disseminated by national meteo-hydrological services on a daily basis.

Figure 5 shows an example of an extreme precipitation alert generated for a specific location during the summer 2007 floods in England. In this case the ensemble approach is used to inform about the likelihood of precipitation exceeding different thresholds.

If localising the data is a common way to make the information relevant to the final user, another way of achieving the same objective is by mapping the weather information into a more user-relevant set of variables. A good example in that respect is represented by the energy sector which is interested in prediction of the total energy consumption across several regions or the entire country. This is normally a function of both weather and many non-meteorological parameters, including user behaviour. Working closely with experts from the UK energy industry the Met Office has developed tools to estimate the weather-related element of energy demand using the regional MOGREPS ensemble.

Figure 6 shows an example of ensemble temperature predictions averaged across 11 UK sites weighted according to local population density. This information is particularly useful for the UK-based energy companies as it can feed directly into national gas demand prediction. Generally predicting the impacts (user-relevant variables) is perceived as more useful than predicting large-scale climate (model variable).

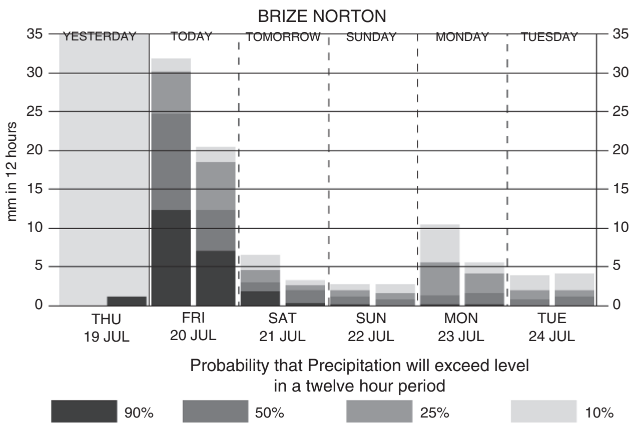

Figure 5. Probability of intense precipitation for a central England location during 2007 summer floods obtained from the Met Office ensemble prediction system.

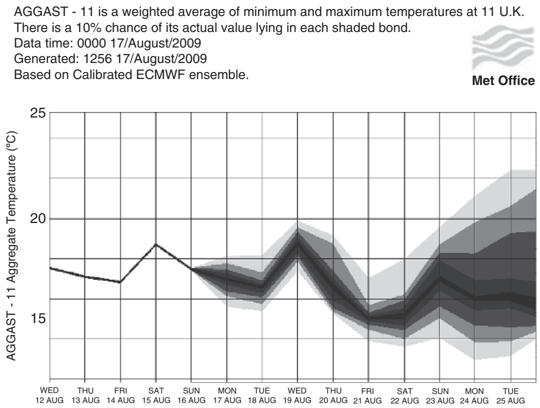

Figure 6. UK temperature average over 11 sites weighted according to local population.

2.2. THE ENERGY PROJECT (EP2): USING PRESENT DAY SENSITIVITY TO INFORM LONG TERM DECISIONS

In the private sector, energy is one of the areas more directly affected by weather and climate. Consumption, production, distribution and supply are all processes that are very likely to be affected by changes in environmental parameters. As a consequence of the publication of the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC AR4 2007) several energy companies have started to take a particular interest in the climate issue. This means on one side a new impulse to develop cleaner technologies which may help mitigation of climate change, and on the other increasing interest by energy companies in how climate change is likely to directly affect their production processes.

In conjunction with key energy players, the Met Office has developed practical ways to respond to the challenge of climate change in the areas of renewable, conventional and nuclear generation, transmission and distribution network planning, energy trading and forecasting. The energy regulator, OFGEM and the Department for Business, Enterprise & Regulatory Reform (BERR) have been informed and advised of the challenges that may need to be addressed. The main findings of the project regarded network design standards, including changes in risk profiles for critical elements such as transformers, cables and conductors, the reduction in thermal plant output, the wind power potential and the vulnerability of infrastructure to extreme events such as snow and wind storms. The project also assessed changes in energy demand (gas and electricity).

This work was done before the release of the datasets associated with the UK Climate Projections 2009 (UKCP09) which now provide, for the UK, probabilistic information on climate change. The results are based on a sophisticated statistical-ensemble technique developed at the Met Office.

In order to provide the energy companies with results resembling those that will become available via the UKCP initiative the Met Office regional climate model has been run at high resolution for different emission scenarios. The data post-processing, which maps weather parameters into impacts for the energy companies, was largely driven by present-day sensitivity to weather. In that respect EP2 represents a model for multi-scale climate risk assessment. On the long time scale the analysis has provided energy companies with guidelines on how to deal with climate projections and their related uncertainties. On the shorter time scale the project has represented the first practical application of the decadal prediction technique. Up to date climatology for weather parameters relevant to energy demand were provided using a combination of recent observations and decadal projections.

2.3. EXPLORING CLIMATE CHANGE UNCERTAINTIES AT REGIONAL SCALE

Unlike sensitivity or predictability studies, practical applications require information on uncertainties due to the formulation of the prediction model. On long time scales, such uncertainties are dominant (Cox and Stephenson, 2007). The Met Office Hadley Centre, in the QUMP project (Quantifying Uncertainty in Model Predictions, Murphy et al., 2004) has pioneered the technique of ensemble climate predictions, to systematically explore the uncertainties in climate projections associated with the structure of the model, the internal variability of the system and the greenhouse gas emissions. Bearing in mind that by definition climate projections represent an extrapolation exercise this innovative ensemble approach can be used to provide guidelines on the likelihood of specific future conditions. Using the ability of each ensemble member to reproduce present day climate it is possible to construct quantitative estimates of future climatic conditions.

UKCP09 uses data from the QUMP ensemble and a complex statistical post-processing technique to derive probabilistic predictions for changes in several meteorological parameters over the UK, on climate time scales. The statistical methodology developed to deal with this innovative and large dataset, though in principle available to use for other similar applications, is too expensive and complex to be applied to every situation of interest.

Recently a much simpler but still informative approach has been followed to provide the government of Egypt with estimates of future changes in water resources in the Nile basin. The Nile represents a crucial resource for the economy of eastern and north-eastern Africa. Agriculture, energy production and livelihood in general depend strongly on the river. For this reason assessing the impact climate change may have on water resources is of critical importance for the people living in the Nile Basin. The Met Office regional climate model has been run several times using different QUMP members as driving conditions, to create an ensemble of regional (high resolution) predictions, likely to be more informative than simulation based on a single model scenario. The procedure, which is not country-specific, can be easily adopted in other regions.

3. Conclusion

Climate, seasonal and weather models share a common logical and mathematical structure independent of the specific time scale for which they have been developed. Sometimes, as is the case with the Met Office atmospheric model, component models are common to predictions systems designed to address different time scales. Users' sensitivity to weather and climate is similar for most time scales: learning about the weather sensitivity of a specific human activity or process helps to develop understanding of the effects of changes operating on longer time scales.

It is important for the meteorological community to start developing multi-scale tools that tackle and communicate, through a similar interface, the operational needs of all customers. On the technical side, attempts have been made to unify post-processing methods and extend the use of tools appropriate for adding value to predictions for one time scale to other time scales (Palmer et al., 2008). This interaction between tools developed to deal with different problems and different times scales is a promising way to improve the usefulness of model predictions.

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METEOROLOGY, CLIMATE AND ENERGY

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Abstract. After studying the needs within various energy sectors, this chapter aims to present solutions that meteorologists can provide, using specialized tools (Satellite observation, climatology, modelling) combined with their know-how and knowledge.

Keywords: Energy needs; meteorological solutions; climatology; forecast

1. How Meteorology Developed

Climatic and meteorological events have punctuated people's lives since time immemorial, affecting them every day, week, season and year. With the emergence of new technological possibilities in the twentieth century, much progress was made in the field of meteorology, opening up new perspectives for weather forecast users.

Weather forecasting appeared with systems based on differential equations, solved according to the physical rules governing atmospheric movement. In order to be able to solve these equations, based on the continuous movement of the atmosphere, and forecast meteorological situations before they even took place, calculation times had to be reduced:

- By removing the less significant parameters to simplify the equations
- By taking into account a horizontal resolution of several tens of kilometres
- By limiting the number of vertical levels
- By considering a greater incremental time for atmospheric changes

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Today, the tools have clearly evolved:

- Transmission systems have changed making it possible to define a satisfactory atmospheric state in a short amount of time.
- Observation data have been transformed with the arrival of satellites: these provide a substantial amount of information at a high frequency (every quarter of an hour) and covering the entire planet, including the oceans and uninhabited areas.
- Developments to IT tools continue to make headway. With the emergence of supercomputers and their new architectures, more calculations can now be run (today's order of magnitude is the teraFLOP: 1,000 billion operations/s). This has led to improved system resolution accuracy and extended forecasting ranges. With the enhancements made to computerised data storage capacity, it is now possible to work on observation and forecast data bases.

These developments have provided National Meteorological and Hydrological Services (NMHS) with a higher quality and greater number of tools to ensure the safety of property and people, which is part of their mission. The other part of their job involves providing top-quality information about forthcoming weather conditions for the benefit of every individual. The reliability of the information allows professional users to include it in their risk management and hence optimise their activity and, consequently, their profits.

This safeguarding role explains why the aviation and marine sectors were the first professional users of weather forecasts. However, energy sector professionals were probably the first to actually integrate meteorological information in the day-to-day management of their activity (and their profits).

2. The Meteorological Needs of Energy Specialists

The primary role of energy specialists is to supply each energy subscriber with the energy they need (electricity, gas, oil, etc.). To do this in an affordable manner, the specialist has to forecast the possible consumption of their customers as accurately as possible. This is so they can better manage available energy in terms of source, storage (if applicable), production and transmission.

Like meteorologists, energy specialists rely on systems of equations, to be solved in real time, in order to constantly plan ahead for future consumption. Of course, the different parameters used in consumption calculation systems include economic information (consumption on a week day differs from that on a public holiday), but also data about the weather conditions (e.g. a drop of 1°C across France means an additional national consumption of 2,100[1] MW).

Owing to the fluctuation of energy prices on the markets, the input data for these systems (user consumption profile, meteorological data, availability of production means, etc.) are strategic for energy specialists. This is why they constantly strive to improve their consumption and/or production calculations by including new parameters or new methods in order to obtain the best value from their model input data.

From a historic point of view, the first forecasts produced by these specialists were based on consumption. Today, the need to optimise procurement costs (for purchasing or production) has created new meteorological requirements. Similarly, given the national importance of energy supplies for all users, governments require energy transmission means to be managed in the best conditions.

Depending on the specific problem of the energy specialist, different meteorological parameters are used.

2.1. TO ESTIMATE CONSUMPTION

- Temperature is the parameter offering the highest correlation. Its biggest effect is in the winter when heating is used, but it is becoming increasingly important in summer with the appearance of air conditioning systems in houses and buildings.
- Modelling of the consumption linked to lighting is based on cloud cover.

Depending on the energy specialist's sector (electricity, gas, etc.), consumption is calculated according to the need for heating, air conditioning and lighting. This is why temperature and nebulosity are useful parameters for such specialists.

2.2. TO OPTIMISE PRODUCTION MEANS

Depending on the production techniques used, energy specialists have different needs in terms of meteorological data and may be required to forecast their production.

[1] Information collected by RTE, the French transmission system operator, in October 2008.

- Hydroelectricity: the history and data relating to rainfall are useful when decisions have to be taken about whether or not to use hydropower dams to produce electricity.
- Wind electricity: at the early stage of a project to set up a wind farm, energy specialists may call on NMHSs to determine the geographic areas offering the best wind potential to produce electricity.
- Photovoltaic electricity: as with wind energy, specialists may need to use weather forecasting services to target the most advantageous locations for installation.
- Temperature: the efficiency (and even use) of many production means (e.g. nuclear power plants and cogeneration plants) varies according to temperature.

2.3. TO OPTIMISE TRANSMISSION

When transmission facilities are located outdoor they are subject to weather conditions. These conditions have to be taken into account in order to ensure better management and prevent loss:

- Depending on the temperature, the transmission capacity of high voltage lines may be lowered.
- Extreme events (such as strong winds, icing, etc.) must be forecast as early as possible so that maintenance teams are ready to act. It should be noted that transmission specialists who are aware there is a risk of icing (based on temperature, humidity, etc.) can adopt transmission methods to reduce this risk.

2.4. TO PLAN INFRASTRUCTURES

Energy specialists generally need to plan ahead for the infrastructures needed in the coming decades, if not the next century. This is why their planning has to take into account future lifestyles, industrial resources and climate conditions. With the current change in climate, forecasting climatic conditions is of prime importance, at least in terms of the parameters with the highest energy correlation.

3. Meteorologists' Solutions to Energy Specialists' Problems

The French NMHS, Météo-France, has the meteorological skills to match the aforementioned needs of energy specialists. Its expertise covers the following areas:

- Climatology
- Studies associated with climatology
- Supply of real-time observations
- Short and medium-term weather forecasting
- Long-term weather forecasting

Each type of data provides energy specialists with information enabling them to better manage the risks relating to their activity.

3.1. CLIMATOLOGY

NMHSs are generally in charge of saving data about the weather, in other words the meteorological data measured in stations across the country. Depending on the agency's capacity, the information saved and archived may or may not be re-usable (electronic or hand-written data, data that may or may not be integrated into databases, etc.).

Today, such data can be backed up by the new observation means available. Additional information can be provided by satellites but it is also possible to recreate climatological data using atmospheric models.

3.1.1. *Conventional Climatological Data*

The various NMHSs across the world have set up coordinated observation networks and transmission systems so that the meteorological information measured in their stations is accessible to all. Used for research purposes and by other NMHSs, this information is of course available to other users within the framework of international, commercial and institutional agreements.

Each NMHS is thus responsible for its observation network. Each network is characterised by its density, the parameters measured, the periodicity of measurements, the rules for transmission on the WMO Information System (WIS) and archiving.

As a general rule, all hourly data measured are now archived thanks to the introduction of automatic systems. In the past, only 3-hourly, or even 6-hourly, data were kept.

The parameters available are:

- Temperature in a sheltered location
- Humidity
- Wind (force and direction)
- Rainfall
- Pressure

Other parameters may also be available but not necessarily in every station or country:

- Ground temperature
- Radiation (diffuse, direct and/or global)
- Cloud cover
- Current weather encoding

Generally speaking, all the existing data in data bases can be made available to customers in the form of a computer file. This availability may or may not depend on local commercial agreements.

3.1.2. *Climatology Satellite Pictures*

Since around 1980, atmospheric observations have been backed up by satellite observations. The latter provide meteorologists and users with spatial data at a higher production rate.

NMHSs like Météo-France validate and match up the data measured using surface meteorological stations. The pictures (and corresponding data) are archived by NMHSs and may be re-used in studies.

3.1.3. *Climatology Using Atmospheric Models*

All atmospheric models analyse the state of the atmosphere before calculating forecasts. Through this analysis, all observations, whether based on spot data (from meteorological stations, radio surveys, etc.) or spatial data (from satellites) are transformed into points on model grids.

The analyses are archived according to the native resolution of the model: for example, the ECMWF (European Centre for Medium range Weather Forecasts) provides information every 0.5° (with this resolution all points on the globe are less than 43 km from a grid point) at different altitude levels.

In some cases, it is necessary to work on long series of data. Analyses must therefore be homogenised as their results depend on the quality of the model. To provide homogeneous data, the ECMWF and its members have created an archive of re-analyses over a 40-year period. The data is referred to as ERA-40 and is available with a 1° resolution (all points on the globe are less than 90 km from a grid point) at different altitude levels.

3.1.4. *Combining Different Sources*

To ensure better results, it is often necessary to link up different observation systems in order to extend the limits of one system thanks to the qualities of another. The joint use of spot data (i.e. measurement points) and spatialised data (satellite or radar pictures) offers spatialised information with a resolution of 1 km. Ground measurements are used to complete satellite or radar images hence providing high resolution spatial views. Pyranometers and satellites can be used to generate radiation maps and data making it possible to measure potential sunshine. Likewise, rain gauges and radar images can be used to measure rainfall and hence define the size of hydropower facilities.

3.2. USING CLIMATOLOGICAL DATA FOR STUDIES

The study of climatology is often associated with excellent skills in mathematical and statistical techniques. This high level of knowledge is generally available in NMHSs.

3.2.1. *Temperature Studies*

The first possible use of temperature data is to calculate the correlation between the temperature and the electricity consumption of a given place. This kind of spot study can be extended to a study involving different meteorological stations in a country in order to calculate a weighted temperature correlated with a more global consumption. It is thus possible to forecast the consumption of an entire country. Such forecasts are highly useful for companies in charge of transmitting and distributing energy to customers.

This first type of information provides all energy specialists with a preliminary estimation of energy use. In this way, it can be used to define long-term energy purchasing and sales. This first type of study is relatively simple as it involves the direct use of data that is archived and validated by NMHSs. The study can be improved by homogenising the data in order to take into account modifications to series of measurements (e.g. changes in station location or station sensors) and to fill in any measurement gaps. The tool needed to homogenise the data uses Fourier Transforms.

Based on such homogenised data, new tools can be made available to energy specialists. In fact, data homogenisation helps to provide a better definition of the current climate change. Hence, correlating historical data with global warming is a means of improving statistical studies. It opens up the possibility of calculating temperature distributions and working on extremes: these studies can then be used, for example, to determine how long new extreme events will last. With the right kind of risk management, energy specialists can then set up the necessary means. Depending on their activity, these may involve energy storage systems (water in dams, gas, etc.), production or transmission facilities, and so on.

3.2.2. *Cloud Cover Studies*

The use of cloud cover data has pointed to a relationship between cloud cover and electricity consumption due to the lighting in buildings and the greenhouse effect, which acts on their heating. This kind of study is possible everywhere thanks to the observation networks near major cities (stations at airports obliged to measure cloud cover are usually close to cities where consumption can be high).

Today, these studies can be improved using satellite data and the automatic cloud determinations developed by NMHSs such as Météo-France. These improvements will make it possible to focus on the real cloud cover of the area consuming the electricity rather than on the airport, which, although it might be located close to an urban area, is not necessarily representative of the largest conurbations. They will also provide greater accuracy, by differentiating areas according to consumption, and make it possible to pool information covering larger regions. The different possibilities will provide energy specialists with several solutions based on cloud cover information.

3.2.3. *Wind Studies*

As with other studies, wind surveys can simply be based on the parameters measured by NMHSs sensors, for example to plot ground wind maps and wind roses at observations points. In other words, they can be used as a starting point in terms of wind potential. However, Météo-France has expertise that allows it to push beyond the limits of physical observations (e.g. number of measuring points and a single measuring height [generally 10 m] for the anemometer).

By using model-based climatology and scaling down data, Météo-France is able to plot potential wind energy maps. These have a highly accurate scale of roughly 1 km and meet the height required by energy specialists (between 80 and 120 m). Once the areas have been determined, tools such as wind roses or frequency tables can be supplied to estimate the wind energy potential of a given area. These tools provide information about the different activities in the sector (construction, project development, finance, etc.), the number of hours during which the wind turbines will be able operate, together with the different efficiency values, and hence the amount of electricity they should produce. Based on these studies and using an even more detailed mapping system, it is possible to determine the exact location of the turbines to guarantee optimal efficiency.

3.2.4. *Radiation Studies*

As previously stated, it is possible to use the climatological data provided directly by station sensors but, again, the same restrictions apply: depending on the country there may be a limited number of sensors.

Météo-France takes things a step further by merging this data with the climatology provided by satellite pictures. Thus, climate-related information can be spatialised and provide data every square kilometre. Météo-France has already done this for France. The atlas quality and resolution for other regions in the world will depend on local measuring means.

3.3. SHORT AND MEDIUM-TERM WEATHER FORECASTING

A weather forecasting model has different characteristics in order to meet customer needs:

- The physics behind the model: in some cases, certain parameters can be left out in order to speed up the calculation time. In other cases, they can be taken into consideration although this will have an effect on the forecasting term and extend calculation times. This is especially the case for Non Hydrostatic (NH) models, which are generally non operational and used for study purposes. AROME will be one of the first operational NH models for Météo-France.
- The assimilation method: a model can define its initial state based on an analysis at a given moment or over a given period. In the first case, the analysis is three-dimensional (3D) and static while in the second it is variational and dynamic (4DVAR).
- The type of forecast: if the model is only run once based on the initial state of the atmosphere, it will be considered as deterministic. If the initial state of the atmosphere is modified several times and the model generates forecasts for each new initial state, it can be considered as probabilistic.
- The model resolutions: the spectral models currently used are defined by their level of truncation (number of waves used in equation solving), their number of vertical levels and the horizontal resolution between grid points for which there are equations to be solved. The temporal resolution defines the time required to solve the differential equation. These calculation resolutions must not be confused with the model output information, which has a lower resolution for storage reasons.
- The model terms: depending on the model, the terms can vary between several hours and several days or weeks.

- The meteorological parameters: these are generally all required to solve the atmospheric thermodynamic equations. However, these data are initially only available on the model's grid points.

On top of the physical principles and the model-based calculation, the different results of a model and its output can also be useful to energy specialists. This is what we shall see in the next part.

3.3.1. *The Different Parameters*

Logically, energy specialists use the same parameters in their forecasts as the parameters with correlations in climatology. Meteorologists, therefore, aim to forecast the same basic parameters. Generally starting with data from models, this forecasting is then fine-tuned with statistical adaptations that take into account all the elements in the model able to improve the correlations between the model's forecasts and observation.

Temperature: depending on the energy specialist's field (gas or electricity), and the modelling means they use, the temperature data may be more or less integrated: they may take the form of forecast temperature on an hourly basis or forecast temperature on a daily basis (minimum, maximum and average temperatures).

Cloud cover: with the interest of cloud cover being mainly linked to lighting and the greenhouse effect in buildings, the most important forecasts are the daily ones. The lighting and greenhouse effect in buildings depend on this variable.

Precipitations: whether solid (snow) or not, precipitations are also monitored by hydropower producers. Precipitation forecasts can be used to better estimate the potential energy present in dams. But they can also be used to ensure the quality of the river water used to cool down power plants (especially nuclear power plants).

Meteorological phenomena: like any other industrialists with outdoor equipment subjected to bad weather, energy specialists like to be able to anticipate extreme phenomena such as:

- Storms: storm forecasting makes it possible to get teams ready ahead of time so that private electricity users' needs can be met as quickly as possible.
- Sticky snow: by forecasting this kind of snow, its build-up on cables can be prevented by modulating the current going through the lines.
- Thunderstorms and their possible consequences (strong winds, hailstones, heavy rain, etc.) can have repercussions on networks and their maintenance.

Today, such phenomena can be specifically monitored using immediate forecasting tools combining different sources of information. Météo-France, for example, combines radar data with rain gauges (detection and quantification of episodes of rain), satellite pictures with visibility sensors (detection of low clouds), and radar images with the impacts of lightning (detection and qualification of storm areas). It is also possible to link up observations with detailed forecasts drawn up by forecasters or high resolution models.

The wind: with the increasing number of wind parks, both across Europe and the world over, it is often necessary to estimate the production level of these farms in order to provide the best forecast of additional means to be implemented in order to meet peaks in consumption.

Radiation: The use of renewable energy sources like the sun has not yet become widespread. Radiation forecasting is therefore not used very much so far, but Météo-France is getting ready for it.

3.3.2. *Model Terms of Forecast*

With the ECMWF, forecast data are available every 3 h up to D +14. Météo-France also uses these data and different models with more detailed grids for shorter forecasting times. ARPEGE, with a 15 km grid covering Europe, goes up to 108 h, and ALADIN with a 10 km grid, goes up to 54 h with hourly forecasts up to H + 12. Météo-France's NH mesoscale atmosphere model AROME currently goes up to H+30 with a 2.5 km grid over a surface area that includes France.

On top of these possibilities, the ECMWF provides forecasts for the next 4 weeks once a week (on Fridays based on Thursday's analysis). The advantage of these forecasts is that they can point to substantial temperature anomalies in W+3, or even W+4. The cold period at the start of January 2009 was identified in this way by the ECMWF and reported by Météo-France 3 weeks ahead of time owing to the substantial and European-wide cold anomaly.

Using the output from these models, statistical calculations can be adapted to provide hourly data to match given points. These calculations can also take into account the latest observations.

3.3.3. *The Quality of Forecasts*

Meteorologists regularly measure the quality of a model's results against the 500 hPa geopotential forecasts (the measurement is based on the difference between the forecast height and that actually analysed).

For energy specialists, this quality measurement is not explicit enough. It is preferable to measure the quality of forecasts by comparing it to the parameters used (temperature, wind, cloud cover, etc.). Methods to measure this quality must therefore be defined. Météo-France generally proposes two criteria:

- The Root-Mean-Square Deviation (RMSD): this measures the quality of an observation-based forecast.
- The climatological score: this provides the additional information of a digital forecast compared with the usual climatological statistics.

3.3.4. *The Relationship Between Terms and Parameters*

Using climatological scores, it is possible to define the real value of forecasting terms. Even if a forecast has a high RMSD, it can help an energy specialist to better manage a risk if it provides additional information to the climatological data.

Thus, up to D+32, the temperature forecast by the EFC model and statistically adapted by Météo-France enhances the climatological data. However, cloud cover forecasts do not provide very much insight after 7 days. It should be noted that the main air mass movements can be perceived in the long term but that it is still very difficult to translate these into a meteorological situation at a given time.

3.3.5. *Types of Forecast*

Atmospheric changes have always been calculated using deterministic models: the equations are run based on the initial state of the atmosphere, considered to be correct.

However, with the progress made in information technology, these models can now run their calculations several times. The ECMWF has worked on the possibility of changing the initial conditions to check the stability of the chosen solutions in the equation solving. The initial conditions are modified 50 times. Next, 51 equiprobable scenarios are forecast. These create an envelope covering all the possibilities of change in the weather over the next few days.

This allows energy specialists to manage extreme temperature risks according to the desired level. They can also use the 51 scenarios quantitatively by applying their models' equations to each one.

3.4. LONG-TERM WEATHER FORECASTING

3.4.1. *Seasonal Forecasts*

Seasonal forecasting consists in predicting the quarterly average of the meteorological parameters (temperature, precipitations, etc.) for the next 4–6 months, on a scale of an area such as France.

A seasonal forecast expresses the most likely scenario from among three pre-defined scenarios: close, below or above average. For the temperature, this translates as "hot", "normal" or "cold". In terms of rainfall, the reference is to "wet", "normal" or "dry". The idea, for example, is to try and figure out whether next summer will be on average hot and dry or cold and wet in Western Europe.

How are seasonal forecasts made? Global models are used, as in conventional forecasting. But these also reproduce the behaviour of environments that interact strongly with the atmosphere, such as the ocean. The oceanic structure varies much slower than that of the atmosphere. On a seasonal scale the proportion of atmospheric predictability comes precisely from the fact that part of the ocean's slow variation can be found in the atmosphere. Conditions can therefore be found in the atmosphere that are likely to encourage Atlantic disturbance to the far North, or radically modify areas subject to heavy rain in the tropics, or generate considerable heat and drought.

What are the limits of seasonal forecasts? The performance of seasonal forecasting varies greatly according to the place, the season and the meteorological parameter concerned. Performance is better for temperature than for rainfall. Temperature parameters perform better in winter than in summer. Forecasts are highly informative in the tropical belt, on the Pacific Rim. However, temperature forecasting in Western Europe, without being completely useless, is still very poor. This is due to the characteristics relating to the overall circulation of the atmosphere above the Atlantic Ocean at temperate latitudes. These forecasts should therefore be handled with care. Not too much should be read into them, at least under European latitudes.

Why do seasonal forecasting if it cannot be used? Seasonal forecasts are done on a global scale, i.e. they do not just cover Europe. They are extensively used in America, Western Africa and South-East Asia. Comparing seasonal forecasts with observations is probably not the best way to judge their reliability. Their real interest lies in the support they provide decision-makers involved in weather-related activities. By taking into account the probable future weather rather than the average climate, specialists can improve their management, anticipation and decision-making for time periods of several months. Thus, combined with other data, seasonal forecasts do offer a certain advantage for some economic sectors such as energy and the management of energy sources.

Météo-France has set up partnerships with companies working in the insurance and energy sectors in order to assess the economic interest of such information. The main aim of seasonal forecasting is to determine whether the coming season is likely to be hotter or colder than average or simply close to average. It cannot predict the exact temperature of a specific sequence of 1–2 weeks over the course of the 3-month season.

Does Météo-France make seasonal forecasts? For several years now Météo-France has been producing 4-monthly seasonal forecasts as part of an experiment using the Arpège- Climat model. The spatial resolution of this model is roughly 250 km and the parameters forecast are the average temperature and the overall rainfall for the "season". These forecasts are analysed by the Météo-France climatology department, 1 month before the close of the forecast quarter. The results are presented:

- In a "probabilistic" manner: the probability of conditions "below normal", "close to normal" or "above normal" is given.
- In a "deterministic" manner: the deviation from the normal average temperature and overall rainfall for the 3-month period is given for each point on the globe.

Since summer 2005, a second model, again based on Arpège-Climat but combined with an ocean model, has provided Météo-France with a new, normally better, source for its seasonal forecasts. This model will be part of the Euro-Sip experiment designed to produce seasonal forecast maps by blending the results of three models: 1 French, 1 English and 1 from the ECMWF. The ability to forecast meteorological parameters in the long term is indeed improved when there are more data sources. This is why Météo-France draws up a summary of seasonal forecasts based on the results available (generally 15 days before the end of the forecast quarter) from several centres – currently six – including the two models specific to Météo-France.

Who does seasonal forecasting in the world? Most large digital forecasting centres do this kind of forecasting. There is Météo-France, the ECMWF, NMHSs such as the Met Office in the UK, the Japanese, Korean, Chinese, Indian, Canadian, Australian and Moroccan offices, the American National Center for Environmental Prediction (NCEP), research organisations such as the Max-Planck Institute in Germany, the International Research Institute for Climate Prediction (IRI) in the United States and the CPTEC Brazilian research centre.

3.4.2. *Climate Studies*

Based on the scenarios outlined in the 2007 report of the IPCC (Intergovernmental Panel on Climate Change), Météo-France uses the ARPEGE-Climat atmospheric climate model developed by its research centre to simulate the climate for a given region in the world.

These simulations can then be adapted to the world of energy. For example, Météo-France has created town-by-town, chronological, 3-hourly temperature sequences for the coming century (the scenario considered in this case has a constant climate). This data can be used to create a statistical envelope reflecting the climate in the twentyfirst century and making it possible to plan ahead for changing energy needs and the corresponding infrastructures.

4. Conclusion

As can be seen, Météo-France and its weather specialists are constantly striving to improve their atmospheric observation and forecasting tools in order to better fulfill their state missions. The improvements linked to calculation capacities and observation transmissions are of course beneficial to the industrial and energy sectors. However, these sectors above all benefit from the studies carried out by the agency within the framework of commercial agreements. Finally, it has to be said that, given its importance, the energy sector has also spurred the progress made by National Meteorological and Hydrological Services.

USE OF INDICATORS TO IMPROVE COMMUNICATION ON ENERGY SYSTEMS VULNERABILITY, RESILIENCE AND ADAPTATION TO CLIMATE CHANGE

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Abstract. This paper outlines anticipated climate change impacts on energy systems. It presents a set of indicators to determine: the level of vulnerability of a particular energy system; the capacity to implement energy adaptation projects; and how successful proposed implementation measures will be in increasing energy system resilience. Wind, solar, hydro, biomass, nuclear and fossil fuel energy systems are addressed.

Keywords: Climate change; energy systems; vulnerability; resilience; adaptation; wind; solar; fossil fuels; biomass; hydro; nuclear; transmission; indicators; assessment

1. Introduction

New insights have been gained over the last 10 years about the essential role of energy system resilience in the prosperous development of society. A growing number of case studies have revealed the tight connection between resilience, diversity and sustainability of social and ecological systems. Currently energy policies in industrialised countries are increasingly driven by the need to mitigate greenhouse gases. However measures under

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the Kyoto Protocol to mitigate the climatic impacts of energy production have failed to take into account the expected consequences of increased climatic variability: cold years, flood events, seasonal droughts, storm surges, extreme wind speeds, freezing conditions, heat waves.[1] Adaptation is fast becoming the order of the day, not only in geographically-vulnerable countries such Bangladesh and Tuvalu, but also in northern and moderate latitudes.

Climate change directly impacts both the demand- and supply-side of energy production. Energy systems and equipment are already subject to substantial temperature and other climatic changes. Climate change can also indirectly impact any part of the energy sector. For example, a change in electricity supply can affect energy distribution and consequently energy users.

Given the importance of energy in the economy and in the promotion of ecodevelopment.[2] It is vital that vulnerabilities within the energy sector are reduced. Energy systems must be adapted to withstand anticipated climate change and impacts. This can be achieved by increasing the resilience of the energy system, e.g., by reinforcing its technical equipment, diversifying energy supply sources, siting power equipment differently, expanding its linkages with other regions, and investing in technological change – renewables, efficiency, etc. – to further expand the portfolio of options. Moreover, given the slow rate of capital stock turnover in the energy sector and the long lifetime of equipment, it is important that energy providers, policy makers and citizens be well-informed as to the possible impacts of climate change on the energy sector so that necessary mitigation and adaptation measures can be taken. Ultimately, the resiliency of a country's energy system is underpinned by at least two key elements: its adaptive capacity and the country's level of ecodevelopment.

In order to better understand how to trigger and sustain positive synergies, HELIO has developed a straightforward methodology and set of indicators to assess the vulnerability and resilience of energy systems to climate change. The entry point for this work is the national level. The final objective is to help identify policies and measures (PAMs) that can best facilitate

[1] http://data.ukcip.org.uk/resources/publications/documents/4.pdf

[2] Ecodevelopment became "sustainable development" (SD) with the 1987 Brundtland Report. The abstract notion of SD has been variously operationalised. It can be broken down into three distinct sets of activities aimed at: (1) satisfying basic human needs; (2) creating communities that establish norms, rights, and collaborative behaviour as a prerequisite for participating in social and economic development; and (3) translating the more abstract needs of future generations into action today, e.g. BRAC, Bangladesh, Sekem and a social enterprise called WasteConcern, Spain.

and support adaptation activities. This process must involve – simultaneously and on an equal footing – government officials, business, environmental non-governmental organisations (ENGOs) and relevant agencies that collectively assess whether the implemented PAMs are effective in supporting/ promoting adaptation of energy systems thereby contributing to increased resilience and ecodevelopment.

2. Why a Metric for Vulnerability and Resilience Is Needed

Since the development of global climate policy in the early 1990s, the process has been dominated by emissions reductions policies and measures, i.e. mitigation. It was only with the start of negotiations on the post-2012 climate policy regime, that adaptation to climate change was given as equal importance as mitigation activities. The Adaptation Fund, financed by the adaptation tax on Clean Development Mechanism (CDM) projects, was implemented in early 2008.

Compared to mitigation, where a common metric in terms of "ton of CO_2 equivalent reduced" has been used for many years, evaluation of adaptation measures is still in its infancy (see Stratus Consulting and UNFCCC, 2005). There are no commonly accepted parameters and indicators (see Tyndall Centre, 2004; USAID, 2007) to compare adaptation needs and the effectiveness of adaptation measures. Possible metrics would be the number of disability-adjusted life-years saved and the value of property protected. However, determining the baseline impacts without adaptation will be extremely challenging.

This paper aims to contribute to the development of such parameters and indicators for energy systems. It builds on HELIO's earlier work that carried out a preliminary assessment of energy and ecosystem resilience in sub-Saharan Africa.[3] Based on feedback from this work and HELIO's 10 years of experience in applying indicators, HELIO has now developed a set of indicators to measure: (1) the vulnerability of energy systems; and (2) measure the effectiveness of adaptation efforts in the energy sector.

HELIO's philosophy is that the underlying metric – the actual measurement or statistic used – must be generally available for most, if not all, countries. Data collection and vector calculation must be do-able and if calculation is required to derive an indicator, it must be simple to do.

Overall the indicators themselves must:

[3] A Preliminary Assessment of Energy and Ecosystem Resilience in Ten African Countries, 2007 see: http://www.helio-international.org/energywatch/2007.cfm

- Be clearly definable, simple to understand, and easily communicated to citizens and decision-makers alike
- Be relevant to actual or anticipated policies
- Reflect an important aspect of the social, economic, environmental, technological or governance elements of the energy system
- Measure something of obvious value to observers and decision-makers; and
- Have robustness, durability and long-term relevance

3. Climate Induced Impacts on Energy Systems and Related Vulnerabilities

Climate change can cause different impacts. For example, the mean of climatic parameters as well as the intensity of meteorological extreme events can change. Possible changes for temperature are shown in Figure 1. Moreover, they can be translated to other climatic parameters such as precipitation, wind speed and sunshine. With climate change, temperature and wind speed are likely to increase in most regions; precipitation and sunshine can either increase or decrease.

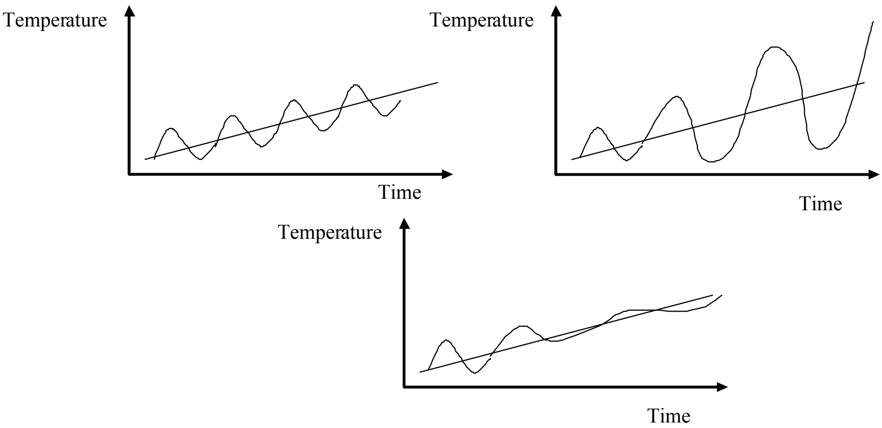

Figure 1. Changes of meteorological parameters due to climate change. *Top left*: Increase of average temperature without change in temperature variability. *Top right*: Increase of average temperature with increase in temperature variability. *Bottom*: Increase of average temperature with decrease in temperature variability.

It is obvious that impacts will be larger if variability increases. But even in a situation with decreasing variability, impacts will occur if the meteorological parameter passes the design threshold of a given infrastructure.

Impacts can also be direct or indirect. Frequently, indirect impacts are much stronger. For example, an increase in temperature alone is extremely unlikely to destroy any energy infrastructure. However, the melting of glaciers induced by temperature increase will have a strong impact on hydropower resources.

Table 1 gives an overview of direct and indirect impacts of change in meteorological variables. It also outlines various cross-effects, i.e. interactions between different impacts.

Changes in meteorological variables will have an impact on energy transmission and use regardless of how the energy is produced. Extreme events increase the risk of destruction of transmission lines and reduction of electricity demand due to destruction of electricity-consuming entities, e.g. business, industry, households (Table 2).

TABLE 1. Direct and indirect impacts of changes in meteorological variables ([a]Also influenced by changes in wind speed and overall humidity).

Direct change	**Direct impact**	**Indirect impact**	**Cross effects**
Temperature increase	Heat-wave	Increased electricity demand	
	Glacier melting	Short term increase of water flow, long term reduction	Droughts/floods
		Formation of moraine lakes with outbursts	Floods
		Sea-level rise	Floods
	Increased evaporation[a]	Reduction of stream flow	Droughts
	Stronger cyclones/storms		Floods
Increase in precipitation	Floods		
Decrease in precipitation	Droughts		
Decrease in cloud cover	Increased evaporation	Reduction of stream flow	Droughts
Increase in cloud cover	Decreased evaporation	Increase of stream flow	Floods

TABLE 2. Direct and indirect impacts of climate on electricity systems.

Change in meteorological variable	**Impact on electricity transmission**	**Change of electricity use due to change in meteorological variable**
Temperature increase	Some	Increase due to higher cooling needs Decrease if sea-level rise displaces population and industrial production
Decrease in cloud cover	None	Decrease due to reduced lighting needs
Increase in cloud cover	None	Increase due to increased lighting needs
Increased frequency and/or strength of storms/cyclones	Failure of transmission lines	Reduced electricity demand due to damage to houses and factories
Floods	Failure of transmission equipment from flooded power plants	Sharply reduced electricity demand due to interruption of production in flooded factories/cessation of electricity consumption in flooded houses
Droughts	Risk of destruction of transmission lines due to forest fires.	Slightly reduced electricity demand due to interruption of production in factories whose supply of raw materials has been depleted/cessation of electricity consumption in houses of people abandoning the drought area

In the following sections, impacts of change of meteorological parameters are assessed for different energy production systems. They are grouped according to generation of energy and transport of energy to the user.

3.1. WIND ENERGY

Wind energy is generally harnessed in a decentralised manner and in locations chosen for their high average wind speed. Usually, wind speeds are measured for several years before investors decide to set up a wind turbine. Wind turbines start producing electricity at a certain wind speed and increase electricity generation with a power of three as wind speeds increase. At a certain maximum wind speed, the turbine automatically shuts off to prevent damage. Modern turbines can withstand wind speeds of 70 m/s before being destroyed.

Climate change can affect average wind speeds. An increase in average wind speed would generally increase electricity generation unless the increase only occurs in the highest wind speed categories. A decrease in wind speeds leads to a reduction in electricity generation. An increase in the highest wind speeds increases the periods when wind turbines are stopped and raises the risk of destruction of the turbine.

3.2. SOLAR ENERGY

As in the case of wind, solar energy is generally harnessed in a decentralised manner and in locations chosen for their high average sunshine duration. Changes in cloud cover have an impact on electricity production. While photovoltaic cells and solar water heaters can produce electricity even with a certain degree of cloud cover, mirror-based solar thermal applications need full sunlight. Furthermore, the efficiency of solar power production decreases with the ambient temperatures. Thus an increase in temperature will reduce electricity production.

An increase in the strength/frequency of storms and cyclones increases the risk of destruction of solar energy generation equipment.

3.3. HYDRO-POWER ENERGY

Hydro power can be generated in a wide range of power plant sizes ranging from kilowatts to gigawatts in output. Siting of hydropower plants is usually based on multi-decadal river flow measurements. Changes in average precipitation will change river flow. However the impact on hydro power production will depend on plant-specific characteristics. While plants with large reservoirs can buffer river flow variability, run-of-the river plants are directly dependent on the actual river flow. The actual change in power production is therefore strongly dependent on the flow regime and utilisation rate of river flow which is shown in Figure 2.

Normally, hydro power plants are able to withstand flooding events by opening floodgates and shutting down turbine operation. Only in rare cases are hydro power plants and/or dams destroyed by flood events; they are less prone to flooding impacts than other power plant types if well-designed and situated in areas not prone to landslides. However, reservoirs can be filled up by debris and silt thus reducing their long-term power generation capacity.

Given that hydro-power plants are normally robust structures, an increase in the strength/frequency of storms and cyclones only marginally increases the risk of destruction of hydro power plants.

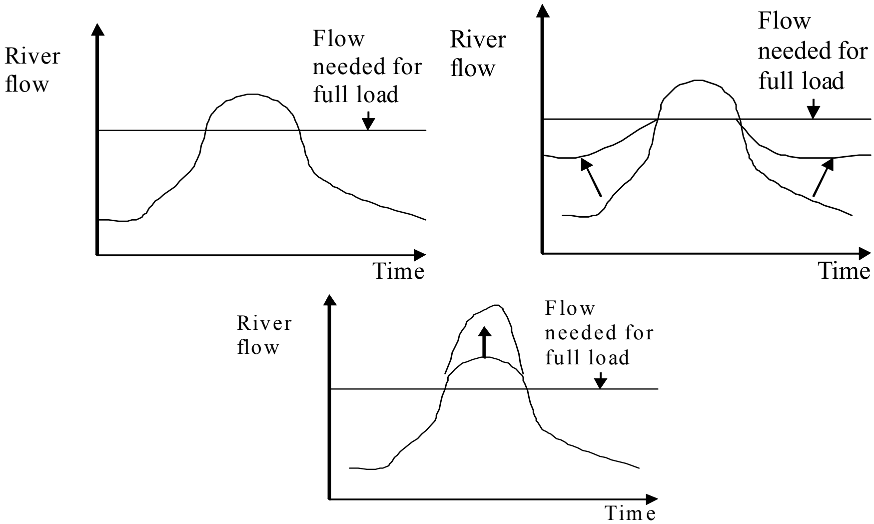

Figure 2. Scenarios for hydro-power river flow utilisation and consequent changes in the flow regime (assuming the glaciers and reservoirs remain stable). *Top left*: Flow regime before climate change: The power plant can only produce at full load during a limited rainy season. *Top right*: Flow regime after climate change: increase of flow in previously lean periods: Now the plant can considerably increase power production. *Bottom*: Flow regime after climate change: increase of flow in previously strong periods: In this case the plant cannot increase production at all despite the increase in river flow.

3.4. BIOMASS ENERGY

Biomass energy comes in many different forms. It can be used for heat generation in small, decentralised devices such as household stoves or for power generation in plants several MW in size. Biomass can be sourced from forests or agricultural residues; dedicated biomass plantations are also possible but rare due to the high costs involved.

Climate change impacts the availability of biomass as well as energy generation facilities, as illustrated in Table 3.

3.5. FUEL FROM MINED RESOURCES

Current energy systems are mainly based on fossil fuels, be it solid fuels like coal or liquid fuel such as oil and gaseous fuels or uranium. Extraction of fossil fuels as well as their utilisation can be impacted by climate change, as shown in Table 4.

TABLE 3. Climate change impacts on biomass energy.

Change in meteorological variable	Impact on biomass availability	Impact on energy generation
Temperature increase	Decrease if plants reach threshold of biological heat tolerance or sea level rise reduces area where plants grow, otherwise increase (provided that no lack of other resources constrains plant growth)	Decrease if power plant is impacted by sea level rise Otherwise depending on biomass availability.
Increase in average precipitation	Increase if increase occurs during the growing season	Increase
Decrease in average precipitation	Decrease unless decrease occurs outside the growing season	Decrease
Droughts	Decrease	Decrease
Glacier melting	If under irrigation: short-to medium term increase, long-term decrease: depends on situation of glaciers with regards to the current and future snow lines, otherwise: none	As per availability
Floods	Decrease if floods affect area where biomass is sourced.	Decrease if power plant is flooded or biomass availability is reduced
Increased frequency and/or strength of storms/cyclones	Decrease if storms affect area where biomass is sourced	Decrease if equipment is destroyed or biomass availability is reduced

4. Possible Adaptation Measures for Energy Systems

Adaptation measures can be categorised into infrastructural/technical and behavioural responses. Technical adaptation tries to make infrastructures invulnerable against long-term changes in meteorological variables and extreme events. Behavioural adaptation adjusts the operation of the infrastructure (both existing and new) and the siting of new infrastructures so as to minimise damages.

4.1. WIND ENERGY

Technical adaptation for wind power would include the construction of turbines able to operate at and to physically withstand higher wind speeds.

TABLE 4. Climate change impacts on fossil-fuel/uranium based energy.

Change in meteorological variable	**Impact on fuel availability**	**Impact on energy generation**
Temperature increase	None, unless pipelines are interrupted by melting pergelisol	Decrease of power plant efficiency due to higher temperature of cooling water
Increase in average precipitation	Reduced coal quality due to higher moisture content of opencast coal mining. Increased coal availability if coal seam fires are extinguished	None
Decrease in average precipitation	Decrease due to higher probability of coal seam fires	None
Droughts	Decrease due to lack of water necessary for mining air conditioning and operations	Decrease due to reduced availability of cooling water
Glacier melting	None	Increase in the medium term (for power plants located close to the glaciers) due to lower cooling water temperature and higher availability of cooling water. Decrease in the long term once glaciers have vanished
Floods	Decrease if floods affect mines	Decrease if power plant is flooded or fuel cannot reach the plant.
Increased frequency and/or strength of storms/cyclones	Decrease if storms affect vulnerable mining equipment such as offshore oil platforms or opencast coal mine excavation equipment	Decrease if equipment is destroyed or fuel availability is reduced

Regarding behavioural adaptation, siting could take into account expected changes in wind speeds during the lifetime of the turbines, as well as sea-level rise and changes in river flooding. Insurance schemes for long-term wind power yields and damage from storms should be developed. This would require good statistics of wind speed changes and extreme storm events from climate information (including forecasts). Moreover, rapid emergency repair teams could be set up to repair damaged turbines as quickly as possible.

4.2. SOLAR ENERGY

For all solar technologies, technical adaptation is limited as they cannot be more robust than the building on which they are located. Behavioural adaptation would include siting according to expected changes in cloud cover. Large concentrating solar power (CSP) plants should be designed to make them robust with regards to storms. For distributed systems, mobile repair teams would be key to get systems operational after damage from extreme events.

4.3. HYDRO-POWER ENERGY

Technical adaptation for hydro projects can include building desilting gates to "flush" silted reservoirs. Moreover, dams can be increased in height and floodgates enlarged to accommodate increased river flow extremes and variability. Upstream land management can also reduce possible erosion and dam siltation.

The change in flow regime could allow for expanded, installed capacity. Increased flows from glacier melting should be taken into account if they are likely to persist over the technical lifetime of the system's extra capacity. Behavioural adaptation would include changes in plant operation to account for changes in river flow patterns.

4.4. BIOMASS ENERGY

Biomass availability can only be increased if selected crops that have a higher biological heat tolerance and tolerate higher water stresses are used. The expansion of irrigation systems or improvement of efficiency of existing irrigation can counteract drought impacts provided sufficient water is available from sources outside the drought-hit area. This might necessitate tapping unconventional sources such as desalinated seawater or fossil water resources. Protection against floods can be provided by building dikes and improving drainage. Regarding biomass power plants, the robustness of the construction should be increased if they are located in storm-prone areas.

Behavioural adaptation would include early warning systems for rainfall and temperature anomalies, support for emergency harvesting of biomass in the case of an imminent extreme event as well as the provision of crop insurance systems. Biomass power plants should be sited in less flood and storm-prone areas.

4.5. FUEL FROM MINED RESOURCES

Technical adaptation for fossil fuel/uranium mining means improving the robustness of mining installations. This is especially important for offshore installations that are vulnerable to storms. Opencast as well as underground mines are also vulnerable to both flooding and shortage of water to sustain mining operation.

Behavioural adaptation would include siting of future mines in areas that have a limited exposure to flooding or drought risk. Power plants should preferably be sited at places with an ample supply of cooling water and preferably with a low water temperature. Air cooling could be used to replace water cooling.

4.6. INTERACTION OF ADAPTATION MEASURES BETWEEN DIFFERENT ENERGY FORMS

In several cases, adaptation measures of different energy forms influence each other. For example, behavioural adaptation of hydro power plants due to an improved operation schedule may conflict with an improved irrigation schedule of a downstream irrigation system. Likewise, desilting reservoirs may negatively impact the water supply used for downstream irrigation. The rush of power plant developers to claim sites with limited flood risk may result in a decrease in the number of suitable sites in the future.

5. Indicators for Energy Systems' Vulnerabilities to Climate Change

The following section presents a set of indicators for the vulnerability of each energy system.

5.1. TRANSMISSION SYSTEMS

The vulnerability of transmission systems would be shown by the following indicator:

- VT1: Length of above-ground transmission lines (km) – including provision for alternative routes

Decentralised systems are much less vulnerable to failures in the transmission systems and to high temperatures (heat waves) than centralised ones (see WADE, 2007).

5.2. WIND ENERGY

The vulnerability of the wind energy system would be shown by the following indicators:

- VW1: Number of wind turbines at less than 1 m above sea level. Sea level rise might impact turbines below this level during their lifetime.
- VW2: Projected change of average wind speed over the next 20 years, which is the average lifetime of wind turbines (%).
- VW3: Projected share of average annual wind speeds over 25 m/s over the next 20 years (at this wind speed most wind turbines have to be switched off).
- VW4: Projected likelihood of a storm with gusts over 70 m/s reaching areas where wind turbines are located (% over 20 years). At this wind speed destruction of wind turbines is likely.

VW4 should be based on past experience coupled with the best tools to provide climate scenarios, e.g. using regional climate models.

5.3. SOLAR ENERGY

The vulnerability of the solar energy system would be shown by the following indicators:

- VS1: Expected temperature increase over the next 20 years which is the average lifetime of PV panels/CSP installations (°C).
- VS2: Projected change in cloud cover over the next 20 years (%).
- VS3: Projected likelihood of storm gusts over 70 m/s reaching areas where solar power plants are located (% over 20 years). At this wind speed destruction of plants is likely.

VS3 should be based on past experience coupled with the best tools to provide climate scenarios, e.g. using regional climate models.

5.4. HYDRO-POWER ENERGY

The vulnerability of the hydro energy system would be shown by the following indicators:

- VH1: Expected precipitation change over the next 50 years, different-tiated by watersheds (%). Historical experience shows that 50 years is a good proxy for the lifetime of hydro plants.
- VH2: Projected additional runoff due to glacier melting over the next 50 years, differentiated by watersheds (million cubic meters).

- VH3: Projected flood frequency over the next 50 years (number of floods that have a greater intensity than a flood with a 100 year recurrence cycle).

When runoff forecasts are available, VH1 should use runoff instead of precipitation.

5.5. BIOMASS ENERGY

The vulnerability of the biomass energy systems would be shown by the following indicators:

- VB1: Probability of temperature increase beyond biological heat tolerance of relevant crop over the next 20 years (%). Twenty years is the estimated average lifetime of biomass power plants.
- VB2: Expected precipitation change during the growing season over the next 20 years, differentiated by crop regions (%).
- VB3: Projected drought frequency over the next 20 years (number of droughts that would result in a reduction of crop yields by more than 20%).
- VB4: Projected flood frequency over the next 20 years (number of floods that would result in a reduction of crop yields by more than 20%).
- VB5: Number of biomass power plants located at less than 1 m above sea level and situated in an area that has a 100 year flood cycle.
- VB6: Share of sheltered storage.

Indicators should be calculated for each crop that generates residues used for energetic purposes.

5.6. FUEL FROM MINED RESOURCES

The vulnerability of the fossil fuel/nuclear energy systems would be shown by the following indicators:

- VF1: Expected temperature increase of cooling water for thermal (including nuclear) power plants over the next 30 years (°C).
- VF2: Expected number of droughts that would lead to a decrease in capacity of thermal power plants by more than 10% over the next 30 years. Thirty years is the typical lifetime of fossil fuelled power plants.
- VF3: Number of thermal power plants located by a river fed by glacial melt where the glaciers are unlikely to vanish over the next 30 years.

- VF4: Share of offshore oil and gas installations likely to be hit by a storm of more than 70 m/s gusts over the next 20 years (%). The lifetime of such installations is not well known, but should be shorter than that of power plants. At a wind speed of 70 m/s destruction of plants is likely.
- VF5: Number of coal mines plants located at less than 1 m above sea level and situated in an area that has a 100 year flood cycle.
- VF6: Number of thermal power plants located at less than 1 m above sea level and situated in an area that has a 100 year flood cycle.
- VF7: Number of days of available stored stock.
- VF8: Share of protected storage in tanks or covered depots.

6. Indicators for Countries' Capacity for Implementation of Energy Adaptation Projects

Countries differ considerably in their capacity to implement adaptation measures in the energy sector. Capacity can be differentiated into monetary, technological, human and administrative components. The following section develops indicators for each type of capacity.

6.1. MONETARY CAPACITY

- CM 1: Domestic capital formation (million euros/year)
- CM 2: Domestic investment into the energy sector (million euros/year)
- CM 3: Domestic investment into renewable energy (million euros/year)
- CM 4: Capital of domestic insurance companies (million euros)

6.2. TECHNOLOGICAL CAPACITY

- CT 1: Number of technical engineers graduating annually as a percentage of the total population
- CT 2: Number of domestic engineers specialised in energy technology (if possible separated into renewable and fossil/nuclear technology specialisations) as a percentage of the total population
- CT 3: Number of domestic companies able to construct renewable energy plants
- CT 4: Availability of hazard maps for droughts
- CT 5: Availability of hazard maps for floods
- CT 6: Availability of coastal maps with a 1 m altitude contour

6.3. HUMAN AND ADMINISTRATIVE CAPACITY

- CH 1: Number of domestic technicians trained to repair renewable energy systems
- CH 2: Number of domestic companies specialised in servicing renewable energy systems
- CH 3: Availability of early warning systems for meteorological extreme events
- CH 4: Existence of plans to react to meteorological extreme events and of mobile teams
- CH 5: Existence of siting guidelines for new power plants, taking into account climate change impacts
- CH 6: Existence of guidelines for power plant robustness with regards to storms, floods, heat waves

7. Indicators for Successful Interventions that Increase Resilience

A necessary condition for adaptation is the capacity to implement adaptation activities. In the context of developing countries, this capacity needs external support, for example through the financial mechanisms of the international climate policy regime. To avoid inefficient spending of scarce funds a set of criteria has been developed to gauge the efficiency of adaptation efforts.

7.1. WIND ENERGY

Indicators for effective adaptation efforts in the context of wind power could be as follows:

- EW 1: Domestic regulation for storm-proofing wind power plants is enacted and enforced. The regulation ensures that during the technical lifetime of the wind turbines, they withstand the highest wind speed that is likely to occur in the area during that period.
- EW 2: A siting map for wind power plants has been developed, taking into account also projected changes in wind speeds, floodplains and area impacted by sea level rise.
- EW3: An insurer offers insurance against wind turbine storm damage.

7.2. SOLAR ENERGY

- ES1: A siting map for solar power plants has been developed, taking into account also projected changes in cloud cover.
- ES2: Domestic regulation for storm-proofing CSP.
- Plants has been enacted, which ensures that during the technical lifetime of the CSP plant it withstands the highest wind speed that is likely to occur in the area during that period.

7.3. HYDRO-POWER ENERGY

- EH1: All new dams are equipped with desilting gates
- EH2: Mapping of hydro plants that should expand their capacity due to projected improvements in river flow regime has been carried out
- EH3: A siting map for new hydro-power plants has been developed, taking into account also projected changes in river flow
- EH4: A plan for optimising hydro-power plant operations under projected flow regimes has been developed and includes upstream land management to reduce possible erosion and resultant dam siltation

7.4. BIOMASS ENERGY

- EB1: An irrigation masterplan has been developed, taking into account also projected changes in drought occurrence
- EB2: A research budget for heat and drought resistant crops has been allocated and a realistic plan for this research has been drafted (for small countries: participation in Consultative Group on International Agricultural Research [CGIAR] activities for crop improvement research has been organised)
- EB3: A siting map for biomass power plants to prevent siting biomass power plants in floodplains and areas impacted by sea-level rise has been developed
- EB4: Domestic regulation for storm proof biomass power plants (e.g. ensuring that over its lifetime the biomass plant can withstand the highest wind speed that is likely to occur in the area during that period) has been enacted

7.5. FUEL FROM MINED RESOURCES

- EM1: A siting map for mines has been developed, taking into account also projected flooding and drought-prone areas
- EM2: Domestic regulation for siting of thermal power plants at sites with sufficient cooling water availability over the next 50 years has been enacted

8. Conclusion

It is possible to assess adaptation needs for the energy sector and to determine indicators for vulnerability, adaptation potential and effectiveness of adaptation support. Human resources for rapid reaction in case of meteorological extreme events are necessary, but not sufficient for successful adaptation. Energy systems are strategic infrastructure and can only be as resilient as the environment and human milieu in which they are located.

Using planning tools such as indicators to assess resilience and adaptation options is key to avoid siting future power plants in areas prone to impacts from extreme meteorological events. Moreover, understanding the vulnerabilities of a particular energy system allows for improved robustness of plant design to take into account projected changes in wind speeds, precipitation and sunshine and how to design plants to adjust to changing energy resources.

To do this, energy planners need both the tools and the knowledge of scientists, energy analysts, economists and citizens. Users who legitimately represent the needs of present and future generations and know their own needs must also be included if we are to ensure the resilience of our energy systems in the face of climate change impacts.

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CLIMATE SERVICES FOR DEVELOPMENT IN AFRICA WITH A POTENTIAL FOCUS ON ENERGY

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Abstract. Climate Services for Development in Africa (ClimDevAfrica) Programme is a joint initiative of the African Union Commission (AUC), the United Nations Economic Commission for Africa (UNECA) and the African Development Bank (AfDB), to the inception of which the author has contributed since 2005. The programme has been mandated at regional meetings of African Heads of State and Government, as well as by Africa's Ministers of Finance, Planning, Economic Development, and Environment and it responds to the urgent challenge that climate variability and change pose to the achievement of Africa's sustainable development objectives. Although the programme encompasses all sectoral activities influenced by climate (agriculture, health, water management, etc.), energy should be one of the sectors with potentially high-impact demonstration projects. Weather and climate conditions are in fact critical for both energy supply and demand, including aspects such as production and transmission. The energy sector could therefore provide benchmarks for other sectors. The flow of information and climate risk knowledge across sectors should be facilitated by the holistic approach taken in the ClimDevAfrica programme. In this chapter, most of the emphasis is on the main aspects of the ClimDevAfrica programme as a whole, without specific links to the energy sector but the reader is encouraged to reflect on potential energy projects that could be developed under the upcoming ClimDevAfrica programme. This chapter gives some indications on the necessary partnership initiation to support a multi sectoral and multi stakeholder development programme needed to cope with climate variability and change. Some pilot activities for ClimDevAfrica, have started and one of them is highlighted in Appendix A.

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1. Background and Justification for ClimDevAfrica

Although Africa contributes only 3.8% of total greenhouse gas emissions, Africa's countries are among the most vulnerable to climate change impacts. With a majority of poor countries and communities, Africa will suffer earlier and harder because of weaker resilience and greater reliance on climate-sensitive sectors like agriculture. Recent modelling indicates that a temperature increase of 2°C could mean a loss of 4.7% of GNP in the region. Most of this would be as a result of loss in the agricultural sector. A temperature rise of 2.5–5°C would be even worse; with hunger for 128 million and 108 million affected by flooding and a sea-level rise of 15–95 cm. Climate variability lies behind much of the prevailing poverty, food insecurity, and weak economic growth in Africa today. Climate change will increase this variability. The severity and frequency of droughts, floods and storms will increase, leading to more water stress. Changes in agricultural, livestock and fisheries productivity will take place, and Africa will face further food insecurity as well as a spread of water-related diseases, particularly in tropical areas.

The Climate Services for Development in Africa (ClimDevAfrica) programme has been under development since a stakeholder inception workshop held under the auspices of UNECA in Addis Ababa, April 2006. Its scope has expanded from solely addressing the need for greatly improved climate information for Africa to also strengthening the use of such information for decision-making, by improving analytical capacity, knowledge management and dissemination activities, and implementing pilot projects demonstrating the value of mainstreaming climate services into development. This came about after a clear realization that information by itself would not lead to effective policies.

The programme therefore seeks to overcome the lack of necessary information, analysis and options required by policy and decision-makers at all levels. ClimDevAfrica will construct a solid foundation in Africa for the response to climate change, building on solid science and observational infrastructure, enabling strong working partnerships between government institutions, private sector, civil society and vulnerable communities, and creating and strengthening knowledge frameworks to support and integrate the actions required.

As such ClimDevAfrica will strengthen Africa's climate and development institutions at regional, sub regional and national levels. The programme will seek to increase the level of activities for Adaptation to Climate Change (ACC) in Africa, and reduce fragmentation among these activities. ClimDevAfrica will provide a coherent framework for coordination of ACC activities in the region. It will also assist in sound policy-making based on information and analysis on policy options. The programme will improve climate practices in sectoral institutions through much enhanced policy environments, and by leaders and resources managers actively owning the problem, raising awareness of its importance, and encouraging establishment of climate risk management processes. It will contribute to addressing the present weaknesses in both demand for, and supply of, pertinent climate services, which have contributed to the limited use of climate data in development processes in Africa. In this regard, the programme will seek to engage National Meteorological and Hydrological Services (NMHS) in the national development agendas with a view to bridging the disconnection between weather and climate services and development priorities. ClimDevAfrica will contribute to rectifying the current situation where there is little use of weather and climate knowledge in development practices. The programme will also engage local communities (rural/urban) in the whole process of disaster and climate risk management and adaptation to climate change.

2. Programme Stakeholders and Beneficiaries

ClimDevAfrica is a continental programme with a reach down to the communities in charge of natural resources management at the local level. The immediate beneficiaries will be the group of "Policy Makers" that ClimDevAfrica serves. These are: Regional Economic Communities (RECs); River Basin Organisations (RBOs); National governments (including NMHSs); Parliamentarians; African negotiators; and, in between, policy makers and policy supporters, and development practitioners/natural resources managers.

This group of policy makers is supported with knowledge, decision support and recommendations from a group of beneficiaries here called "Policy Support":

- Civil Societies (including interest organisations representing agriculture, forestry, fisheries, water resources, energy, health, tourism, transport, infrastructure and representatives of exposed population groups)
- Universities and Research Institutes
- Mass Media

- Financial Institutions (banks, insurances, stock markets)
- Local Authorities (appointed and elected)
- And, when called upon, International Organisations in a knowledge and know-how support function

Through these bodies, the programme seeks to increase the resilience of Africa's population to climate change, enabling effective adaptation activities. The *ultimate beneficiaries* will be:

- Rural communities with climate sensitive livelihoods, especially, rain-fed farmers
- Food insecure communities
- Communities vulnerable to malaria and other climate sensitive diseases
- Communities dependent on uncertain water and other natural resources
- Communities at risk of disasters
- Communities with poor energy access
- And urban communities with climate sensitive livelihoods, as health, weather related disasters, and seasonal employment

From the above, we can list the main stakeholders in ClimDevAfrica Programme:

i. Poor rural people whose livelihoods are sensitive to climate variability.

ii. Development practitioners who need to integrate ACC in their areas.

iii. Policy analysts and researchers who need climate information as input to their work on identification of policy options and best practices ahead.

iv. Sub-regional and national climate, meteorological and hydrological services and other relevant research institutions that provide the data and information services required. The following five regional institutions working with climate information in Africa will be among the key beneficiaries and implementers of the programme: ACMAD, the African Centre of Meteorological Applications for Development with continental mandate, based in Niamey, Niger; CILSS/AGRHYMET, which works on environmental matters related to agriculture, land and water management; also based in Niamey; ICPAC, the IGAD Centre for Prediction and Application of Climate based in Nairobi; the SADC-Drought Monitoring Centre (DMC-SADC), based in Gaborone; and the Observatoire du Sahara et du Sahel (OSS) based in Tunis.

v. RECs and RBOs that coordinate sub-regional ACC action. and

vi. Relevant national sectoral ministries.

3. Programme Mandate

ClimDevAfrica Programme has received strong political endorsement from the AU Heads of State and Government and the International Community. The programme preparation and planning process entailed the following:

i. The Global Climate Observing Systems (GCOS) and UNECA Addis Ababa April 2006 Stakeholders workshop, which formulated the Strategy and Action Plan for "Climate for Development in Africa."

ii. The Africa Union Eighth Ordinary Session held in January 2007, which endorsed the April 2006 "Action Plan for Africa", and urged "Member States and RECs, in collaboration with the private sector, civil society and development partners, to integrate climate change considerations into development strategies and programmes at national and regional levels". The Session requested "the Commission, the Economic Commission for Africa, the African Development Bank to develop and implement the Plan on Climate Change and Development in Africa and to report on progress biannually."

iii. A Special Working Group, including 25 eminent experts in Climate and Development, convened by AUC on 18–19 March 2008 in Addis-Ababa to provide further input into programme design.

iv. The approval of the establishment of African Climate Policy Centre (ACPC) by the First Joint Annual Meeting of the African Union Conference of Ministers on the Economy and Finance, and the UNECA Conference of African Ministers of Finance, Planning and Economic Development held in April 2008 in Addis Ababa. and

v. The endorsement from the 12th Session of the African Ministerial Conference on the Environment (AMCEN) in Johannesburg 10–12 June 2008. This 12th Session specifically supported "the process of developing the ClimDevAfrica programme" and requested "the AUC, UNECA and the AfDB to accelerate the finalisation of the programme document and the dissemination of this information to ensure the participation of AMCEN in the Climate for Development in Africa programme". The Session went on "to welcome and support the establishment of the ACPC at the UNECA, emphasising its role in supporting the integration of climate change into economic development and planning processed in Africa, and to call upon UNEP, WMO and other relevant institutions to play an active role in this initiative."

4. Programme Description (Goal, Results, Activities and Inputs)

The ClimDevAfrica Programme super goal is: Sustainable attainment of the poverty reduction and other MDGs in Africa. The overall expected accomplishment of the programme is that "Policies and decisions on practices in Africa take full account of climate change risks and opportunities at all levels (regional, sub-regional, national, local, community and individual)." The ClimDevAfrica Programme purpose for the Inception and First Phase (1 + 3 years) is to strengthen the institutional capacities of national and sub regional bodies to make climate-sensitive policy effectively.

ClimDevAfrica is organised into four result areas (or components).

4.1. RESULTS AREA ONE: WIDELY AVAILABLE AND DISSEMINATED RELIABLE AND HIGH-QUALITY CLIMATE INFORMATION

The objective of this first results area is to ensure that policy makers across Africa, policy support organisations and the population at large have access to comprehensive and understood climate information.

Under this results area, ClimDevAfrica will support the upgrading of observation networks and infrastructure in order to enhance the provision of essential data for climate services, policy and best practice development for ACC. This programme component will also include support to capacity building, assessment and research on early warning systems, seasonal forecasting and long term continental, sub-regional and further downscaled climate projections and scenarios.

Activities under this results area will include:

1. Rescuing historical meteorological and hydrological data
2. Data management of climate and hydrological data
3. Upgrading telecom, observation and data collection systems for upper air and surface networks
4. Quality monitoring of greenhouse gases, air quality, inland lakes, African oceans, coastal environments and glaciers
5. Observing and managing hydrological data
6. Detecting and attributing carbon sources and sinks
7. Early warning and seasonal forecasting
8. Making long-term climate projections and scenarios; and
9. Climate information packaging for all climate sensitive sectors and end users

Africa's climate, weather and water organizations, including the NMHSs, are the main beneficiaries under this results area.

4.2. RESULTS AREA TWO: QUALITY ANALYSIS FOR DECISION SUPPORT AND MANAGEMENT PRACTICE

The objective of this results area is to generate enhanced scientific capacity producing effective and quality policy-supporting analysis and best practices on different levels (regional to local).

In this results area, quality policy support, including efficient sharing of information, climate change impact assessments and decision support tools for adaptive management will be provided primarily by the research communities of Africa.

Importantly, this results area also involves identification of best practices in climate-sensitive sectors, which, through communication and networking, will result in local community involvement towards preparedness for extreme weather events and for adaptation to climate change. The component will also ensure production, communication and dissemination of useable and accessible information packages, enabling local communities with information to continue to better adapt to an ever-changing climate. Hence, all supported projects will have and follow an outreach plan.

The activities of this results area include the following:

1. Institutional capacity mapping followed by capacity building
2. Knowledge management system for shared information building, knowledge, experience and best practice sharing
3. Risk, vulnerability, impact and cost/benefit analyses and assessments
4. Development of decision support tools for policy making and adaptive management
5. Policy reviews identifying policy areas for improvements
6. Identification, analysis and recommendations of policy options
7. Best practices for climate change preparedness on all levels (for application down to community and individual use)
8. Policies for national implementation of international conventions
9. Scientific and best practice outreach to all levels (for application down to community and individual use); and
10. Knowledge support to African negotiators

4.3. RESULTS AREA THREE: INFORMED DECISION-MAKING, AWARENESS AND ADVOCACY

Under this results area, ClimDevAfrica will contribute to policy dialogue and support ACC and development policymaking processes at the continental, sub-regional, national and local levels. It will strengthen sub-regional and national development programmes through drafting and implementation of policies that integrate ACC. It will also promote best practices for mitigation and adaptation to climate change. The Programme will continuously enhance the application of best practices through sustained continental knowledge sharing, and sharing of policy ideas and solutions.

One of the most pressing activities of this result area is to facilitate Africa's contribution to the negotiations process on the post 2012 climate agreement through analytical studies and consultative workshops and providing support for the development of a common African position on climate issues.

Activities of this results area include:

11. Capacity building and knowledge support to policy makers
12. Capacity building and knowledge support to negotiators
13. Capacity building of, and support from, RECs and SROs
14. Inclusive and informed policy-making
15. Training and awareness-raising
16. Effective communication; and
17. Outreach to all levels

4.4. RESULTS AREA FOUR: DEMONSTRATED VALUE AND DISSEMINATION OF BEST CLIMATE ADAPTATION PRACTICES

Many African countries and communities are increasingly requesting support to effectively design and implement projects and programmes that will enable them adapt to both short-term climate variability and long-term climate change. This component will support the implementation of pilot adaptation projects so as to provide useful lessons and models to African countries and communities.

Activities of this results area include:

18. Support to the integration of climate change resilience into national strategies
19. Training of countries in the use of tools to identify projects that are at risk of climate change

20. Implementation of pilot adaptation practices that are climate resilient; and
21. Support to the identification of best practices that can be scaled up and replicated

Political leadership of ClimDevAfrica will be provided by the AUC, who will co-ordinate the Continental policy response and global negotiations. Results will be delivered in the four results areas above through two input areas, namely the African Climate Policy Centre (ACPC) and a ClimDevAfrica Trust Fund, the Climate Fund.

4.5. INPUT AREA A: THE AFRICAN CLIMATE POLICY CENTER (ACPC)

Programme Policy Management will be established within UNECA as the ClimDevAfrica Policy arm. The ACPC will perform three key functions to enable ClimDevAfrica objectives to be achieved: (i) enabling the development of Africa's climate policy capacity; (ii) facilitating the processing and management of projects funded by the Climate Trust Fund, and performing Secretariat and administrative functions. Subject matter and sectoral impact assessments, sthematic studies and synthesis work by ACPC will contribute to the results areas outlined above. ACPC programme management activities will include contribution to identification, preparation and feasibility studies of priority operational projects; regular supervisions of national/regional activities; mid-term review; project completion review; annual external audits; and contributions towards the cost of external evaluations.

4.6. INPUT AREA B: THE CLIMDEVAFRICA TRUST FUND

Fund Management will provide a channel for demand-led funding of implementing agencies across Africa. Activities consistent with the achievement of the results areas objectives will be funded. The Climate Trust Fund is in the process of being established within the African Development Bank.

5. Programme Governance

The programme will be governed by the following organs:

22. The Programme Executive Board (PEB) of the AUC/ECA/AfDB Joint Secretariat and the Chair of the African Ministerial Conference on the Environment (AMCEN) will provide the programme oversight function. The PEB will ensure that the vision, purpose and objectives of ClimDevAfrica are maintained. Final accountability for the operation of

ClimDevAfrica will therefore rest with the PEB. The PEB shall receive the Annual Report of the operation of ClimDevAfrica (covering both activities and funding) as well as the minutes of all Steering Committee meetings.

23. Under the PEB will be the Programme Steering Committee (PSC). The PSC will provide technical oversight to the Programme by endorsing projects that qualify for funding by the Climate Trust Fund and making decisions on the allocation of the resources of the Fund. In particular, the PSC shall:

   i. Set strategic direction and exercise financial oversight over the Climate Trust Fund
   ii. Be responsible for the approval and control of the Climate Trust Fund work plans and budgets
   iii. Review the annual reports of activities financed from the resources of the Fund

The PSC shall be a multi-stakeholder organ composed of decision-making members (drawn from AUC, UNECA, AfDB and AMCEN) and other members with only an advisory role. The latter membership shall consist of one other UN agency (to be determined annually by the principal partners), the Global Climate Observation System (GCOS), the World Meteorological Organisation (WMO), one donor acting in the interests of all funding partners, and two other stakeholder representatives appointed annually by the Principal Partners (AUC, UNECA, AfDB).

An Annual Conference will be held in order to ensure that linkages with all relevant stakeholders engaged in the ClimDevAfrica process are maintained. The annual conference will thus act as a forum for consultations around the operation of ClimDevAfrica, provide opportunities to exchange information and learn in relation to the operation of ClimDevAfrica and similar or related activities, and build coherence of ClimDevAfrica with other activities, among others.

In addition to these main organs, Technical Advisers as required will be called upon from a Panel of Experts to ensure that policy development and the technical review of proposals for funding complies with international best practices.

6. Implementation and Monitoring

ClimDevAfrica will be implemented in progressive phases. The vision is that once the core capacity is established in the ACPC to co-ordinate policymaking and manage ClimDevAfrica operations, engagement with and demand from the Regional Economic Communities and other regional weather and climate as well as River-Basin Organisations will increase.

PHASE ONE

It includes the following indicative inception actions in 2009:

i. Putting in place the basic management capacity of the ACPC, including establishing the office at the ECA, recruiting staff (using the UN system and rules), initiating an ACPC website (using the ECA web management facilities), and drafting detailed project implementation documents and plans

ii. Initiating policymaking activities; and

iii. Implementing the ClimDevAfrica Trust Fund, including finalising fund procedures and processes, criteria for approval of funding, call for funding applications from prioritised organisations, implementing the Action Plan for Africa (Addis Ababa April 2006)

PHASE TWO

It will be embedding the functioning of ClimDevAfrica (2010–2012). This phase will entail deepening the work of the programme. Actions for years two and three will be finalised during year 1, with final plans agreed subsequent to the inception review to take place during the last quarter of year 1.

Monitoring and reporting of the programme will take place in three areas, namely the operation of the overall Programme; the activities funded by the ClimDevAfrica Trust Fund; and the performance of administrative and financial functions.

The design of ClimDevAfrica has taken into account best practice and lessons learned in implementing wide-scale co-ordination of policy and programming. As such, the programme design responds to the critical lessons learned. The need to assure political will, ownership and accountability is met through the political commitment of African Heads of Government, Ministers of Finance and Planning, and Ministers of the Environment which has driven the development of the programme.

The Joint Secretariat of the Chief Executives of the three African institutions and the Chair of AMCEN will provide direct oversight of the African Climate Policy Centre and the operation of the ClimDevAfrica Trust Fund. This demonstrates the very best practice in terms of political ownership and accountability.

The joint management arrangements, where AUC, UNECA and AfDB collectively take decisions for the implementation of the activities, seek to ensure institutional coherence.

To deal with overlapping sub-regional mandates, the operation of ClimDevAfrica will take account of ongoing assessments of the capacities and capabilities of the Regional Economic Communities and other sub-regional organisations. As a result, care will be taken in the implementation of the programme to clarify mandates, build sub-regional capacity, and progressively build the involvement of sub-regional organisations within ClimDevAfrica's operations.

The operation design of the programme consisting of its two key elements, the ACPC and the Climate Fund, are based upon similar recent activities that have demonstrated initial success. These initiatives are the UNECA-based African Trade Policy Centre (ATPC) and the AfDB-based Congo Basin Forest Fund (CBFF). Governance of ClimDevAfrica and operation of the ACPC and Climate Trust Fund substantially draw upon lessons learned from the recent design and implementation CBFF.

Appendix A: African Early Warning and Advisory Climate Services (AEWACS)

This project, implemented since January 2009 by ACMAD and supported by the French Fund for Global Environment (FFEM) and AfDB and other partners, may be regarded as a component of ClimDevAfrica, and perhaps a precursor of its implementation.

6.1. PROJECT DESIGN

Through all its components, achievements, and in "background task", the project aims to stimulate and feed the dialog between the community of NMHS and the political, scientific and technical communities in charge of the sustainable and economic development. It addresses concrete sets of themes all related to climate risk management and the climate variability.

The project is mainly demonstrative and its main objective is to develop products and methodologies for the implementation of early warning and advisory products and services which can be replicated at various levels in Africa: regional, national, possibly local. Evolution from a demonstration project to larger scale actions will be facilitated by the organization of implementation arrangements.

The project will work with African countries. It is intended that most advanced countries, and North Institutions (Météo France, IRI, IDDRI, the U.K. Met Service, Spanish INM, Italian IBIMET, etc.) will provide the required expertises in coordination with ACMAD. A Scientific and Technical Multidisciplinary Committee will be set up to overview this process.

The project is based on subsidiarity which aims to give responsibility to the adequate actors at each level, in particular national, for the development and maintenance of climate early warning products and services.

The project must make it possible for ACMAD (i) to develop its function of central operator of ClimDevAfrica; (ii) to concretize orientations of its strategic plan; (iii) to install and implement reinforced procedures of management; (iv) to extend, in operational situation, its multidisciplinary network of scientific resources for the adaptation and the prevention of the climate risks; (v) to consolidate its role as a “hub” for the network of regional and national climate institutions in Africa; (vi) to reinforce synergies with the ECA’s networks for an increased implication of political decision-makers for mainstreaming adaptation in development policies.

The project must make it possible to develop concrete applications mobilizing recent progresses regarding climate forecast capacity. According to the products, short range, medium range, seasonal or several years forecasting will be considered.

7. Appendix B: Resolution 855 (XLI, 2008) of the First Joint Annual Meeting of AU and ECA Ministers of Finance and Planning on Climate Change and Development in Africa

Recognizing the challenge that climate change poses to sustainable development in Africa, in particular the major implications for Africa of the outcomes of the UNFCCC COP13/Kyoto Protocol MOP-13 held in Bali, Indonesia, in December 2007;

Mindful of the need of African countries to be prepared for the series of negotiations leading to a new international climate change agreement by December 2009;

Recalling Decision (Doc.Assembly/AU/12 (VIII)) of the Eighth Ordinary Session of the Assembly of the African Union and Resolution 852 (XL) adopted by the fortieth session of the ECA Conference of African Ministers of Finance, Planning and Economic Development on Climate Change and Development in Africa;

Recalling also the 2005 G8 Gleneagles Summit pledge to support efforts to help developing countries and regions to obtain full benefit from placement of observational systems to fill data gaps, develop in country and regional capacity for analyzing and interpreting observational data, develop decision support systems and tools relevant to local needs and, in particular, work to strengthen the existing climate institutions in Africa;

Noting with appreciation the initiative by the Economic Commission for Africa, the African Union Commission and the African Development Bank in developing the "Climate and Development in Africa" (ClimDevAfrica) programme with particular emphasis on policy;

Convinced of the need to put in place institutional mechanisms to assist in strengthening the capacity of African countries and their intergovernmental organizations to mainstream climate-related issues into national, sub-regional and regional development policies and programmes;

The Conference of Ministers

1. Welcomes and endorses the establishment of the African Climate Policy Centre (ACPC) with the objective of providing policy guidance to member countries and urges ECA to take the necessary action for its immediate implementation;
2. Requests the ECA, in collaboration with AUC and AfDB to take the necessary measures for the effective implementation of ClimDevAfrica through relevant national, sub-regional and regional institutions;
3. Further requests the Economic Commission for Africa and its proposed African Climate Policy Centre to provide the necessary support to and strengthen its partnership with the African Centre of Meteorological Applications to Development (ACMAD).

Addis Ababa, April 2008.

8. Appendix C: Climate and Environmental Services for Development[1]

This section discusses Climate and Environmental Services for development for Africa as a component of the ClimDevAfrica programme. Despite the growing understanding of the climate and its potential impacts on society, climate information is still not routinely useful in decision making. A mechanism is needed that connects the relevant climate science to decisions that build resilience to climate change and variability. While we cannot be prescriptive about specific services for individual countries, there are factors that each of these services should have in common. In particular, informed decision making is based on a wide range of physical and social science information. Acquiring it requires cooperation between many institutions across many disciplines and across national boundaries. It depends on forging new partnerships between the traditional providers of environmental information and between the users and beneficiaries of this information. At present few, if any, countries provide comprehensive national

[1] This section is extracted largely unaltered from the paper "Climate and Environmental Services for Development" by Rogers et al. (2007).

climate and environmental services so there is no obvious single institutional model on which to base the development of these new services.

National Climate Services are an essential instrument in helping to increase the resilience of countries to the adverse effects of climate. These services must encompass a wide range of environmental and social science disciplines to provide the necessary tools to make well-informed decisions. They must draw on the existing expertise from many organizations, while vesting in a single governmental body to coordinate and integrate the climate-related activities. In the short term, it is particularly important to ensure that climate change risk is factored into public sector investment strategies. Therefore it is important to establish and strengthen the link between climate, development and public policy within the leading government ministries.

ClimDevAfrica already provides the rationale for the development of climate and environmental services and climate networks. Together AUC, AfDB and UNECA can provide the impetus leading to the formation of National Climate Services. In turn, these would become a mechanism for the implementation of ClimDevAfrica.

Even more, this independent reflexion on Climate and Environmental Services for development and the ClimDevAfrica Initiative which started in 2006 are going to be discussed globally at the forthcoming World Climate Conference -3 (WMO Geneva, Sept 2009), which should provide nations with the opportunity to jointly formulate an appropriate global framework for climate service provision and application over the coming decades; and to help ensure that every country and every climate-sensitive sector of society is well equipped to access and apply the growing array of climate prediction and information services made possible by recent and emerging developments in international climate science and service provision arrangements.

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The author wishes to acknowledge the fundamental contribution of Dr Jim Williams (independent consultant in environment and natural resources management, UK) in helping to structure and develop the ClimDevAfrica Programme. The ClimDevAfrica Programme has received contributions from many experts and institutions from Africa and its Partners, so many that it will take few pages to just name them, and our first wish is to thank them. The second wish for now is that they will pursue their commitments to see all the objectives implemented to the benefit of the communities in need within an ever changing climate and a challenging development.

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WEATHER/CLIMATE SERVICES IN EUROPE AND CENTRAL ASIA: A KEY TOOL FOR ENERGY SECTOR ADAPTATION TO CLIMATE CHANGE

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Abstract. Countries in Europe and Central Asia (ECA[1]) face the same broad energy challenges as the world at large, with some regional distinctions. This chapter makes the case that modernization of national hydro-meteorological capacity to provide high-quality weather/climate services could help capture emerging economic gains, enable risk management in the energy sector, and support national economies in multiple sectors.

Keywords: Energy; weather; climate; national meteorological service; NMS/NMHS; risk management; severe weather warnings; forecasting; climate change projection; climate adaptation

1. Introduction

Countries in Europe and Central Asia (ECA) face the same broad energy challenges as the world at large, with some important regional distinctions. The region accounts for 10% of the world's energy demand, but only 5% of

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[1] The World Bank's Europe and Central Asia region comprises the countries of Central and Eastern Europe and the former Soviet Union that range from middle to low-income countries. In alphabetical order: Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, FYR Macedonia, Georgia, Hungary, Kazakhstan, Kosovo (under United Nations administration), Kyrgyz Republic, Latvia, Lithuania, Moldova, Montenegro, Poland, Romania, Russian Federation, Serbia, Slovak Republic, Slovenia, Tajikistan, Turkey, Turkmenistan, Ukraine and Uzbekistan.

world GDP, energy and carbon intensity are high[2] and the region is one of the most energy-inefficient world-wide in terms of both consumption and production of energy. Sector assets employ old and outdated technologies, many running beyond design life; the average age of power generation facilities is 35–40 years with nearly 80% installed prior to 1980. A lack of investment in major maintenance throughout the 1990s has compounded this issue, leading to inefficient, unreliable and polluting operations.

The region is resource-rich, but large-scale oil and gas resources in particular are concentrated in a limited number of countries (Russia, Azerbaijan, Kazakhstan, Uzbekistan, and Turkmenistan) and deficient transit infrastructure hampers delivery particularly in southeastern parts of ECA. Much of the region is dependent on Russian gas imports raising concerns about energy security and cost. Hydropower is a mainstay in South Eastern Europe, the Caucasus and Central Asia, but this energy source has not been optimally developed due to an evolving regulatory and incentive structure, evolving and at-times contentious water management institutions, civil society concerns, and recent extremes in climate variability (especially drought).

Energy supplies must double over the next 20 years if the region's economies are to fulfil their potential; else, according to present trends the region may become a net energy importer by 2030. Demand is expected to rise in the period to 2030[3] and fossil fuels are expected to remain the most dominant source of energy. Future gas and electricity shortages are possible in several sub-regions (South Eastern Europe, Central Europe, Turkey and Russia) threatening rapid growth. Considering these factors together with rising gas prices and concern about reliance on Russia for fuel, the region is tending towards a growth pattern characterized by more-polluting but locally-available coal and resistance to shutting down aging nuclear reactors.

Large-scale investment in new generation capacity and rehabilitation of existing assets will be required. By 2030 nearly 50% of generation capacity (as of 2005) is projected to be rehabilitated and 40% retired from service, while around 726 GW of new generation capacity is projected, mostly thermal (72%).[4] Coal-fired and nuclear generation are projected to increase

[2] Electricity and heat production account for over 50% of the region's carbon dioxide (CO_2) emissions.

[3] Based on national energy strategies compiled from ECA governments and energy agencies, to sustain 5% GDP growth in the region, and fulfill economic growth potential, requires average annual growth of 3.7% in electricity supply, including substantial investment in energy efficiency and energy conservation, World Bank estimate.

[4] The remainder is projected to be in nuclear power (15%), hydro power (9%) and renewable energy sources (4%).

over 2006–2030, to 35% and 20% respectively.[5] Overall, investment costs are estimated at US$1.2 trillion (2008). While significant advances will be required in clean-coal technologies, including carbon capture and storage, the renewal of sector assets in the period to 2030 provides a window of opportunity to curtail the sector's carbon footprint and increase the resilience of the sector to climate change.

Strategies proposed to ensure energy security and address the demand-supply gap have increased emphasis on efficiency[6] of supply and consumption, the development of local renewable energy resources and improved regional cooperation and trade. In parallel, the sector will need to adjust to incorporate environmental sustainability issues and to manage the risk of climate change.

Against this backdrop the region is experiencing changes in weather patterns, including variations in mean conditions and in extremes (Westphal, 2008). Greenhouse gas emissions are among the drivers of human-caused change, and their accumulation in the atmosphere is expected to rise in coming decades. In the period 2030–2050 anthropogenic trends are projected to include increased warming in all parts of ECA; changes in precipitation (means and extremes) with increases expected in northern regions and significant reductions in southern and eastern parts; significantly declining water availability (run-off) on average as well as increasingly frequent heat wave and drought conditions in South Eastern Europe and Central Asia; flash flooding in central Europe; rising wind strength particularly in northern parts of ECA, with increased variability; and increased solar radiation especially around the Mediterranean. It should be recalled that the share of this change that should be attributed to anthropogenic versus non-anthropogenic trends is not clear. The past and future effects of climate drivers such as volcanism and solar activity, for example, may be significant and have not yet received consensus assessments (cf. IPCC AR4 TS.2.4).

Supply-demand challenges may be affected on a number of fronts by projected changes in climate, both means and extremes. Energy demand may prudently be expected to change particularly in summer months due to rising cooling needs, while generation capacity in some countries will be affected, for example due to changes in the timing and volume of flow to storage systems and available run-off for hydropower assets. The operation of thermal and nuclear power facilities in some countries will be challenged

[5] Hydropower and gas fired generation decline to 12% and 29% respectively over the period 2006–2030.

[6] Energy efficiency policies could contribute to 80% of avoided GHGs and substantially increase supply security (G8 Summit, 2007).

by water availability and temperature concerns due to their dependence on significant volumes of water for cooling and we may prudently anticipate impacts on power transmission efficiency and capacity including from extreme weather events. Rising temperatures in Arctic and Siberian Russia could open up major economic opportunities offshore but may have negative impacts on energy infrastructure and access particularly in zones of discontinuous permafrost. In some areas opportunities for renewable energy could open up with increased potential for solar and wind power generation.

Based on the above considerations, a discussion of the role that efficient weather/climate services can play in managing the risk of climate change on the energy sector is given in the rest of the chapter. Weather services concern the state of the atmosphere at a given place and time; climate services concern time-averaged weather, including variances and trends. At present, the energy sector makes use of both weather and climate services for operations and maintenance planning, for dispatch planning, for site selection and the design of energy infrastructure; indeed, the energy sector is one of the sectors most dependent on and sensitive to weather and climate information. In the future, global trends including climate change will increase the potential value of weather/climate services.

The case for modernization of national hydro-meteorological capacity to provide high-quality weather/climate services which could help capture potential gains, enable risk management in the energy sector, and support national economies in multiple sectors is made here. However, service modernization would need to be guided to ensure that ultimately the right data is provided to decision makers, in a timely manner and in a format that is useful for the energy sector.

2. Energy Sector Use of Weather/Climate Information

Energy is one of the economic sectors most affected by weather, together with agriculture, transport and construction. Besides that, energy is also one of the sectors most sensitive to weather *information*, from strong basic forecasting and climate services to new types of service including long range forecasting, satellite imagery and climate projections.

Forecasts of temperature, visibility, wind speed and direction, and icing, for example, are used to manage fuel transport: pipelines, transmission lines, and transport by sea, road and rail. Forecasts of temperature and natural illumination/cloudiness are used to predict energy use, while hydrological forecasts support optimization of power production.

Climate services – including data delineating trends, maps of historic weather patterns and measures of typical variability – are essential inputs for planners when selecting sites and designing energy infrastructure.

Information on solar irradiance, wind speed, temperature extremes, and river flows (e.g., as input to full river hydrographs) are needed in the design of power generation both traditional and renewable; information on wind and icing patterns are required by planners when designing transmission lines. Newer, less-traditional weather/climate services are also coming into wide use. For example, long-range weather forecasts drawing on indices of El Niño Southern Oscillation (ENSO) or the North Atlantic Oscillation to forecast temperature and precipitation can help to support more-efficient reservoir operations and hydropower planning. Satellite imagery is expected to improve forecasts of maximum/minimum daily temperatures and in turn load forecasts. Reliable climate change projections are a hoped-for tool to support decision making for planning and for operations and maintenance, particularly for long-lived assets.

3. Global Trends Affecting Energy Sector Use of Weather/Climate Services

Four global trends are likely to influence the way that the energy sector uses weather and climate information in the future: climate itself is changing; the skill[7] of weather/climate services is rising significantly; other sectors are joining the energy sector as users of skilled weather/climate services; and, lastly, skills gaps are emerging that distinguish the value of information available in countries that have invested in capacity for weather/climate services from the value of information available in countries that have not invested at a similar level.

3.1. CLIMATE IS CHANGING

As noted above, standards for design of energy-sector infrastructure take climate into consideration but are based on historic data and assumptions of a stable average climate: stable variances around stable mean values. However, it is increasingly clear that climate is changing: both its mean values and the scale of variances. Climate models show that such changes could have greater range in the future than in recent records of climate variability.

Although climate change projection is an extremely active study area that has achieved improvements in expected reliability, many uncertainties remain which limit project application. First, projections vary significantly from one scenario to the next depending on base assumptions of economic

[7] *Skill* is a measure of the accurate analysis of current weather patterns above the accuracy of forecasts based on 'blind' guesses such as persistence and climatology.

growth and CO_2 accumulation in the atmosphere as shown for example in Figure 1(a); second, projected precipitation trends for the same development scenario differ between atmospheric models as shown for example in Figure 1(b). There is closer correlation between atmospheric and economic models for temperature compared to precipitation.

A further issue relates to the scale of projections (mostly sub-continental) versus that of projects (typically at the sub-basin). A given sub-region with strong climate trends, such as South Eastern Europe for which projected warming is strong and reduced precipitation is significant, when viewed on a smaller scale may nevertheless manifest a wide variation in projected changes, even up to the direction of change, which may contrast with the projected average for the sub-region (Figure 2).

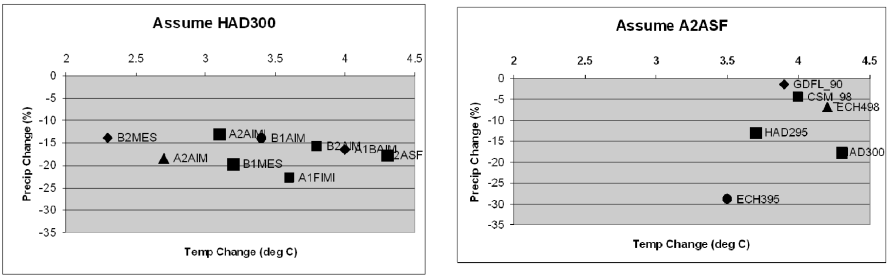

Figure 1. Projected change in temperature and precipitation calculated at a single grid point. (**a**) Projections from nine different economic scenarios, using one atmospheric model (HAD300). (**b**) Projections from six different atmospheric models, using one IPCC economic development scenario (A2ASF).Source: Bruci (2007), © World Bank.

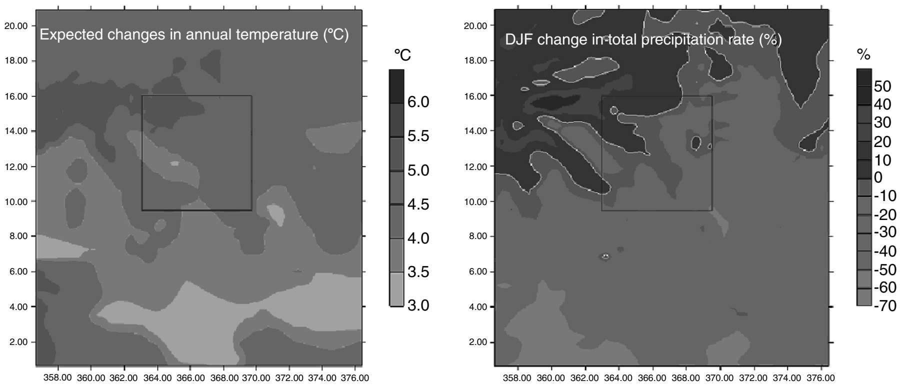

Figure 2. Projected climate change over South Eastern Europe calculated at 50 km grid spacing based on IPCC development scenario A2ASF and climate model HAD300. (**a**) Annual average temperature. (**b**) Winter precipitation. Source: Projection by Hadley Center; figure from Bruci (2007), © World Bank.

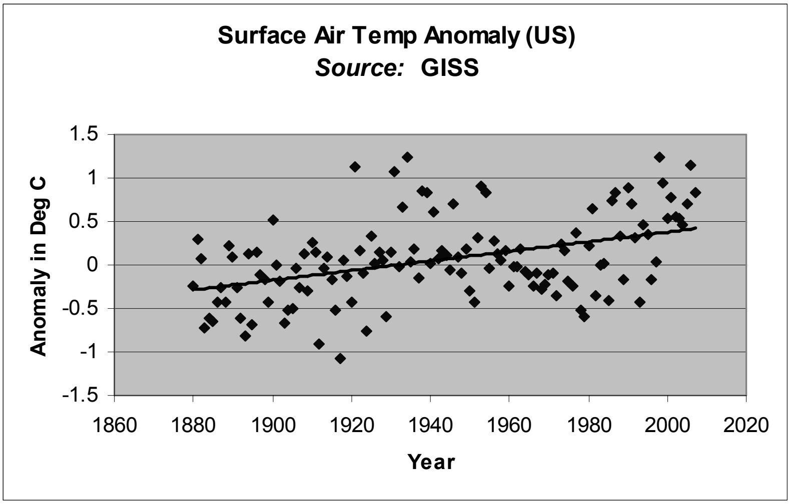

Figure 3. Air-temperature anomaly by year over the United States, 1880 to present, area average. Black line: best-fit linear trend. Source: Data from Goddard Institute of Space Sciences.

Another complicating element is illustrated in Figure 3, which shows that temperature variation comprises several components: not only the century-long trend that is a candidate for the footprint of greenhouse gas influence, but other oscillations as well as large year-to-year variations. It seems likely that natural components of climate variation are large, considering that large variations have been observed in past centuries. As yet, these are not well understood.

In summary, the climate is changing significantly but there is room for improvement in future climate projections to improve convergence for variables other than temperature (precipitation is particularly important), and to better account for the scale of natural (non-anthropogenic) observed variation. These uncertainties highlight the existence of risks to be managed – the first global trend.

3.2. SKILL OF WEATHER/CLIMATE SERVICES IS RISING

While long range climate projections are still at an early stage of development, the accuracy of routine weather forecasting has risen dramatically in recent decades (Figure 4). This is the second global trend. Forecasting skills are rising because new technologies are being deployed to ever-greater effect: radar, satellites, telecommunications, and above all supercomputing. New data processing methods are the single greatest contributor to rising forecast skill, possibly more important than satellite and all other new forms of data taken together.

Additionally, global cooperation is essential for routine weather forecasting. As Figure 5 illustrates, a 5-day advance forecast of local weather requires data on current weather from most of the world. To that end, cooperative institutions have been developed through the World Meteorological Organization.

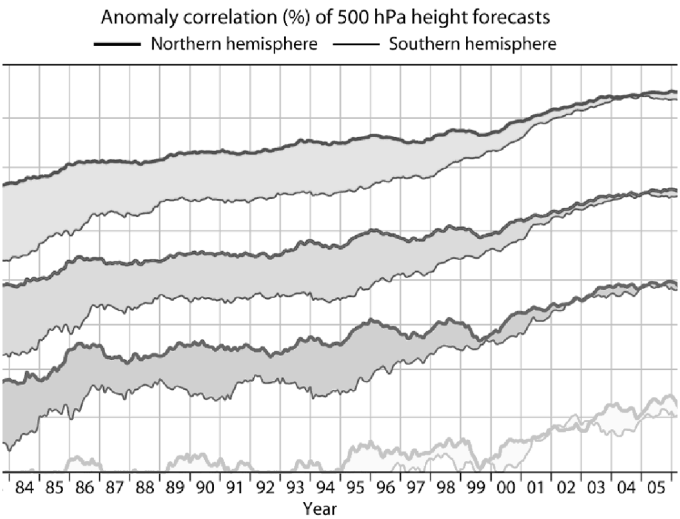

Figure 4. The rising accuracy of weather forecasts. Source: European Center for Medium-range Weather Forecasting, 2007. Used by permission.

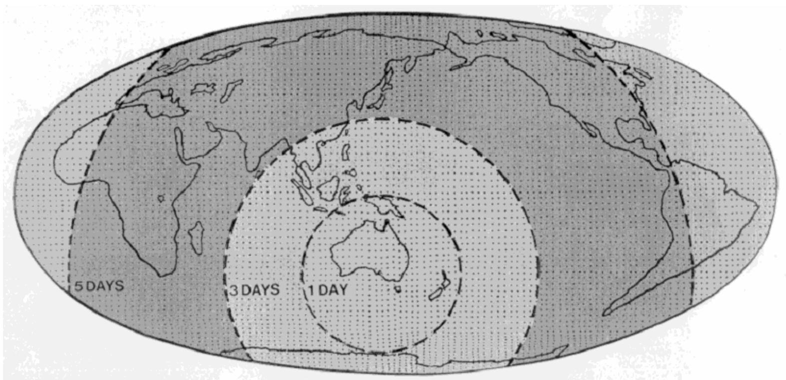

Figure 5. Data requirement for a local forecast to 1 day, 3 days and 5 days. Figure developed by the Australian Bureau of Meteorology based on a study by ECMWF. © Commonwealth of Australia. Used with permission.

3.3. MANY ECONOMIC SECTORS ARE USING WEATHER/CLIMATE SERVICES

The third global trend: As weather/climate services improve and forecasts become more accurate, users in many economic sectors including the energy sector have identified uses for this information.

Aviation, a long-standing client of weather services, relies on weather forecasting for safety and load optimization. *Agriculture* seeks longer-lead-time and increasingly accurate forecasts to guide cost-effective deployment of expensive inputs. *Disaster mitigation* benefits from forecasts of very near-term severe weather conditions, including flooding. *Water resource managers* look to the day when hydrological forecasting can benefit from accurate precipitation forecasts. Besides these examples are many others. As a consequence, improvement in public weather forecasting can yield economic benefits to enterprises at many scales, across many sectors.

3.4. SKILL GAPS ARE EMERGING

While forecasting skills are rising globally, the rise is not even; many countries are falling behind in relative skill. In Europe and Central Asia, some transition economies – countries once at the scientific forefront – today suffer the effects of low levels of public investment in weather forecasting during the difficult transition era. Evidence of the skill gap emerged in profiles of national meteorological and hydrological services (NMS/NMHSs) commissioned by the World Bank in 2005 (and subsequently updated in the course of operational work). Four criteria were identified as flags (not measures) of capacity, namely: (i) Does the NMS/NMHS run a high-resolution numerical weather prediction model (local area model, or LAM) tailored for the national airspace? (ii) Does the NMS/NMHS launch at least one upper atmosphere sonde on a regular daily schedule? (iii) Does the NMS/NMHS have at least one operating meteorological radar? (iv) Does the NMS/NMHS assess its telecom link to its own remote stations as adequate? Table 1 presents the outcome of this assessment and highlights sub-regional skill gaps. South Eastern Europe has high capacity, led by Croatia and Serbia, while capacity gaps in Bosnia Herzegovina and Albania need urgent attention. There is good capacity in Eastern European countries, although Moldova's service is weaker. Capacity is weak in the South Caucasus and Central Asia, especially the weather-vulnerable mountain republics of the Kyrgyz Republic and Tajikistan.

TABLE 1. Emerging infrastructure gaps by sub-region in Europe and Central Asia (Hancock et al., 2008, and references cited therein, © World Bank).

Sub-region		NMS/NMHS runs LAM (1), no LAM (0), other cases (0.5)	At least one atmospheric sonde daily (1); no daily sonde (0)	At least one met radar (1); no met radar (0)	Telecom connection to remote stations adequate (1); significantly deficient (0); other cases (0.5)
South Eastern Europe	Croatia	1	1	1	1
	Serbia	1	1	1	1
	Bulgaria	1	1	1	0
	Macedonia	1	1	1	0
	Montenegro	1	0	0	1
	Bosnia	0	0	0	1
	Albania	0	0	0	0.5
European CIS	Ukraine	0.5	1	1	1
	Belarus	0.5	1	1	1
	Moldova	0.5	0	0	1
Caucasus	Armenia	0	1	1	0.5
	Azerbaijan	0	1	1	0
	Georgia	0.5	0	1	0
Central Asia	Uzbekistan	0	0	1	0.5
	Kazakhstan	0	1	0	0.5
	Tajikistan	0	0	0	0
	Turkmenistan	0	0	0	0
	Kyrgyz Republic	0	0	0	0

To measure the real impact of such under-equipment, several surveys were conducted of the lead time provided by severe weather warnings. The surveys drew on a methodology, questionnaire and comparator data borrowed (with permission) from the United Kingdom's Met Office. Results showed (Figure 6) the human importance of under-financing in target countries: severe weather alerts do not afford the lead time available in the United Kingdom. To some extent these warnings are not comparable, because different climates manifest different types of severe weather events; nevertheless, this dataset distinctly suggests that under-financing of weather agencies has a measurable impact on daily security.

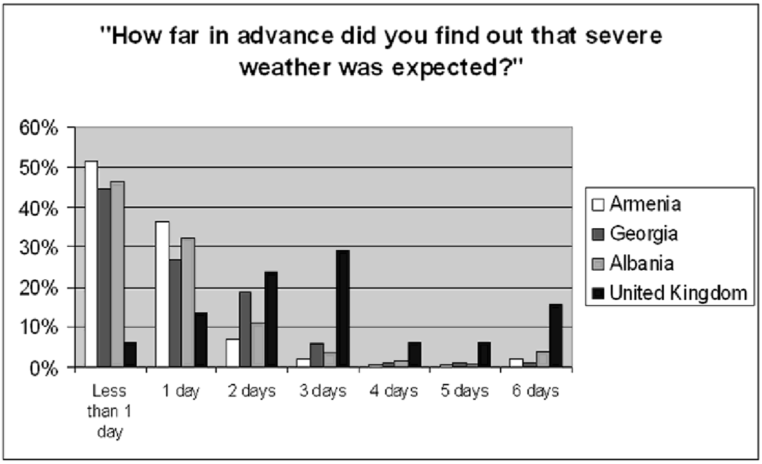

Figure 6. Lead time for severe weather warnings: single-occasion surveys in four countries Source: Hancock et al., 2008, and references cited therein; © World Bank.

4. National Benefit from Modernization of National Meteorological and Hydrological Services (NMS/NMHSs)

Building the capacity of national meteorological and hydrological services (NMS/NMHSs) to provide high-quality weather/climate forecasts through service modernization could help capture potential economic gains and enable risk management in the energy sector. Four criteria can be used to highlight countries where investment in modernization could be particularly beneficial.

4.1. VARIABILITY OF NATIONAL CLIMATE

Good forecasts are most valuable for countries where there is significant variability in weather over the time frame of forecast services (1–10 days). In Europe and Central Asia, not surprisingly, the continental interior has high variability in temperature, while more-variable precipitation is experienced over mountainous regions and areas to the east of the regional seas.

4.2. ECONOMIC EXPOSURE TO WEATHER RISKS THAT COULD BE MITIGATED BY WEATHER/CLIMATE FORECASTING

Economies that are most exposed to weather risk include countries where energy, agriculture, transport and the construction industry comprise a large share of GDP. In these sectors particularly, weather events can lead to significant losses, and timely and accurate forecasts may help mitigate damages or provide more lead time for optimization of sector operations. For example: Azerbaijan's offshore oil operations and tanker operations in the Adriatic Sea off Croatia's coast rely on marine weather forecasts; Albania's hydropower-dependent economy needs good weather forecasting to optimize power production and demand; wind forecast data is an important tool in the management of oil spill risks in the Caspian and Black Seas; and long term forecasting is important for sector operations in Russia's zones of discontinuous permafrost. In some countries, other information-dependent sectors such as tourism may also be very important.

4.3. STATE OF THE NMS/NMHS

Investment benefits depend on the state of weather services. While the relationship is not linear, it is clear that large national economic benefits will accrue if a NMS/NMHS can turn the corner to a baseline capacity such as operational forecasting at 2-km grid spacing, thus effective 10-km spatial resolution. While Table 1 presents some capacity issues, more broadly the skill of the NMS/NMHS is linked to: the state of the monitoring network, adequacy of telecoms, information technology, staff training and the age profile of the workforce, effectiveness of dialogue with information users, existence of cooperative agreements with neighbours, and capacity to provide services tailored to different decision makers, among other circumstances.

4.4. SECTOR INFRASTRUCTURE AND CAPACITY

The energy sector is relatively well-equipped to make use of additional weather/climate data and improved forecasts. However, other sectors that are in principle co-beneficiaries are not always able to make use of better forecasting. Farmers may need training to use cutting-edge forecasts; gains in information support for irrigation will not have much effect where irrigation infrastructure is weak or missing; the transport sector may not be equipped to provide truckers with up-to-date road weather information; civil protection may be unable to disseminate short-lead-time warnings in time to make a difference. Thus, the value of modernization of weather/climate services depends in part on the preparation of the economy to make use of new information.

5. Rapid Assessment of NMS/NMHS Modernization

To understand the benefits and costs of NMS/NMHS modernization and to identify "low-hanging fruit" among investment opportunities, the World Bank undertook rapid assessments in eight countries in Europe and Central Asia. Three assessment methods were used: (i) sector-specific assessments of the current level of weather-related losses and the benefit that could be realized with higher quality forecasts with longer lead time; (ii) "benchmarking" national economies against average global cost-benefit statistics for NMS/NMHS investment based on the economic characteristics of each country; and, (iii) in two countries, household surveys to understand the value of an increment of weather information and household willingness to pay for improved data.

Table 2 presents selected findings from this assessment, which concluded that NMS/NMHS modernization could avert economic losses *each year* of around 33–100% of the investment cost required for a modest but significant service modernization. Even taking into account incremental operating costs for the NMS/NMHS (about 15% of investment), modernization appears well justified. Alternative estimates of economic benefit are if anything usually higher than those presented in Table 2.[8] Household surveys confirmed strong public interest in additional weather information with interest dependent on the household's involvement in weather-dependent activities and hence its vulnerability to weather events.

6. Conclusion

Modernization of weather services is cost-effective. Improved NMS/NMHS capacity can support energy sector planning, investment, operations and maintenance as well as mitigation of potential weather related damages. But realization of such benefits depends on a number of factors including whether technical weather/climate information is tailored or interpreted to support decision making at a sector level and whether information is communicated to key stakeholders in a timely and effective manner. It is important that institutions and operators at a sector level have the capacity, knowledge and infrastructure to use information and adapt their activities in light of additional data and forecasting. Risk management tools and probabilistic weather/climate information are also necessary for policy makers and operators alike to prioritize vulnerabilities and identify adaptation and management needs across the supply chain.

[8] See: Hancock et al., 2008 and Tsirkunov et al., 2007.

TABLE 2. Key inputs and results of rapid assessment of the economic benefits of NMS/NMHS modernization. Source: Tsirkunov et al., 2007, Hancock et al., 2008, © World Bank.

Parameter	Albania	Azerbaijan	Armenia	Belarus	Georgia	Kazakhstan	Serbia	Ukraine
Average annual GDP (USD mln)	4,229	7,061	2,579	15,011	3,620	23,991	9,763	38,305
Territory (‘000 km^2)	28.8	86.8	29.6	207.6	69.7	2,720.0	89.0	603.7
Population (mln)	3.1	7.8	3.0	10.3	4.9	15.1	8.1	47.1
Average annual NMS/NMHS funding (USD mln) (% of average annual GDP)	0.44 (0.01)	1.70 (0.02)	0.47 (0.02)	2.96 (0.02)	0.47 (0.01)	4.21 (0.02)	5.15 (0.05)	7.70 (0.02)
Share of agriculture in GDP (%)	24	12	30	10	25	7	17	9
Weather dependent sectors as % of GDP (%)	65	51	69	43	62	45	44	46
Meteorological vulnerability (index)	Relatively high	Relatively high	Relatively high	Relatively high	Relatively high	Relatively high	Average	Relatively high
State of NMS/NMHS	Poor	Poor	Poor	Poor	Poor	Poor	Satisfactory	Poor
Annual weather related losses as % of GDP – benchmarking methodology	1.0	0.5	1.3	0.4	1.0	0.3	0.4	0.40
Annual losses in mln USD – benchmarking methodology	42	36	32	58	36	78	43	150
Annual losses in mln USD – bottom up multi-sector assessment approach	32	55	50	72–83	54	–	95	190–500

Parameter	Albania	Azerbaijan	Armenia	Belarus	Georgia	Kazakhstan	Serbia	Ukraine
Preventable annual losses in mln USD – benchmarking	11	14	7.0	29	9	39	34	70
Economic efficiency[9] of NMS/NMHS today as % – benchmarking methodology	430	170	280	210	360	200	220	200
Incremental annual effect of NMS/NMHS improvement in USD mln – benchmarking methodology	2.5	3.8	1.6	8.6	2.2	12	5.5	20
Incremental annual effect of NMS/NMHS improvement in USD mln – bottom-up multi-sector assessment approach	1.8–3.9	12	9.2	7.9–9.1	8.0	–	4.3	26–70
Estimated cost of modernization in USD mln	4.0	6.0	5.3	12	6.0	15	4.4	45
Investment efficiency across 7 years								
Benchmarking (as %)	**440**	**430**	**210**	**530**	**260**	**540**	**880**	**310**
Sector assessment (as %)	**320–680**	**1,440**	**1,070**	**480–550**	**1,050**	–	**690**	**410–1,080**

[9] Economic efficiency is calculated by comparing benchmark estimates of prevented losses to NMS/NMHS funding. The result is a conservative estimate of efficiency, because benchmarking tends to under-state prevented losses, but even so, it suggests that the efficiency of NMS/NMHS funding is rather high, from about 170% for Azerbaijan to about 430% for Albania. That is, for each dollar spent on its NMS/NMHS, Azerbaijan averts US$1.70 of economic losses; for each dollar of support for the Albanian NMS/NMHS, Albania averts US$4.30 of losses, etc. (Hancock et al., 2008).

The good news is that the energy sector is resilient and has experience in operating and adapting to harsh climates, developing innovative technologies and managing risk. The power sector has vast experience with short-term forecasting to manage load and demand that could be adapted for longer-term climate adaptation. Best-practice adaptation measures and operational experience can be found in other countries for many of the climate-related risks that face the region's energy sector; e.g., Alaskan and Canadian experience in the oil and gas sector in zones of discontinuous permafrost can be readily translated to address Siberian needs. The challenge will be to harness this expertise to ensure that win-win and no-regrets adaptation options are identified, and to avoid over- or mal-adaptation.

The other challenge, financing of weather services, is a distinct dilemma: the frequently-used cost-recovery approach to financing development of weather/climate information products raises thorny economic issues, aggravated by the public importance of the product and the global inter-dependence it is built upon. Restricting information to those best able to pay will limit overall economic benefits.

In summary, modernization of national meteorological and hydrological services to get the right data to energy-sector decision-makers, in a timely manner and in a format that is understandable, will help to ensure basic service provision, sensitize regulators to climate change, support better decision-making, facilitate a flexible and risk-based strategy for climate adaptation, and enable optimization of the water/energy tradeoff.

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CLIMATE RISK MANAGEMENT FOR THE ENERGY SECTOR IN AFRICA: THE ROLE OF THE AFRICAN DEVELOPMENT BANK

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Abstract. Africa, with its wide spread rural poverty, relatively high dependence on irrigated and rain fed agriculture and chronic energy crises, has of all regions the lowest capacity to adapt to a changing climate. Furthermore, impacts due to increased climatic variability are felt hardest on the continent. Adverse weather events such as droughts, floods, torrential rains and cyclones have significantly increased both in force and frequency over the last 20 years. Thus, the UN Development Programme (UNDP) and the World Bank estimate the cost of adaptation at $2–7 billion US per annum. Obviously, those costs exceed by far the currently available resources, available in the Global Environment Facility (GEF) adaptation funds. The four Funds amount together to US$250 million; whereby the envisaged adaptation fund as outcome of COP 14 is estimated to be at US$700 million. Henceforth, the African Development Bank actively engages the triple challenge of (i) Climate Risk Management both in project due diligent and country initiative level; (ii) Fostering clean Energy Development and; (iii) Increasing universal energy access by 2030. The key guiding strategic documents on both mitigation and adaptation are the Clean Energy Investment Framework as well as the Climate Risk Management and Adaptation Strategy. Furthermore, the Bank is building in both climate change areas staff capacity as well as Regional Member Countries (RMC) strength to develop best practice project designs. For instance, in the Banks energy sector department, holistic approaches, that consider climatological forecasts as well as early warning systems for enhanced dam and reservoir management are already being implemented. Finally, a major obstacle for Climate Risk Management in the African energy sector is its uniqueness in

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terms of under funding and often lack of sound operation and maintenance procedures. Extreme weather events, combined with the mentioned short comings in operations often result in disastrous consequences.

Keywords: Climate risk management; Africa; energy sector

1. Introduction

Climate change has emerged as a serious threat to sustained economic growth, poverty reduction and overall political stability in the world. In the last 2 years, two compelling reports – the 2007 Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC)[1] and the Stern Review[2] – have shed light on the phenomenon, its most likely driving factors, and the risks and challenges that it presents. IPCC presented consensus empirical evidence of near-certain cause-and-effect linkages between human socio-economic activities and greenhouse gases (GHGs), and between the latter and climate change. The Stern Review, on its part, undertook a comprehensive cost-benefit analysis of international response to climate change. It estimated that climate change could result in economic losses of the order of 5% of GDP world-wide. When a wider range of environmental and social impacts are factored in, potential losses could rise as high as 20% or more of GDP.

In the light of mounting evidence of global climate change, the Heads of State and Government of the G8 States, at their Gleneagles Summit in July 2005, called upon the World Bank and other multilateral development banks (MDBs) to prepare specific proposals on three interrelated challenges: to increase access to quality energy supplies especially for the world's poor; reduce global emission of GHGs, mainly by promoting clean energy development; and adapt to increasing climate variability and extreme weather events. At the subsequent summit meetings at St. Petersburg (in July 2006), Heilingendamm (in June 2007), and Hokkaido Toyako (in July 2008) the G8 Leaders, and their counterparts from major developing countries, reiterated their commitments on these three challenges.

[1] The IPCC's 4th Assessment Report, 2007 in essence states that for the last 600,000 years we are experiencing an unprecedented rate of global warming. Ice core drillings have confirmed that for the last 150 years, the global mean temperature has risen sharply. Furthermore, the report confirmed as well that Africa is the most vulnerable continent to climate change and increased climate variability.

[2] Stern Review on the Economic of Climate Change, November 2006.

1.1. BACKGROUND

African countries themselves, in recent years, have become more aware of the threats posed by climate change. They have witnessed extreme weather events – historic hot spells, droughts, torrential rains, cyclones, floods, and extreme fluctuations of river flows and lake water levels. Heads of State and Government devoted a segment of the January 2007 AU summit to discussing appropriate responses to climate change, including improved availability of quality information on climate and development, and the harnessing of science and technology. They endorsed an Action Plan for Africa on Climate Information for Development Needs (ClimDevAfrica) elaborated by the Economic Commission for Africa (UNECA), AfDB, and Global Climate Observing System (GCOS), under the leadership of the Commission of the African Union (AUC).

In response to the mandates from its regional and non-regional member states, the AfDB has been developing its response to climate change along multiple parallel tracks:

- A Clean Energy Investment Framework outlining the Bank Group's strategic approach to supporting African countries' efforts to attain energy access for all by 2030 and to increase their contribution to global climate change mitigation efforts was endorsed by the Boards of Directors in March 2008.
- As one of the first Multi-Lateral Development Bank's (MDB) the African Development Bank has developed a stand-alone Climate Risk Management and Adaptation Strategy for Africa – given the significance of adaptation for the African continent, this separation underscores the relevance of the subject at hand.
- The Bank has been working closely with the governments of Central African Countries and the United Kingdom in developing a Congo Basin Forest Initiative aimed at reversing deforestation by strengthening the capacity of local communities to sustainably manage forest resources thereby maintaining benefits, and by assisting them to find alternative environment-friendly livelihoods compatible with improved quality of living.
- The Climate Information for Development "ClimDevAfrica" Plan is under preparation and expected to become operational in September 2009. The program aims to increase climatological data availability on the continent, and hence contribute to build climate resilient societies.

2. The Clean Energy Investment Framework at the Bank

In light of the mounting evidence of the causes and effects of global climate change, the Heads of State and Government of the G8 states, at their Gleneagles Summit in July 2005, called upon the World Bank and other multilateral development banks (MDB's) to prepare specific proposals to address three inter-related challenges: expanding access to reliable energy supplies, particularly for the world's poor; promoting investment in clean energy and low-carbon approaches to economic development; and supporting developing countries undertake concrete measures to adapt to climate change and strengthen their capacities to cope with increasing climate variability and extreme weather events. This report presents a comprehensive framework for dealing with these triple challenges in Africa.

2.1. PILLAR I: EXPANDING ENERGY ACCESS

Africa has considerable energy potential but it consumes the least amount of energy per capita in the world, and is a significant net exporter of energy resources. Endemic low per-capita consumption of energy is both a cause and a consequence of Africa's prolonged poor socio-economic performance since the early 1970s, particularly in oil-importing Sub-Sahara African (SSA) countries. In these countries in general, less than 10% of the rural population has access to modern energy services. An estimated 400,000 deaths yearly – predominantly women and children – are linked to the use of traditional fuels in poorly-ventilated cooking places. There is a steady deterioration in the quality and reliability of electricity supply, due to chronic under-investment in capacity expansion and operations and maintenance.

Access-for-all to safe, reliable and affordable energy supplies is an imperative, in order to improve the quality of life, strengthen the capacity of African economies to compete more effectively in the global economy, and reduce poverty. However, energy development and access to safe and reliable energy and power supplies for the entire population in Africa, particularly in SSA, are hampered by several major constraints. These include: inadequate attention paid to energy development in national development plans and poverty reduction strategies; lack of energy supplies stockpiling, transportation and distribution infrastructure (including the high capital costs of extending national electric power transmission grids to rural areas and building local distribution networks at the village level); low tax revenues and limited capacity to provide public funding to infrastructure capital investment and consumer subsidies to poor households; limited private domestic savings due to high levels of poverty; tremendous pressures on energy infrastructure due to rapidly rising populations, rural-to-urban migrations and the rising concentration of populations in unplanned peri-urban areas.

2.2. PILLAR II: CLEAN ENERGY DEVELOPMENT

Expanding energy access is a priority for Africa. However, the right balance must be struck between this goal and following a low-carbon path, limiting GHG emissions per unit of GDP. As one of the regions most vulnerable to global warming, Africa has a vested interest in rendering effective support for global mitigation efforts. As a demonstration of the utmost importance that Africa attaches to preventing excessive global warming, African countries may need to provide contributions of their own (albeit voluntary and nonbinding ones) to global emissions reduction. More effective use of flexible mechanisms under the Kyoto Protocol negotiated under the United Nations Framework Convention on Climate Change (UNFCCC), in particular the Clean Development Mechanism (CDM), provides a limited but crucial avenue for Africa to mobilize badly needed financing to buy down the initial cost of low-emission energy generating capacity. Africa is endowed with enormous renewable energy potential that remains largely untapped. African economies can progressively switch to cleaner sources of energy and cleaner development practices if resources are correctly priced taking into account their replacement value and pollution clean-up costs.

African private enterprises, civil society, NGOs, and research institutions also should invest greater effort in understanding the new exigencies, opportunities and challenges of the transition to clean development. Possible innovations include installing and using clean and more efficient stoves; switching to solar power; setting up viable decentralized community-level energy and power utilities to harness local resources such as wind energy, micro and small-scale hydro-power, biogas from communal waste, and sustainable managed community forests; popularizing energy-saving (or passive) housing architecture; licensing energy-efficient appliances; favouring energy-saving bulbs; and undertaking waste recycling. Communities should be provided adequate incentives to preserve local forest and wetland ecosystems, thereby avoiding deforestation and wetland destruction.

2.3. PILLAR III: CLIMATE RISK MANAGEMENT AND ADAPTATION TO CLIMATE CHANGE

As aforementioned, the consensus among experts is that Africa is one of the most vulnerable continents to climate variability and change because of multiple stresses and low adaptive capacity. Countries' situations are exacerbated by anterior development challenges, particularly the high incidence of poverty, poor governance and weak institutions, limited access to capital, infrastructure and technologies, environmental degradation, and complex disasters and conflicts. Most countries are not effectively facing up to current climate variability and extreme weather events, such as floods, cyclones and tornadoes, periodic droughts, and water scarcity, let alone being ready to face up to greater variability due to changing climate in the years ahead.

Thus, the Bank develops on a parallel track the climate risk management and adaptation strategy. This process will be guided through two main delivery modalities:

- Climate risk management as part of the due diligence in Bank Group projects and country/sector planning: Climate risks directly affect Bank operations.[3] These risks should be addressed in project preparation processes and appraisals similar to other risks: systematic analysis and incorporation into project design and decision-making. Eventually, a large share of the Bank's operations will include systematic climate risk management, as part of due diligence in country programming and project preparation.
- Support for climate risk management by regional member countries The main entry point for regional member country support should be the Bank's own country operations. The Bank should identify high-risk investment cases, where external resources can be found for climate risk management add-ons. These cases can be used as a trigger for broader climate risk improvements in regional member countries.

The aim is for climate issues to be integrated into national, sub-national, local and sectoral development planning and decision-making processes. This includes ensuring complementarily with national frameworks such as Poverty Reduction Strategy Papers (PRSPs), sectoral strategies and plans, as well as national and local strategies for sustainable development. Furthermore, a key issue is integration into economic planning and the budgetary process, within and across all sensitive sectors.

2.3.1. *Climate Risk Management*

Many of the most effective measures to adapt to future climate change coincide with those that can reduce vulnerability to current climate risks.

[3] Particular areas of present and increasing vulnerability are existing infrastructure such as roads, bridges, railways, power supply systems, etc. Furthermore, agriculture, water resources, health, ecosystems and biodiversity including forestry and coastal zones, safety of human settlements, are under threat by increased climate variability.

This principle lies behind climate risk management, which integrates management of current climate variability and extremes with adaptation to climate change. Climate risk management offers immediate benefits to economic development in Africa, as well as longer term security in the face of a changing climate.

The systematic integration of climate risk management in development operations is receiving increasing attention in various development agencies and development banks. Examples of the methods and tools that are being developed for this purpose include the World Bank's Climate Risk Screening Tool; methods from the Asian Development Bank's CLIMAP program; and risk screening tools developed by the UK's Department for International Development (DFID). Besides the development of these tools, there is further a growing body of projects implemented by development banks that explicitly include climate risk management. The private sector, in particular insurance and reinsurance companies, are also beginning to take the lead in integrating climate risks into their insurance products.

The African Development Bank is planning to integrate climate risk management into its regular operations, and to support enhanced climate risk management by regional member countries. Thus, the institution is currently developing a climate risk management strategy to guide its efforts as well as preparing a number of project interventions, including the CARLA project on climate adaptation for the food security and agriculture sector in Malawi. The strategy will address two key gaps in current Bank work. First, it will help Bank operations integrate the notion that the future climate will be different from the past, which changes investment opportunities and risks. Second, it will address the underinvestment in climate adaptation and in climate risk management, even in light of current climate variability and extremes.

In addition, the AfDB is working with key partners, namely the African Union and the United Nations Economic Commission for Africa, on implementing a UK DfID-sponsored program 'Climate Information for Development Needs' (ClimDevAfrica). The goal of ClimDevAfrica is to improve the availability and use of climate information and services in support of sustainable development and achievement of the MDGs. ClimDevAfrica should result in better food security, improved protection from malaria and other climate-sensitive diseases, enhanced management of water resources, better disaster risk management, more judicious use of energy resources and improved environmental sustainability.

2.3.2. *Africa's Special Climatic Situation*

Africa faces a number of special challenges that makes the continent more vulnerable to climate change than other parts of the world.

Key economic sectors – specifically agriculture and other natural resource-based sectors – are highly sensitive to climate variability and change.

- Many systems are already close to their tolerance limit for temperature or changes in rainfall.
- Multiple stresses – including endemic poverty, complex governance and institutional dimensions, limited access to capital, ecosystem degradation, disasters and conflicts – combine to exacerbate Africa's vulnerability to climate variability and change.
- Availability of climate information is limited in most African countries, and the quality is significantly below WMO standard.
- Competing priorities, and short-to medium-term decision-making horizons, often result in lack of attention by politicians and other decision makers to the need for adaptation to climate change. Low priority of adaptation is given due to the fact that it does not have a clear immediate economic output of its own. Hence, it is often considered less important than other development objectives.
- Currently available funding for climate change adaptation in Africa does not come even close to the amount needed.
- The infrastructure to cope with grave disturbances and catastrophic events is weak/underdeveloped.

Climate change does however bring some opportunities for Africa.

- Attention paid to climate risks in the face of climate change can help to reduce the impacts of climate variability and extremes that Africa is already facing today.
- New and improved technologies, and innovations in climate science, are becoming available that could help Africa adapt to climate change.
- Innovative private sector instruments, management practices and business approaches are being developed that can help to cope with climate risks.
- Climate change can act as a catalyst to enhance partnerships between government departments, the private sector, non-governmental organizations, and national as well as international providers of scientific information.
- New adaptation funding provides resources for enhancing the effectiveness of current investments, or developing and implementing innovative practices.
- Incorporating climate risk management into projects results in a re-orientation of project planning and development, and better operation and maintenance, with both immediate and long-term benefits.

3. The Provision of Energy and the Link to the MDG's

Although there is no Millennium Development Goal on energy, sustainable, reliable, and affordable energy services are indispensable to achieve economic growth: to increase the availability and distribution of productive capital, to increase the creation and productivity of enterprises and to increase employment and incomes. The strong correlation between economic growth and poverty reduction is well illustrated by the experience of countries like China, Vietnam and India. They experienced sustained economic growth and a significant poverty reduction.

Goal 1: Eradicate extreme poverty and hunger. Energy services are needed to reduce hunger. Ninety-five percent of the food produced needs to be cooked to be ingested. Without affordable energy for cooking, people cannot eat sufficiently to live healthy and productively. As fuel scarcity increases or when cooking fuel prices increase, families with limited cash incomes will decrease the quantities of food cooked. Women will be the first ones to be affected, as they leave their share to their children and husbands.

Goal 3: Promote gender equality and empower women. The probability that a woman will read is strongly related to the presence or absence of electricity in the home. Educated adults, especially women, further ensure educated children. Research has shown that education for girls is the most effective way of tackling poverty.

Goal 4: Reduce child mortality. Women with even a few years of basic education have smaller, healthier families. Each additional year of female education is thought to reduce child mortality by 5–10%.

Goal 6: Combat HIV/AIDS, malaria, and other diseases. Energy services are needed to improve health services: lighting and power is needed to improve safe child delivery and save mothers' lives. Electric lights at night reduce household accidents such as paraffin burns associated with other commonly used fuels. By powering equipment for health clinics, energy enables health clinics to refrigerate vaccines, operate medical equipment, and provide treatment in the evening. By allowing the use of modern tools of mass communication for health education, energy helps fighting of HIV/AIDS and other preventable diseases. Energy services are needed to draw safe water or boil water, and save the debilitation or lives of children subject to diarrhoea.

The energy scenario today is that 1.6 billion people still lack access to modern energy services. 2.6 billion people rely on traditional biomass for cooking. Indoor air pollution (from cooking and heating with biomass over open stoves) is a leading cause of women, infant and child mortality in developing countries ahead of malaria and tuberculosis combined. The poorest, the one billion who live on less than one dollar a day, spend up to one third of their disposable cash income – US$10 a month – on poor quality energy services for cooking and lighting.

The aforementioned findings have major policy implications for developing countries to meet their energy needs and achieve the MDGs, in particular the need to integrate energy in all development programs. Further, to diversify primary energy resource portfolios for instance, Africa is rich in natural resources, in particular in hydro-power resources and other renewable energy sources – wind, solar, geothermal, which today are little developed. Africa also has great potential for regional energy trade, in power and hydrocarbons. With a more diverse energy portfolio, Africa can improve its oil intensity and secure its longer term energy needs. Finally, a strong need to focus on energy efficiency, both for energy service suppliers and for energy consumers, is a necessity especially in times of rising oil prices. Improved energy efficiency is the least-cost opportunity to increase the availability of energy resources, as well as reduce energy expenditures. This applies to electricity generation, transport and distribution, as well as to energy use in large and small industries or at the household level.

3.1. SNAPSHOT OF THE AFRICAN ENERGY SECTOR

In North Africa universal access to electricity has nearly been attained thanks to significant public investments by state-owned power utility operators. The challenge is now to make sure that the financial viability of utilities is secured over the long run. Key challenges include reforming existing energy price subsidies, developing adequate incentives to stimulate investments in energy efficiency and implementing frameworks to mobilize public as well as private investment in additional generation, transmission and distribution infrastructure. Strengthening power interconnections among countries and connecting to the European power grid through the Mediterranean Sea, including exporting renewable energy to Europe, are currently under consideration.

Large hydropower sources dominate the energy mix in most African countries, followed by oil and natural gas – particularly in Nigeria, Ivory Coast, Sudan, Senegal, Kenya, Ghana, and Tanzania. Southern Africa, on the other hand, relies heavily on coal as a source of power. As a result of this energy mix, CO2 emissions from the energy sector in Africa are modest. Land use and deforestation contribute a much larger share of total GHG emissions on account of the heavy reliance on biomass use for cooking and heating. There are three exceptions to this basic premise.

- South Africa, which relies heavily on coal-based energy, contributes to more than 65% of sub-Saharan Africa's total GHG emissions – making it the 14th largest emitter in the world.
- Nigeria – as a result of gas flaring and oil production – is the second largest emitter in sub-Saharan Africa, and
- North Africa has experienced one of the highest global rates of growth in emissions – attributable to oil producers such as Egypt and Algeria and to rapid urban growth.

The potential for hydropower remains very large. Concerns over the environmental and social effects of building large dams have, until recently, slowed investments in hydropower. The remaining hydropower potential in developing countries and, most particularly, in sub-Saharan Africa is very large. Several developing countries are focusing again on this source of electricity, driven by rising demand for electricity. As described in the Water Annex, there is a growing consensus that countries should follow an integrated approach in managing their water resources, planning hydropower development in co-operation with other water-using sectors.

3.2. IMPACTS OF CLIMATE CHANGE ON THE ENERGY SECTOR

As aforementioned, climate change presents additional challenges to Africa, which has already been hit hard by high oil prices. As a result of more erratic rainfall patterns, climate change has severely affected power generation capacity of hydro-power dams in Ethiopia as well as in both Eastern Tanzania, Uganda and Western Ghana. Thus, these countries are being forced to spend their limited resources to add emergency generation capacity, most of which relies on diesel fuel-based systems[4] – thus aggravating greenhouse gas emissions. The impact of climate change on large hydropower projects will mean that future investments in this area will need to be designed with more attention given to hydrological variability.

Consequently, Africa is faced with the dual challenge of increasing energy access while simultaneously making maximum use of clean energy options. Africa has a number of options for clean energy development in view of its enormous untapped renewable energy potential – especially hydro-power, geothermal energy, solar and wind power – as well as more efficient use of biomass and improved energy efficiency. Regional co-operation in energy

[4] In Uganda 300 MW of Diesel generators had to be installed in 2008, as the delays in the Budjagali hydro power station forced the country into this more expensive and polluting energy source.

development – in particular in the context of river basin water resources management (refer to Water Annex) – will be required and ancillary challenges must be overcome. The combination of (i) greater access to carbon finance and (ii) necessary adaptation to climate change in the water sector can provide Africa with the opportunity and incentives to develop cost-effective options to developing clean energy, in particular hydropower. Thus much greater access to energy (and to water) could help propel Africa to a higher, more diversified economic growth path.

However, past experiences in operation of e.g. hydro power stations in Africa have revealed that an integrated approach to climate risk management is absolutely critical. In particular the adequate training of operating staff is vital to insure proper reservoir management and maintenance of the generating equipment. For instance at the Manzenian 2 MW mini-hydro power station in Lesotho, the flood in 2006 severely damaged the power house. Although the flood was well within the design parameters, poor operations and maintenance have resulted in this disaster.[5] Furthermore, in order to fulfil the prerequisite given by the World Commission on Dams (WCD) of multi-purpose utilization (irrigation, hydro power, flood prevention etc.), two vital aspects need to be considered:

1. On one hand regional communication and integration, as e.g. the flood prevention in Mozambique starts already as far upstream as Zambia. Hence, in order to prevent adverse impacts downstream, early regional warning systems need to be run.
2. On the other hand, Integrated Water Resource Management (IWRM) needs to be considered on a national level. This also involves the close collaboration with local meteorological services and, on long term bases, the integration of climatological data. In essence, the goal is to inter-link dams operations with short term predictions in order to insure (a) the continuous and reliable supply of cheap hydro power on one hand, and (b) on the other hand, to prevent floods down stream.[6]

[5] Given That Lesotho is short of 5 MW generating capacity, the involuntary shut down of the plant had significant ramifications for the economy in Lesotho. Furthermore, as the whole region suffered from load shedding, the almost 2 year non operationally of the plant is hard to comprehend. Hence, this case is evidence for the need to strengthen utilities technical capacities.

[6] The aspect of reservoir management is critical, as operators often run the reservoirs at very high levels for continuous hydro power generation. However, in case of torrential rains, the flood prevention purpose is defeated, as flush gates have to be opened in an emergency in order to avoid damages on the dam. This results in downstream flooding, often without any warning for the population.

Furthermore, diversification of generation sources are yet another option of mitigating the risks ahead. For instance, if the climatological data for a region points to increased variability in rainfall patterns, the standard approach to hydro power adaptation would be the increase of reservoir capacity by either modifying the existing dam, or by constructing a second dam upstream. However, Climate Risk Management in the energy sector at this point needs to consider strongly alternative sources such as Concentrated Solar Power, co-generation or even generators to reach the goal of provision of affordable energy. Hence, this presents an opportunity for clean energy development.

As elaborated in Section 2, the Clean Energy Investment Framework, the African Development Bank and the World Bank are promoting a multi-track approach covering:

- Accelerating access to electricity in urban areas and rural electrification
- Extending, upgrading, and interconnecting national power transmission grids
- Integrating national electricity power supplies and helping to develop efficient power trade arrangements
- Promoting off-grid renewable power supply systems; and
- Promoting sustainable household fuels

3.3. RECOMMENDATIONS ON THE WAY FORWARD FOR AFRICA

- Assisting African governments in mobilizing additional financial resources and develop their capacity: Adaptation to Climate Change is an extra financial burden on developing countries. Mechanisms need to insure that the adaptation assistance is distinct from ODA. Furthermore, setting a growth path of a low-carbon economy requires the financing of incremental costs in new technologies, some of which are still in the early stages of commercial application. The combination of large capital cost, higher risk and increased demands on technological capabilities represents an obstacle to early deployment.
- Promoting technology transfer: The massive new investments required in developing countries' energy sectors over the next 30 years provide a window of opportunity for technological transformation, involving technological transfer accompanied by the development of knowledge, capabilities in areas such as maintenance, and the development of national capacities to climb the technology-ladder. This is an area in which international cooperation – including South–South cooperation – has an important role to play in particular in adaptation to climate

change, as diversifying the energy generation sources is by default a means of CRM.

- Continued Assistance and coordination on the negotiations for the post-2012 Kyoto Protocol framework: The Bank already collaborates with the African Ministers Council on Environment (AMCEN) to streamline the African position. This provides an opportunity to establish an architecture for international cooperation that links climate change mitigation to sustainable energy financing.
- Consider biofuels options, keeping in perspective the importance of balancing the food-biofuels competition for arable lands: Faced with mounting energy crises, many African nations are experimenting or have already invested in projects to produce biofuels. These include South Africa, Nigeria, the Democratic Republic of Congo (DRC), Ethiopia; Mozambique and other southern African countries (including Swaziland, Zambia and Zimbabwe). For example, in recent years, the utilization of agricultural and forestry residues for co-generation, as well as biogas from landfills and sewage plants, has shown promise as feed-stock for biofuels production. However, more assessment of feasibilities of domestic production is necessary.
- Further promotion of clean household biomass fuels: Traditional biomass is the predominant fuel source for cooking and heating in SSA, which results in serious indoor air pollution and deforestation (in SSA over 400,000 deaths of mainly women and children per anno are attributed to indoor pollution). To date, three types of solutions have been attempted to address this issue: I. improved stoves; II. fuel substitution with liquid and gas fuel alternatives such as LPG, kerosene, and natural gas; and III. sustainable forestry management. These measures can not only reduce GHG emissions, but also preserve forests. However, the results have been mixed. The higher costs of improved stoves and alternative fuels, as well as efforts to manage the complicated multi-sector institutional arrangements involved, are among the major challenges.
- Promote energy efficiency: Improving energy efficiency is a “win-win” solution to mitigate climate change and address power shortages. Improving energy efficiency and encouraging energy conservation are fundamental pillars of strategies such as the Bank’s CEIF to switch to low-carbon development and poverty reduction paths with minimal capital investment by Africa’s power utilities. Supply-side initiatives, such as reduction of transmission and distribution losses or generation plant refurbishments to increase technical efficiency, could boost electricity supply by 20% or more in a fraction of the time required to build and commission an equivalent power plant. On the demand side,

governments need to encourage and reinforce a culture of energy saving in homes, enterprises, and public institutions. Significant power savings can be realized by encouraging a switch to energy-saving lights. In Uganda, distribution of 600,000 CFLs with less than $1 million investment cut peak demand by 30 MW. ESKOM in South Africa is planning to disseminate 35 million CFLs, which can cut peak demand by 1,750 MW. In essence, reducing the stress on Africa's electricity supply will result in fewer brown- and black-outs and hence contribute also to addressing climate related risks indirectly. The system will absorb an isolated disaster that results in the shut down of a plant or line much easier, when some leeway is budgeted.

DATA HEADACHES

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Abstract. Data provide the foundation of all activities linking weather/ climate and the energy sector, yet accessing data can prove problematic. In this paper an overview of the status of access to weather and climate data is provided to guide those working on the energy side. A background history through which the current status quo has been achieved is summarised, and some useful information sources for the energy sector identified. Further the types of weather and climate information that are available and of potential concern to energy projects are reviewed briefly.

Keywords: Weather; climate; energy; protocols; resolution 40; observations; archives; reanalyses

1. The Symptoms of Data Headaches

Data are fundamental to all science, a statement transparently unnecessary to make. Data are the basis for all development and hypothesis testing of theories, for the validation of systems, for the creation of new capabilities. Without data there would be, within context, no weather or seasonal forecasts or understanding of climate change, nor would there be any capability to use weather and climate information in the energy sector. Data provide an unquestionable public good.

Yet there is a second side to data. Data are costly to collect, archive and distribute. Data, and the information contained therein, are a basis for

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authority, decision-making and wealth generation. Data may be a substantive public good, but equally may benefit, perhaps even more so the relative few, when held in confidence.

Meteorologists and climatologists have been grappling progressively over recent decades with the issues of owning and distributing data, in particular in terms of whether any services provided, including those funded originally by the public purse, are a public good or, perhaps, a commercial opportunity, in part perhaps to recompense the public purse. Such issues become complex as commercial demands, with inherent implications for competitive advantages, increase in sectors such as energy provision. In this paper the background to these affairs of data is summarised and the current situation reviewed from the perspective of weather and climate data; there are, of course, additional considerations regarding data from the energy sector side, but these will not be considered here.

2. A Migraine-Free Beginning

The current UN System body with the longest traceable history is the World Meteorological Organization (WMO[1]), based in Geneva. Its authority is, and always has been, built on that of governmental National Meteorological and Hydrological Services (NMHSs), and their parent ministries, around the World. Although WMO itself has a history since only 1950 its predecessor organization, the International Meteorological Organization, was founded in Vienna in 1873 following discussions that stretched back a further 2 decades.

Data was the issue that brought together Heads of the then newborn Weather Services of Europe and North America. These Heads had been charged with providing weather forecasts out to 24 h in the interests of protecting shipping, both naval and commercial. Shipping losses following some major storms in the Atlantic Ocean had precipitated this demand, although the perception of credibility that accompanied the demand was recorded by the Hansard report on the passing of the UK bill in terms of the mirth amongst MPs that such a feat was conceivable. Many Weather Services originated, and some still remain, in ministries of defence or of transport as a consequence of this original focus.

To an extent the suspended belief of the UK MPs was justified. Meteorology was in a youthful stage at that time, with many of the most important mathematical insights required to produce forecasts not to exist for several decades to come. Indeed certain of the concepts circulating in the mid nineteenth century about the ways of the weather (such as that

[1] http://www.wmo.int

rainfall decreased with height) might bring a smile today. Nevertheless it had been understood by then that atmospheric pressure as measured by a barometer was closely related to the types of weather that could occur on a particular day, that patterns of pressure could be mapped was synchronous information from different locations available, that these pressure patterns moved constantly and the weather moved with them, and therefore that by mapping and predicting the movement of pressure patterns the weather itself might be predicted. So there was hope. All that was needed was to obtain the necessary information from as many locations as possible, to map these data, and then to interpret the results.

Interpretation of the results is not a subject for this paper, but obtaining the data provided a substantive challenge on its own. Handling data within a single country was reasonably straightforward, but particular difficulties arose in transferring data between countries. Such international transfers were essential given that pressure patterns covered areas rather larger than most single countries, introducing an international interdependency that continues until today. Heads of Services at that time were more than willing to exchange data in the interests of what was perceived to be the public good, paid for by the populations through taxation and returned as free information in the form of forecasts.

In different countries what meteorological information as was recorded was often taken with diverse instruments calibrated according to national standards, with readings taken at times specific to each country. The perfidious English and Americans even used different measurement scales to the rest of Europe! Further, the archiving methods used for the data differed between countries. In sum, a system of national ad hoc approaches was patently inadequate to support the needs of the fledgling services. Hence the meetings that led to Vienna 1873.

Important aspects of data exchange covered through international agreements at that time included standardised methods of making observations (including calibration of instruments), quality control of observations, consistent methods of recording, archiving and exchanging observations, and a rapid mechanism for transferring information amongst all countries (rapid then being limited to telegraphic speeds). Those principles remain in place today, with one consequence that modern meteorological and climatological archives are perhaps the most comprehensive, inter-consistent and accessible of any for any discipline. And for many years in the twentieth century the rapid worldwide exchange of data of speedily increasing volume through the Global Telecommunication System, a customised network of communication links even including individual telephone lines, predated the World Wide Web as a beacon for swift information transfer across borders.

The internationally-agreed principle underpinning all of this activity was "the free and unrestricted international exchange of meteorological and related data and products". Such an exchange was necessary to deliver the responsibilities of the Services and to return the public good of the costs borne by the public purse. Essentially that situation remained in place unquestioned for about a century, during which time the community of NMHSs swelled to cover all parts of the globe.

3. The Beginnings of Pain over the Eyes

For numerous decades governments supported the public good nature of Weather Services, as they did those of many other services to the public within the government sector. For Weather Services this was sometimes justified in terms of a national need, including a national need for independence in capability from a strategic defence perspective. But this justification could not last forever. As government responsibilities expanded alongside populations and their demands, and as globalisation progressed inevitably, some trimming of government costs became unavoidable. Together with an equally unavoidable feedback onto the public good.

One early argument that emerged during the mid-1900s appears reasonable. Not only is weather information supplied as a public good to the public and to defence, but it is also supplied to commercial companies using that information for private gain. A counter argument that these companies had in practice contributed taxes and were therefore entitled, as was the public, to receiving information free of charge was unsuccessful. Governments determined that they could cut demands on the public purse if they charged for the increasing volumes of services previously supplied free. Weather Services were one amongst many to which this was applied.

Probably the first country to address the uncomfortable interface between the historic public good of weather services and commercialism was the US. US policy, put in place in the 1950s and essentially unchanged since, has nevertheless given birth to the world's most active commercial weather/climate sector. Put simply the US policy is that the fundamental services to be provided for the public good, including those that serve the highest responsibility of Weather Services, the protection of life and property, will be supplied through and only through the government and paid for in their entirety by taxation. All necessary aspects of data collection and handling, and the production and distribution of forecasts, amongst other aspects, are included under the government umbrella. Given that these have all been pre-paid, all, including data, are then made available at an interface for unrestricted access and use by the public and by companies. It is a logical model that has been followed by no other government. In fact it is a model that has caused discord when information intended only for restricted circulation originating in other countries under different government policies has been made freely available to all through US web sites in the terms of the US Freedom of Information Act.

4. A Throbbing Frowning of the Brow

The speeds at which governments became interested in reducing their fiscal responsibilities, and the approaches used, varied widely, many developing world countries not taking any steps until enforced by decisions made in Europe. Undoubtedly the most precipitous step was taken in New Zealand in 1992 where the original public service was split, one part that supplied forecast services being fully commercialised but with ownership held by the Government, another retained to provide government and privately-contracted research. Most other governments took more measured approaches, the Europeans undoubtedly being in the vanguard.

Under pressure from governments wishing to contain taxation and to recover costs from sales of services the Europeans, through WMO, introduced a slight, but significant, reinterpretation of the phrase "the free and unrestricted international exchange of meteorological and related data and products" that indicated that "free and unrestricted" means 'non-discriminatory and without charge' and "without charge" means 'at no more than the costs of reproduction and delivery of data, with no charge for the data products themselves'. Thus was the door slipped open for charging for data, perhaps only a (often not modest) handling charge but sufficient to enrage users such as universities with projects under which such costs had not been budgeted.

Commercialism, or at least partial commercialism, of NMHSs was the inevitable bedfellow of data handling charges; undoubtedly opportunities existed in the later quarter of the twentieth century for creating commercial arms within NMHSs as part of the cost recovery programme, after all the feasibility of that had been demonstrated clearly in the US, and US and other commercial companies were beginning to compete directly with NMHSs across Europe. NMHSs were ideally placed to secure substantial portions of the emerging markets and to recover costs for governments, and were duly instructed to do so. Without initial proper consideration for the consequences for NMHSs attempting to run public and commercial services in parallel while still competing fairly with external companies, and without consideration for international concerns of data exchange.

Numerous factors combined to encourage NMHSs ultimately to agree through WMO a new protocol for the international exchange of meteorological and climate data, a protocol memorably named as Resolution 40[2] (there is an equivalent Resolution 25[3] that covers hydrological data). Prominent amongst these factors were:

1. The basic fact that some NMHSs became commercial competitors not only to independent commercial concerns but also to NMHSs in other countries that had not developed commercial activities and/or who wished to protect commercial activities in their own countries for themselves.
2. That government policies, including activity funding cutbacks, were enforcing the creation of commercial arms within NMHSs and/or proposals from NMHSs that the commercial side should assist in covering some of the costs for data networks.
3. That in some countries cooperation between the NMHSs and private concerns blurred the distinction between use of the public purse for public and for commercial purposes.
4. That commercial companies on occasion took clients from NMHSs, even when the NMHS was providing an equivalent free service, and undermining that NMHS through gaining free access to data collected by the NMHS.

For developing country NMHSs in particular three further issues stood out:

1. Incursions by commercial organisations into developing countries, incursions that directly threatened activities of the NMHS.
2. The standing of NMHSs in some developing countries is not strong in the eyes of governments faced with substantial issues and costs regarding development; in many of these countries the main services provided are weather forecasts to transport whereas it might be argued that a climate focus is required for national development, a focus in which national skills are often limited. Thus, in what is sometimes known as the ‘CNN Effect’, the authority of NMHSs can be undermined when it is perceived that satisfactory free, or perhaps even competing but better commercial, services are available from elsewhere, perhaps through CNN or perhaps through consultancy.
3. On more than one occasion NMHSs have provided data without charge to international bodies and others but without subsequent acknowledgement of their role; there are further occasions on which data were provide

[2] http://www.wmo.ch/pages/prog/www/ois/Operational_Information/Publications/Congress/Cg_XII/827_en.pdf

[3] http://www.wmo.ch/pages/prog/hwrp/documents/Resolution_25.pdf

without benefit to the NMHS, on occasions being used to create commercial data bases, with the consequence that self-protective policies were introduced.

Within Europe government-enforced steps towards commercialisation lead to the origination of ECOMET[4] in 1995, one responsibility of which is to regulate the commercial activities of European NMHSs within Europe. But strains began to tell in three interacting ways, between the US with its open policy, between European countries with their progressive steps towards paid-for services and information, and between the rest of the world where in the vast majority of cases NMHSs remained public good services. Something had to be done. In 1995 that 'something' was Resolution 40 (and in 1999 Resolution 25).

5. The Core of the Headache?

Resolution 40 is a protocol agreed in 1995 amongst those NMHSs that are members of WMO (effectively all active NMHSs around the globe); it is reconsidered every 4 years at the WMO Congress but at present remains unmodified. Not all organisations involved in collecting and producing meteorological and climatological data lie within the WMO family, but many have followed similar concepts to those embraced in the Resolution in determining their own data policies.

Resolution 40 in effect splits all types of information, including data and forecasts, into three levels, with separate rules for each.

Level 1 — Level 1 data ("minimum" data) may be distributed "on a free and unrestricted basis" being "essential data and products which are necessary for the provision of services in support of the protection of life and property and the well-being of nations, particularly those basic data and products required to describe and forecast weather and climate, and to support WMO Programmes". In other words these are the public good data and information that preserve the intent originated in the nineteenth century. International agreement defines exactly what data and products are covered, although national sovereignty remains the final arbiter. These data are available to all given a handling charge. Undoubtedly data and products within Level 1 are of interest to the energy sector.

[4] The Economic Interest Grouping of the National Meteorological Services of the European Economic Area

Level 2 — Level 2 ("additional" data) is defined to "… also provide the additional data and products required to sustain WMO Programmes at the global, regional and national levels and, as agreed, to assist other Members in the provision of meteorological services in their countries" BUT "Members may be justified in placing conditions on the re-export of such data and products for commercial purposes outside the receiving country or group of countries forming a single economic group, for reasons relating to national legislation or costs of production". Hence these additional data and products, which cover rather more detail both spatially and temporally than those at Level 1, may be distributed freely for data handling charges within the WMO community, and similarly within the university community for research only purposes, but may be charged for at commercial rates to others or blocked altogether (particularly to prevent resale). Level 2 data, with their greater detail, are more valuable to the energy sector than those at Level 1.

Level 3 — Anything else! Such as data from the extensive rain gauge networks that cover some countries. No international protocols cover these potentially invaluable data to the energy sector, each country or organisation determining its own policy.

While organisations other than those in the WMO family may have data policies that resemble those of Resolution 40 they might nonetheless cover other concerns within their policies. Indeed organisations may protect their data for purely commercial or other strategic considerations, or they might embargo information in order to provide academic freedom, such as for the time required by in-house scientists to prepare seminal papers prior to public release of data. Understanding of data policies of individual organisations is the recommended approach to pragmatic reduction of the symptoms of data headaches.

6. Pain Killers

The types of weather and climate data that have and will benefit the energy sector are wide, and include observations from the past, the present and the future, 're-analysed' observations, and of course predictions/projections on all time scales from a few hours to a century or more. Weather forecasts tend to come only from WMO-related organisations, as do many, but not all, longer range (including seasonal and decadal) forecasts. Both NMHSs and universities or other research organisations produce climate change projections. Numerous bodies in addition to NMHSs hold weather and climate observations, although not necessarily to WMO standards. Reanalyses, invaluable in that they are global estimates of weather in the past 50 years or so of greater consistency and accuracy than could have been obtained previously, have been produced mainly by WMO-related organisations.

Fortunately there are archive centres in a number of locations around the globe that are of great help to the user in acting as one-stop sources for a range of data. However original access policies still apply at the centres. Visits to such centres will also assist in clarifying data policies. A few examples follow.

US data policy has already been mentioned and is straightforward. While government organisations provide all public good services, all existing information for other activities are readily available on NOAA web sites, such as http://www.cpc.ncep.noaa.gov/products/forecasts.

A valuable source of information in the UK is maintained by the British Atmospheric Data Centre, a data centre with numerous European contributions: http://www.badc.nerc.ac.uk. Not only is this an excellent source of weather and climate information, it is also an excellent source of data policy statements, referred to on the site as 'Access Rules'. All data from the Centre are free of charge, but not necessarily free of restrictions on use which range from completely free access through to no access apart from to accredited users. By scanning the site a feeling is readily gained that there are rather more data sets with controlled access than there are with unrestricted access; several data sets have time-limited access restrictions to enable owners to produce that key paper. Additionally, the UN manages several data centres that provide information (other than weather and climate) that are of potential interest in the energy sector (such as http://geodata.grid.unep.ch).

Reanalyses might be described as historical global weather maps created using the most up-to-date technology. Several times each day the weather forecasting centres produce 'analyses', which are best estimates of the detailed weather conditions across the globe based on the latest observations – without doubt these are the most accurate worldwide weather maps producible. These analyses provide the starting points for the next forecasts. Naturally analyses have limitations, included amongst which are that the computer model used for making the forecasts is also used (or something equivalent) to produce the analyses and these models improve in time, and that not all observations reach the centres in time to be used for real-time forecasts. With reanalyses the latest approaches to producing analyses are applied to all available past observations to produce a sequence of historical analyses – the best and most consistent sequence of global weather details available other than series at individual high-quality observation sites. So far centres have updated their reanalyses as improved models and more historical data become available. Reanalyses provide invaluable information for the energy sector. Examples may be found at:

- http://www.ecmwf.int/research/era (1958 to 2001)
- http://www.cpc.ncep.noaa.gov/products/wesley/data.html (1948 to present)
- http://gmao.gsfc.nasa.gov/research/merra/ (1979 to present)
- http://jra.kishou.go.jp/ (1979 to 2004)

The relative quality of these reanalyses produces lively debate between centres (it is worth obtaining expert advice before using them) but what can be stated is that in general reanalysis quality declines the more distant the nearest observation point and also backwards in time.

Might data extending further back in time be useful? If so the energy sector will be pleased to learn that work is currently under way on that problem, in part using techniques that assist in estimating what is happening in the upper atmosphere from surface data alone. Naturally the precision of reanalyses for 1909 will not match those for 2009, but the quality should be satisfactory for careful use. A leading project is ACRE,[5] in which it is intended to tap the roughly 50% of surface observations prior to 1939 that have not yet been digitised as well as extensive additional data from the Southern Hemisphere. Resulting from ACRE it is planned to produce in collaboration with other projects global reanalyses from 1891 on, to produce global surface reanalyses back to the 1840s, and then surface analyses for the North Atlantic and Europe only to as early as the mid eighteenth Century.

7. A Headache Cure?

It is probably not appropriate here to make any explicit predictions as to how data policy will be modified into the future, so many are the strands that are causing tensions. Without doubt by far the majority of governments around the world have adopted a commercial model of some form for their meteorological services, with the consequence that control is placed over all data apart from those defined as free access under Resolution 40. Undoubtedly most, possibly all, energy sector requirements for data will be for those on which a charge is levied. If anything the move towards commercial principles is accelerating and it is quite conceivable that more NMHSs, as that for New Zealand, will become commercialised in part or in whole – for example, a commercial sale of the UK Met Office is on the

[5] http://www.met-acre.org/Home

current UK Government's agenda. Only in the US does a public good policy hold firm, and even there the commercial sector is continually attempting to transfer more activities from the public sector into their areas of work.

It is probably naïve to consider what might be being lost with fewer data archived for public good. Certainly larger commercial organisations should be able to adjust according to the new reality, although smaller concerns might be sidelined, while data protocols protect to a large extent the budgets of those engaged in academic research work. Undoubtedly there might be pressure on data managers to prioritise collection and archiving of information saleable today over that that might, or might not, be used tomorrow; and the principle of not archiving information for which an immediate use cannot be seen is not unknown in meteorological circles. Any pressures and priorities might differ between the developed and developing world, as well as influencing data-related interactions between countries.

There are too many imponderables, too may "what ifs" to predict the outlook for data policies. But what is guaranteed is that data headaches are certain to continue into the future.

COMMUNICATING INFORMATION FOR ENERGY AND DEVELOPMENT

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Abstract. Climate change presents current and long-term challenges to development. Agriculture employs up to 80% of the people in the developing world. Access to energy services is critical to economic development, but managing emissions is critical for limiting climate change impacts. Weather and climate are critical inputs for agriculture and renewable energy generation. The climate is changing, creating challenges in sectors vital to growth in developing countries. Climate variability and change already deter economic growth, and fundamental structural changes are required to achieve low-carbon economies that are resilient to a new climate regime. To ensure that development efforts are sustainable, climate change must be accounted for in key sectors. Hydrologic and meteorological information are scarce or hard to access in many developing countries, depriving planners of information they need to design resilient programs and projects. New web platforms can provide access to data and tools from organizations with global resources such as NASA and NOAA, as well as to information developed at local research centres tailored to local needs. Using the web to provide access to data and tools in developing countries can help overcome the information deficit that contributes to slow development.

Keywords: Energy; climate; climate change information development; adaptation; SERVIR; Climate Mapper

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1. Introduction

Climate change presents current and long-term challenges to development. The African Development Bank (2008) estimates that agriculture accounts for about one-third of African GDP and employs 70–80% of the people; the figures are similar for Asia and Latin America. Most future growth in greenhouse gas (GHG) emissions is expected to come from developing country energy and transportation sectors, yet energy and transportation are critical for economic development. Climate variability and change already deter economic growth, and fundamental structural changes are required to achieve low-carbon economies that are resilient to a new climate regime. Much of development assistance addresses the foundations of economic growth – agriculture, fisheries, resource management, energy and transportation – sectors that sensitive to climate change or contribute to GHG emissions. If ignored, climate change could undermine the success of those programs; if incorporated into program planning, there is an opportunity to use all the resources of the donor agencies to address climate change challenges in developing countries.

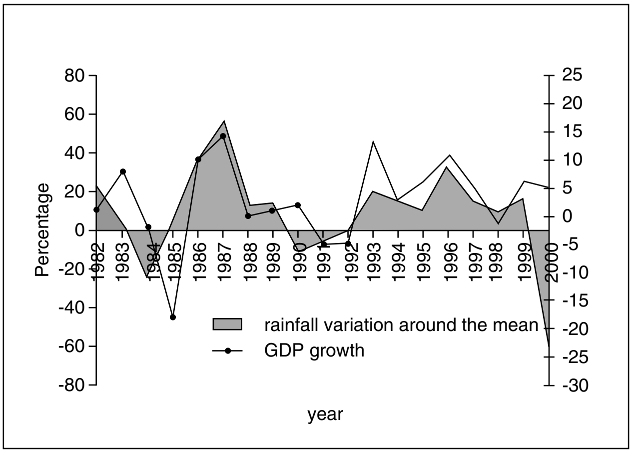
Developing countries are particularly susceptible to the impacts of climate change because their economies tend to be concentrated in a few sectors that are vulnerable to weather and climate disturbances. Vulnerability to the impacts of climate change is a function of exposure to climate variables, sensitivity to those variables, and the adaptive capacity of the affected community. Often, the poor are dependent on economic activities that are sensitive to the climate. For example, agriculture and forestry activities depend on local weather and climate conditions; a change in those conditions could directly impact productivity levels and diminish livelihoods. Adapting to climate change involves reducing exposure and sensitivity and increasing adaptive capacity. Depending upon the development challenge being addressed, this may be done by modifying a traditional approach or by taking a new approach.

Climate variability can cause abrupt disruptions, such as floods, droughts, or tropical storms. These disruptions can take a major toll on a country's economy if a significant part of economic activity is sensitive to the weather and climate. Ethiopia provides a good example of the influence of climate variability on a developing country's economy. Figure 1 shows that GDP in Ethiopia rises or falls about a year behind changes in average rainfall. The World Bank (2006b) estimates that agriculture, forestry, and fisheries account for half of GDP and 80% of jobs; the Ethiopian economy is sensitive to climate variability, particularly variations in rainfall.

The US government budgets over $20 billion annually for aid to developing countries. About a quarter of that is dedicated to sub-Saharan Africa. The

US has not analyzed the portion of its aid portfolio that goes to climate sensitive activities, but one can assume that, given the key regions and sectors that receive US development assistance, significant investments could be vulnerable to disruption from weather and climate events. Estimates from other aid organizations may be instructive: the World Bank (2006a; Van Aalst and World Bank, 2006) estimates that about a quarter of its portfolio is subject to a significant degree of risk from current and future climatic events. As of 2005, only about 2% of Bank project design documents discussed these risks. The African Development Bank (2008) reports that the Organization for Economic Cooperation and Development and the World Bank Group estimate that 40% of the African Development Bank's portfolio may be at risk of direct climate impacts or underperformance of projects.

Most US foreign assistance is implemented by the US Agency for International Development (USAID). USAID has long invested in clean energy and energy efficiency. Reliable access to energy services is critical to development. As recognition of the vulnerability of Developing country economies and livelihoods – as well as US assistance investments – has grown, USAID has increased its emphasis on climate change adaptation. The challenge USAID and all other development agencies face is to provide increased access to energy while limiting the growth of emissions and building resilience into all program areas.



Source: The World Bank. "Managing Water Resources to Maximize Sustainable Growth: A Country Water Resources Assistance Strategy for Ethiopia. "2005.

Figure 1. GDP and rainfall in Ethiopia.

USAID's operations are distributed across roughly 100 developing countries, and work is implemented by USAID staff and local and international contractor support. This distributed management and implementation model helps greatly in tailoring assistance to local and regional needs. However, when a global issue such as climate change arises, new methods are needed to reach a global audience quickly. This paper will discuss some of the methods and tools USAID has created to help a network of development experts across the world to understand how climate change may affect the issues they are working on, help them analyze those impacts and identify alternative approaches to meet their development goals. It will also look at how some of the tools can be applied to the energy sector's need for information on weather and climate, assisting in demand management and hazard resilience.

2. Climate Change, Development, and Adaptation

Climate change is likely to affect developing countries more severely than middle and high income countries. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) paints a bleak picture for the poor in developing countries. Among the anticipated impacts in developing countries are:

- Increased hunger
- Spread of disease
- Changes in water availability
- Infrastructure damage
- Change in forest cover
- Amplified hazards
- Loss of biodiversity
- Sea level rise

What is notable about that list is that, with the exception of sea level rise, these issues have posed problems for decades. Many poor countries are poorly adapted to the current climate, as shown for instance by the volatility of Ethiopian economic growth; climate change will exacerbate or accelerate stresses that already limit growth and compromise health and livelihoods. Helping developing countries build resilience to current climate and climate variability is a good first step toward building resilience to future climate change. In many cases, adapting to the impacts of climate change is a matter of doing the things that already need to be done, but doing them in such a way that they are resilient to a different set of stresses. The foreign assistance community has about a half century of experience in improving food security, health, access to safe water and sanitation, hazard mitigation and resource management. The challenge for the assistance community is to recognize that climate change is not an exotic, far-off, “other” issue, but rather a stress on the areas in which they already struggle to achieve results. Information on climate variability and change should be integrated into development project design in order to ensure that projects perform as well as possible under a range of conditions.

Vulnerability to the impacts of climate change is a function of the exposure and sensitivity of some valued resource to climate stresses, as well as the adaptive capacity of the resource. Exposure and sensitivity help measure whether and how climatic events may affect a resource. Farming is both exposed and sensitive. Raising flowers in a greenhouse reduces exposure by provide control over temperature and other weather variables. Some crops are more sensitive than others. Choosing a crop with a wide temperature or drought tolerance reduces sensitivity. Adaptive capacity is the ability to reduce the impact of an event or to recover from an event. Examples of adaptive capacity are recognizing the need to plant less sensitive crops or changing zoning rules (and enforcing them) to reduce coastal vulnerability.

Adaptation is a matter of building resilience by reducing exposure (diversifying an economy into less-sensitive sectors; avoiding construction in floodplains, etc.); reducing sensitivity (selecting more robust crops, planning for disasters, increasing margin of safety in infrastructure design, etc.); increasing adaptive capacity (through education, economic diversification, access to information and early warnings).

Poor countries are vulnerable to the impacts of climate change because their economies tend to be concentrated in highly exposed and sensitive sectors such as agriculture and tourism, and because adaptive capacity is low due to low levels of education and poor access to information. USAID views economic development as an effective way of building resilience to climate change. The USAID climate change team is beginning to work with USAID offices around the world to help project designers understand that climate change is already affecting many communities, and that good, effective development efforts can reduce the negative impacts.

The Climate Change Team at USAID has developed Adapting to Climate Variability and Change – A Guidance Manual for Development Planning to assist USAID missions and other development partners to understand, analyze, and respond to the potential impacts of climate change on development challenges, and to develop effective approaches to solving those challenges. The manual lays out a six step process for assessing the potential for climatic changes to affect development efforts and for engaging stakeholders in identifying alternative approaches for more climate resilient development. The manual also provides resources for further technical information. The six steps are:

1. Screen for Vulnerability – Vulnerability Screening is a preliminary assessment of whether climate variability or change could compromise the integrity, effectiveness, or longevity of a project within the planning horizon for the project.
2. Identify adaptations – Work with stakeholders to identify alternative designs or management practices that may enable them to better cope with climate variability and change. The emphasis should be on finding measures that increase resilience to climate change, but still make sense under the current climate.
3. Conduct analysis – Examine the consequences of climate variability and change as well as the effectiveness, costs, and feasibility of adaptations that can reduce vulnerability to climate variability and change.
4. Select course of action – Meet with stakeholders to review results of the analysis. Determine if changes in a current project design are required or if a proposed project should feature new adaptations.
5. Implement adaptations – Prepare an implementation plan.
6. Evaluate adaptations – Evaluate the implementation of adaptations and their effectiveness.

2.1. PROVIDING INFORMATION FOR DEVELOPMENT PLANNING

In conducting initial projects based on the Guidance Manual, USAID found that accessing the weather and climate information needed to carry out the initial screening (step 1) and particularly the more detailed analysis (step 3) was difficult for project designers in developing countries. While many development practitioners are concerned with climate change, few have experience with accessing model outputs to evaluate projections. In many developing countries, even finding historical weather data can be difficult (Figure 2).

To overcome these difficulties, USAID began working on an online tool to facilitate access to weather and climate information. The result, called the Climate Mapper, makes the results of climate change models accessible to a broad user community. With the Climate Mapper, users can assess climate change projections for the 2030s and 2050s against 3D visualizations of landscape. This should enhance vulnerability assessments as development planners consider adaptation strategies for projects.

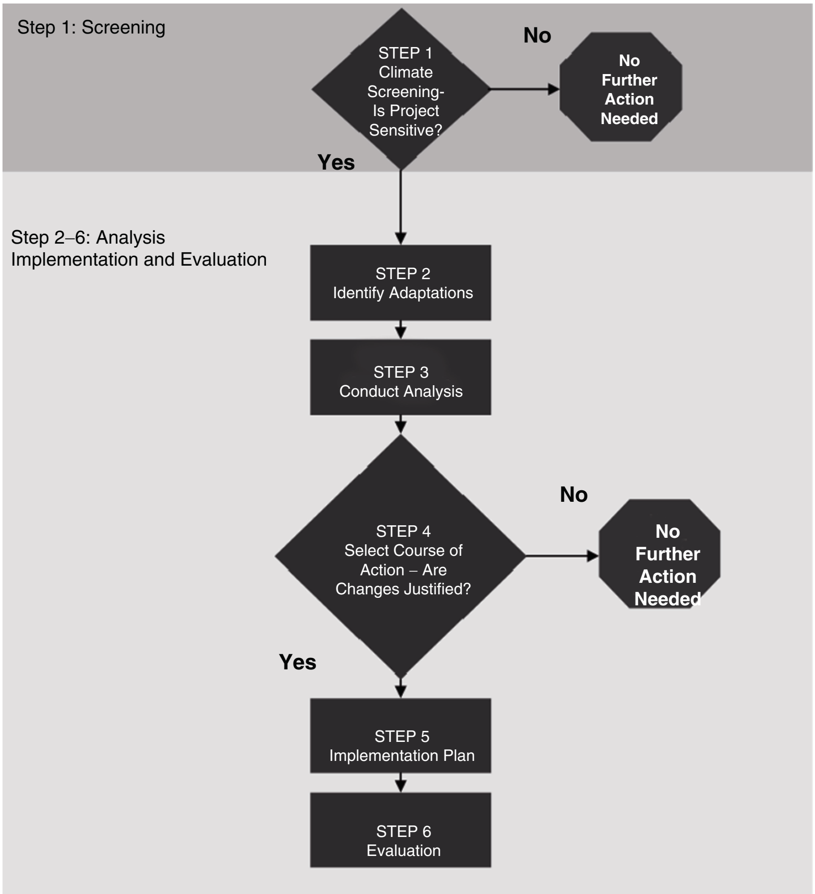


Figure 2. USAID'ssteps to incorporate climate change into project planning.

The Climate Mapper data are currently available for the terrestrial part of Earth for ½ × ½ degree grid cells, or roughly 50 × 50 km near the equator. The Climate Mapper presents historical temperature and precipitation for the base period (1961–1990). These data are taken from the University of East Anglia's Climate Research Unit (CRU) database of monthly climate observations from meteorological stations and interpolated onto a 0.5° grid covering the global land surface (Figure 3).

The modelled data are monthly data averaged over the decades 2031–2040 and 2051–2060. Data are outputs of three of the models used in the IPCC's Fourth Assessment Report: the National Center for Atmospheric Research Community Climate System Model (NCAR CCSM); the European Centre/Hamburg Model (ECHAM); and the Geophysical Fluid Dynamics Laboratory Coupled Model (GFDL-CM21). These models were chosen because they represent the highest, middle, and lowest projections for changes in Africa in the Climate Moisture Index (CMI), a measure of the relative balance of precipitation and temperature. The models were run using the A1B SRES scenario, a scenario of economic activity and carbon emissions that most closely represents the current or business-as-usual economic and carbon emissions trajectory. The data presented as maps and graphs are the difference (delta) of a 10 year average of GCM monthly values for the SRES A1B scenario compared with the 30 year average base period (1961–1990).

In looking for a platform on which to build the Climate Mapper, it was clear that USAID already supported a visualization system called SERVIR. USAID, NASA, the Water Center for the Humid Tropics of Latin America and the Caribbean (CATHALAC), the Central American Commission on Environment and Development (CCAD), the Institute for the Application of Geospatial Technology (IAGT), and a number of other partners have developed SERVIR, a web portal that provides environmental and hydro-meteorological information to a wide variety of stakeholders. SERVIR (www.servir.net), which is Spanish for "to serve", was conceived at a meeting for the Central America Commission for Environment and Development (CCAD) in 2003. The first SERVIR hub serves Central America, and a new hub, opened in Nairobi in 2008, serves Africa (Figure 4).

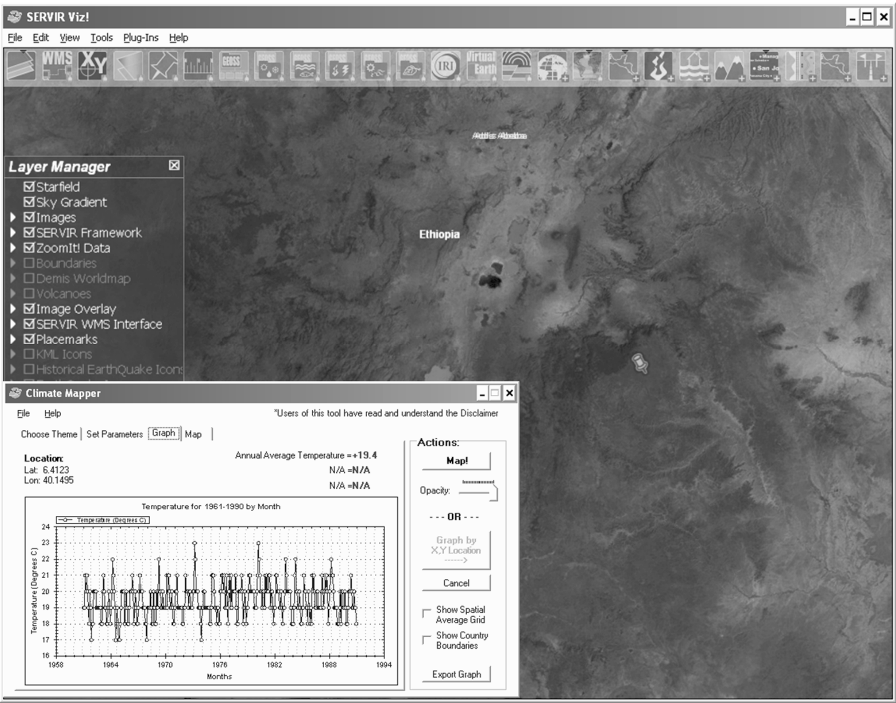


Figure 3. Historical temperature in the Climate Mapper.

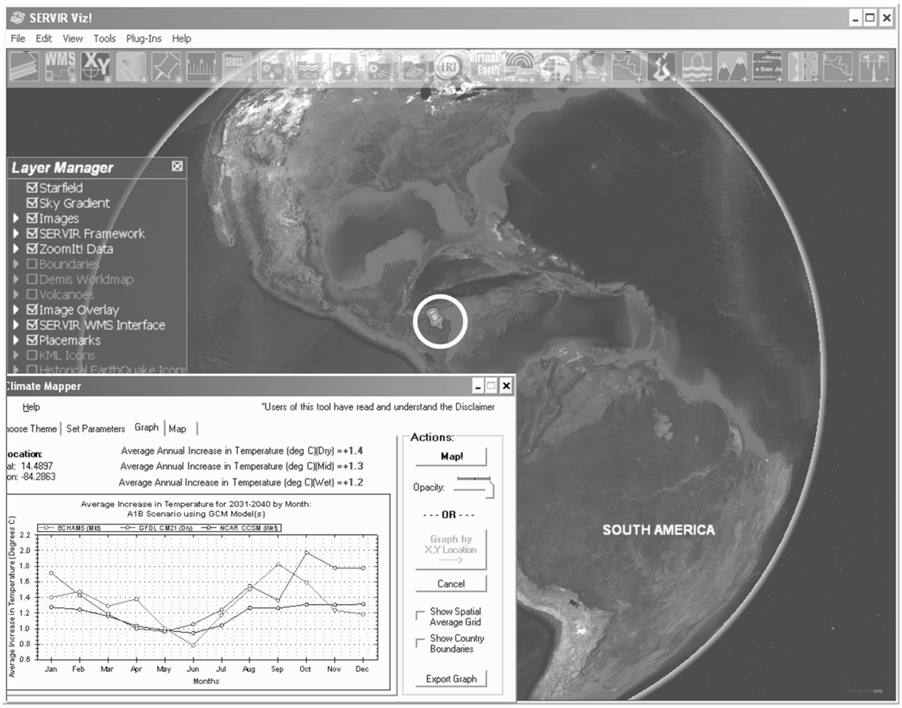


Figure 4. Projections of temperature change in the Climate Mapper.

SERVIR was born out of NASA's work in Central America dating back to the mid-1980s, when a satellite image was taken that showed the political boundary between Mexico and Guatemala; on the Mexican side there was heavy deforestation, while on the Guatemalan side was tropical rainforest. The image prompted the Guatemalan government to work with USAID to create the Maya Biosphere Reserve. In 2004, NASA and its main partner, USAID, established a prototype of the SERVIR system based at the National Space Science and Technology Centre in Huntsville, Alabama. The following year, a regional operational regional system was launched at CATHALAC in Panama. SERVIR national nodes and counterparts were also established in each Central American country.

SERVIR integrates satellite data from a number of agencies with other geospatial data to create a regional visualization and monitoring system for Central America. The system shows how the climate system varies over time, to help provide the region's governments with information useful for management of climate change. SERVIR has a number of applications for both short term disaster management like forest fires, tropical storms and red tide, to longer trends like land use and climate change. Since the SERVIR regional facility in Panama formally opened in 2005, it has experienced a rapid growth in projects.

2.2. SERVIR, DEVELOPMENT PLANNING, AND ENERGY SYSTEMS

Today, the SEVIR systems provide data and information that support disaster preparedness and response and other development and planning concerns. SERVIR is capable of developing information and providing access to information for the energy sector. Among the types of information that might be useful to energy system managers are:

- Projections of change in heating and cooling degree days
- Change in water availability for hydro power
- Change in source/receiving water temperatures
- Change in source water level (flood/cavitation risk)
- Vulnerability of infrastructure to hazards
- Monitoring of CO2 and other gas fluxes
- Wind forecasts
- Thunderstorm forecasts

SERVIR already provides some of this information, thought not with the energy audience in mind. With collaboration, specific information and tools could be tailored to the energy sector.

SERVIR provided particularly valuable services during the 2008 hurricane season. At the end of 2007, the NASA staff in Alabama began developing maps showing accumulated rainfall, storm track, and other information useful to disaster planning. In 2008, the CATHALAC staff was developing more detailed products, some of which are shown below.

Figure 5. Hurricane Gustav: areas at risk of landslides.

The first image (Figure 5) shows areas at risk of landslides in Haiti during hurricane Gustav. The CATHALAC staff combined accumulated rainfall data, landcover data, and information on hill slopes, population centres, and projections of additional precipitation with the passage of Gustav.

The next figure (Figure 6) compares the Savane Jong area outside Gonaives, Haiti. This is a low-lying area that is dry most of the time, but occasionally floods rather extensively. One of the major roads into and out of Gonaives is visible in the left-hand image, and is submerged in the right hand image. This image shows the type of infrastructure vulnerability mapping that could be presented via SERVIR.

Lightning and thunderstorms are responsible for flooding and fire damage in Central America. The SERVIR team launched Next Storm in 2008. Next Storm analyses every cloud in the sky every 30 min and predicts thunderstorms, lightning and heavy rains that often result in severe flooding. In the region, Next Storm will be especially useful because Doppler Weather Radar generally doesn't exist in the region. The image below shows relatively low risk of storms on September 10, 2008. NASA and CATHALAC are rebuilding the Next Storm system. The user will be able to vary the opacity of the storm overlay and zoom into specific locations.

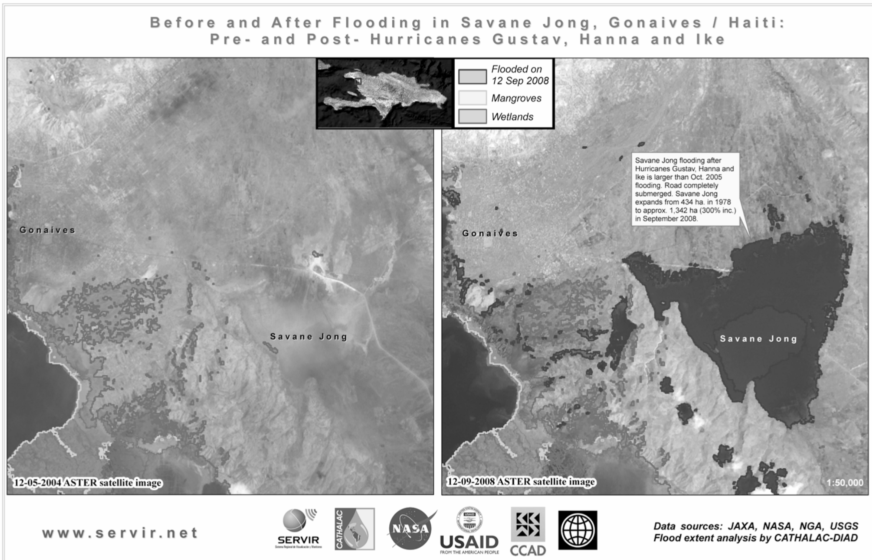


Figure 6. Before and after flooding in Savane Jong, Gonaives, Haiti.

Wind maps and wind predictions would help with both the siting of wind farms and day to day load management. Though SERVIR does not currently offer wind maps, a number of resources are available. US Department of Energy's National Renewable Energy Laboratory (NREL) and Solar and

Wind Energy Resource Assessment (SWERA) have collaborated with other partners to conduct studies of wind resources and solar resources in 24 developing countries. USAID worked with NREL to analyze wind resources in the state of Oaxaca, Mexico. The results are reported in Wind Energy Resource Atlas of Oaxaca. The image below shows a map of wind resources and infrastructure, which could be made available via SERVIR. The arrows point to current high voltage power lines. The challenge for Oaxaca, as in many other places, is that the best wind resources are not near population centres, and are not connected to population centres with transmission lines.

3. Data, Information, and Development in the Future

USAID and NASA see SERVIR as a valuable resource for building capacity in developing countries to create and provide information for development (Figures 7 and 8). Eventually, SERVIR could serve as a portal for a variety of environmental, hydro-meteorological, climate, and socio-economic data, information, and tools to assist with development. The first expansion is aimed at serving Africa. In November 2008, SERVIR expanded to East Africa, with a new hub based in Nairobi, Kenya at the Regional Center for Mapping of Resources for Development (RCMRD). RCMRD has been providing training and services to member governments and individuals in

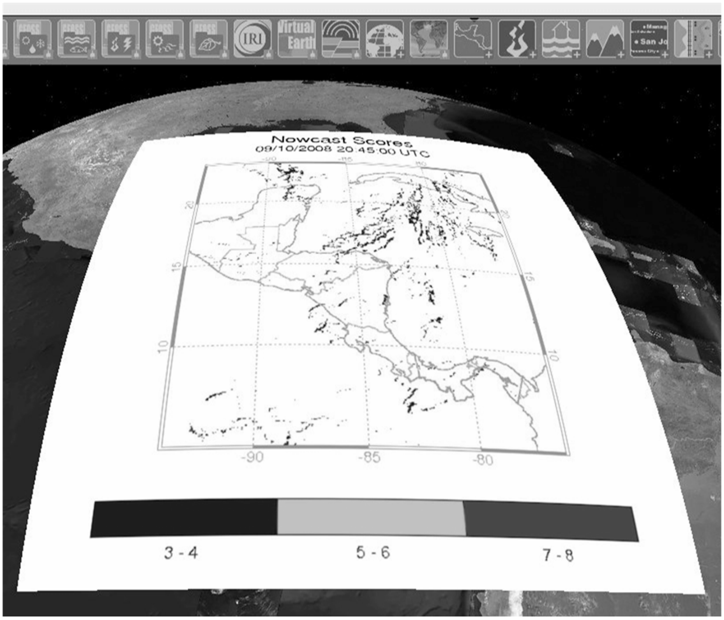


Figure 7. Next storm.

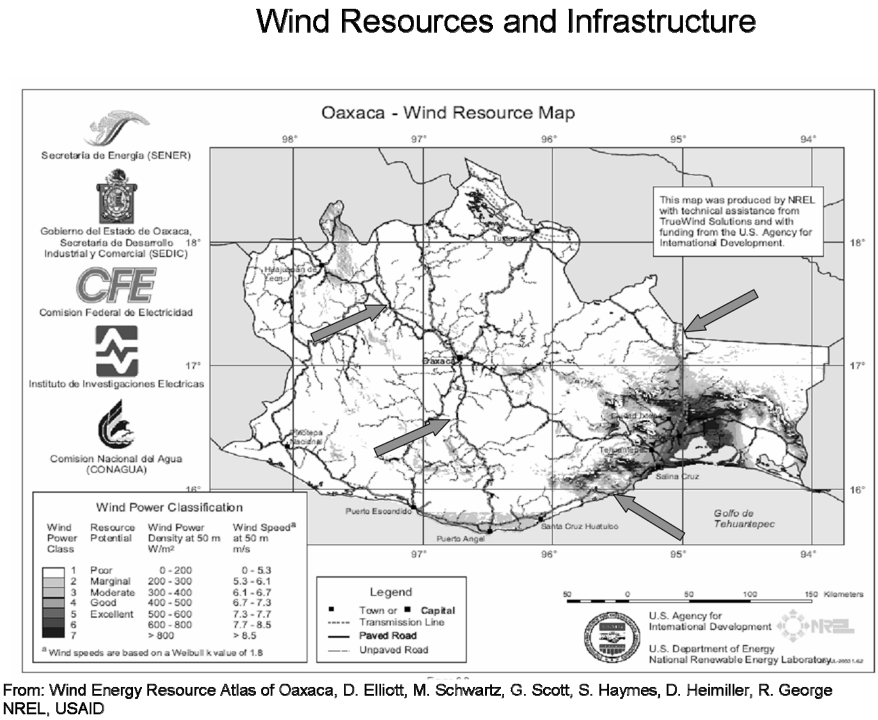


Figure 8. Wind resources and infrastructure.

surveying, remote sensing, map making and photogrammetry since 1975. It is a natural host for the types of services and training that SERVIR provides. The East African SERVIR hub will provide access to a wealth of data that have already been developed for Africa, as well as training professionals in the region to develop and use such information.

USAID, NASA and other development agencies are also collaborating on a new portal to aggregate a variety of data and tools in a single portal called the Climate 1 Stop (www.climate1stop.org) (Figure 9). The Climate 1 Stop will provide the types of data currently available via SERVIR and the Climate Mapper, plus additional data as need is identified; tools to make sense of and apply the data; and lessons and case studies for both adaptation and mitigation projects worldwide. There is certainly scope to include energy management needs in this portal.

To date, SERVIR's resources have been aimed at environmental management and development. If the portal proves useful, it could serve information tailored to energy system managers. To make the information most useful, an ongoing conversation needs to take place between data developers and consumers of that information. The NATO workshop in Italy was an excellent first step. More such exchanges should take place in the future.

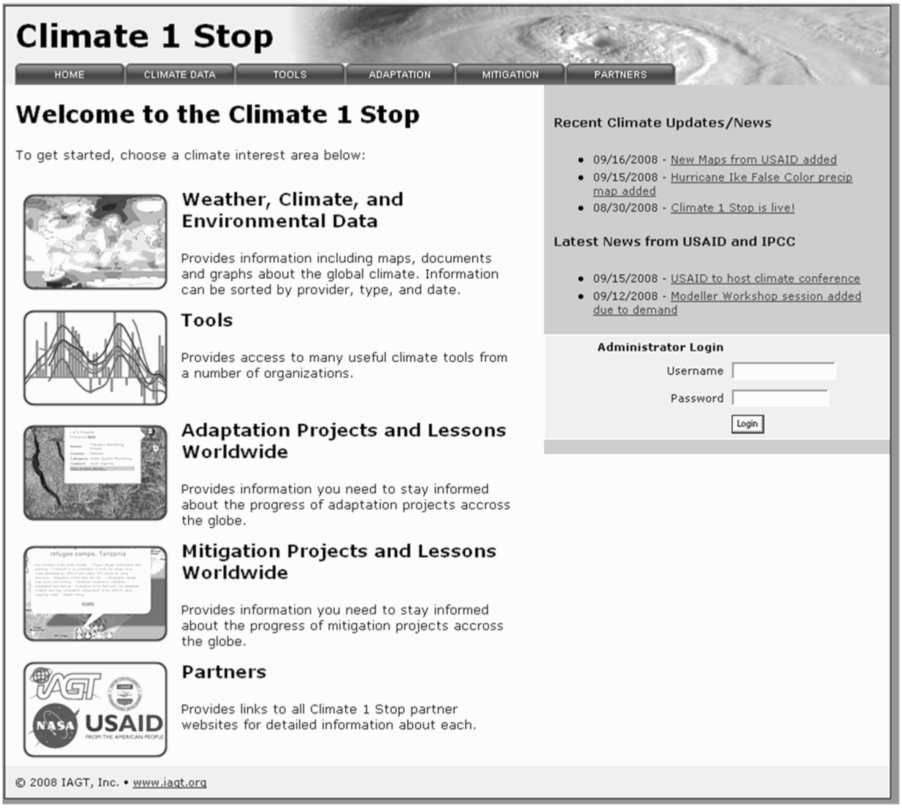


Figure 9. Climate 1 Stop homepage.

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REQUIREMENTS OF OIL AND GAS OPERATIONS FOR CLIMATE DATA, INFORMATION, PRODUCTS AND SERVICES IN THE HIGH LATITUDES

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Abstract. Climate conditions affect oil and gas operations to a great extent. Climate impact could be large taking into account climate variability and change. The article demonstrates mechanisms of climate impacts on various sectors of oil and gas operations and probable consequences of climate change for oil and gas industry.

Keywords: Tailored climate products; dangerous weather events; oil and gas operations; high latitudes; climate change

1. Introduction

Oil and gas operations include the following basic stages: exploration and exploitation of the oil and gas fields, designing and operation of oil and gas pipe-lines, residential and auxiliary constructions and transport system servicing. Each stage requires a set of tailored climate products. Climate variability and change require a more careful approach to climate information especially at high latitudes as they may be prone to disproportionate warming and permafrost melting.

2. Oil Industry

Strong winds represent an impediment to oil industry operations. Strong wind (>15 m/s) swings oil derricks and hinders cementing of boring well

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and rig setting-up. When the wind speed reaches values higher than 22 m/s, all outdoor activities must be stopped.

Low air temperature does not influence directly the oil production engineering. Nevertheless heavy frost coupled with snowstorm (as well as glazed frost and fog) clatter traffic and cause alarm conditions. Air temperature $<-25°C$ increases viscosity of oil and impedes pumping-over.

Thunderstorms are very dangerous for pipeline operation. Therefore thunderstorm warning must be received not later than 2 h in advance, in order to down tools.

Also, different parts of the pipeline can have different temperatures. Soil and pipeline temperature fluctuations cause crimps and gas pockets, which may cause accidents. Hence it is necessary to monitor temperature regime along and across pipelines.

3. Gas Industry

Ambient temperature changes impact gas supply to a considerable degree. If a long stretch of frost weather is forthcoming, gas should be accumulated beforehand in reservoirs because decrease of ambient temperature in winter and strong wind cause significant increase in gas demand: 1°C temperature drop results approximately in 1% increase in gas residential use. In order to redistribute gas stream in time, it is necessary to be able to predict cold snaps not later than 2 days before as gas is distributed at a speed of 50 km/h.

Ambient temperature affects booster station functioning. Turbine capacity is designed to 15°C. With air temperature above this value, gas pressure in the pipeline is insufficient, and turbine capacity is too high: and increased gas volume could not run through the pipeline. In order to use an optimal pressure in the booster station, daily forecast of air and soil temperature as well as atmospheric pressure would be useful.

Dangerous weather events (strong wind, snowstorm, fog, black frost, glaze) impact not so much gas output and pipeline operation as associated structures and utility modules (power lines, radio-relay links, corrective establishment, motor transport).

3.1. MECHANISMS OF CLIMATE IMPACTS ON OIL AND GAS OPERATIONS

Mechanisms of climate impacts on various sectors of oil and gas operations and related energy system are presented in Tables 1 and 2.

TABLE 1. Oil and Gas production and transportation.

Sectors, processes, units	**Tailored climate products**
Oil and Gas extraction (oil derricks construction and operation: drilling rigs, drilling platforms on continental shelf, underground depositories)	– Wind load with return period of 50 years – Return period of wind speed >15 m/s, >22 m/s – Return period of air temperature <–25°C, <–30°C, <–33°C, <–40°C, >+25°C – Absolute minimal air temperature – Thunderstorm, whirlwind, hurricane probability; – Maximal depth of permafrost thawing – Ice conditions
Oil- and Gas pipe lines projection and operation (main, underground, overland, elevated, submarine pipelines)	– Mean maximal soil temperature at the pipe line level – Soil temperature change along the pipe line – Return period of soil temperature <–30°C, <–40°C – Maximal depth of soil freezing and thawing; – Maximal depth of snow cover
Residential and auxiliary constructions (distributing and compressor plants, residential constructions, communication service)	– Return period of air temperature <–30°C, <–40°C – Abrupt drop of air temperature – Thunderstorm, whirlwind, hurricane probability – Wind speed by maximal ice load – Atmospheric pressure fluctuation – Air temperature of the coldest 5 days and 1 day with 0.92 and 0.98 fractiles – Maximal depth of soil freezing and thawing
Equipment and goods traffic (air, sea, motor, railway transport)	– Road slipperiness – Visibility distance – Extreme wind speed – Heavy sea – Ice conditions
Conservancy technology (earth restoration and artificial revegetation)	– Extreme air and soil temperature – Maximal wind speed and precipitation sums

TABLE 2. Energy systems.

System components	**Tailored climate products**
Thermal generating station	– Mean daily air temperature – Air temperature of the coldest 5 days – Air temperature of the hottest 10 days – Air temperature of the coldest period – Dangerous weather event probability

System components	Tailored climate products
Nuclear power station	– Air temperature, wind and ice loads with return period of 10,000 years – Whirlwind and gust probability
High-voltage lines	– Maximal wind and ice loads – Number of days with dangerous weather events (thunderstorm, hail, heavy shower and snowfall)
Heating system	– Mean and minimal soil temperature – Mean and maximal depth of soil freezing and thawing
Energy consumption	– Mean and minimal air temperature – Daylight illumination – Mean effective temperature of heat losses

Threshold values of some tailored climate products and their potential consequences are presented in the Table 3.

TABLE 3. Threshold values of tailored climate products.

Threshold values	Construction vulnerability
Depth of permafrost thawing >30 cm	– Oil wells destruction and ruptures of pipelines are probable – Residential and auxiliary constructions may be damaged – Railways and highways become deformed
Air temperature <–25°C	– Oil thickening increases – Oil transfer is complicated
Air temperature <–30°C	– Pipelines warming and frost – resisting materials use are necessary – Production cycle rises in prices
Air temperature <–40°C	– Alloyed steel use is necessary – Jamming and flows in pipe-lines take place
Wind speed >22 m/s	– Oil derrick assembling, oil wells and surface construction repair are stopped – Pipe-line welding is complicated
Ice-wind load (ice layer >20 mm with wind speed >10 m/s; water-snow layer >35 mm with wind speed >6 m/s)	– High-voltage lines may be destroyed
Thunderstorms	– Explosions of drilling rigs and high-voltage lines destructions may take place – Risk of construction ignition increases

4. Climate Change Impact on the Oil and Gas Complex

Climate variability and change can affect exploration, extraction and distribution of oil and gas in a myriad of ways and require more careful approach to climate data and products preparation. These impacts could be large especially in the high latitudes that may be prone to disproportional warming and then permafrost melting. For example, in the northern part of Western Siberia, where large-scale oil and gas fields are located, air temperatures have risen by 2°C over the last few decades. Some models predict this warming trend will continue.

On the coast of the Arctic ocean, melting permafrost can cause subsidence of the soil, thereby threatening the structural integrity of infrastructure built upon it. A schematic map of the depth of permafrost melting in the northern part of Western Siberia by 2050 year is presented on Figure 1.

Extensive soil testing and unique building techniques are necessary to ensure the long-term viability of the infrastructure in the permafrost region.

There is a significant economic impact on oil and gas exploration from a shorter tundra travel season. Exploration targets have moved farther away from habitable and populated areas, so this calls for more time for ice road building.

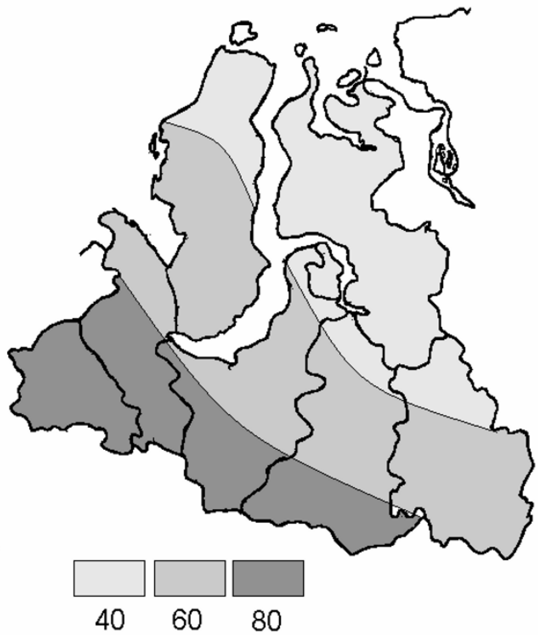

Figure 1. Depth of permafrost melting in the northern part of Western Siberia by 2050 (in centimeter).

Another adverse consequence of climate change in the high latitudes is the increasing number of dangerous weather events. Figures 2 and 3 demonstrate the annual number of dangerous phenomena and their noticeable increase on the Russian territory.

Therefore the correct risk estimation of dangerous phenomena is a matter of great importance for sustainable development of oil and gas complex. Table 4 contains results of risk estimation by empiric method and taking into account fuzzy set theory.

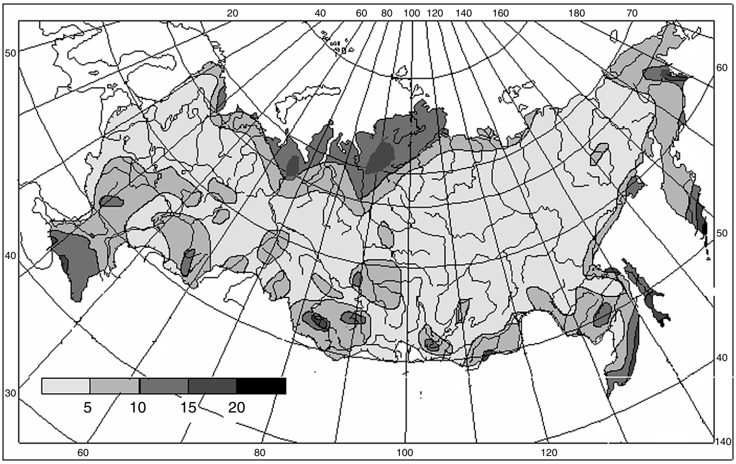

Figure 2. Maximum annual number of days with dangerous weather events.

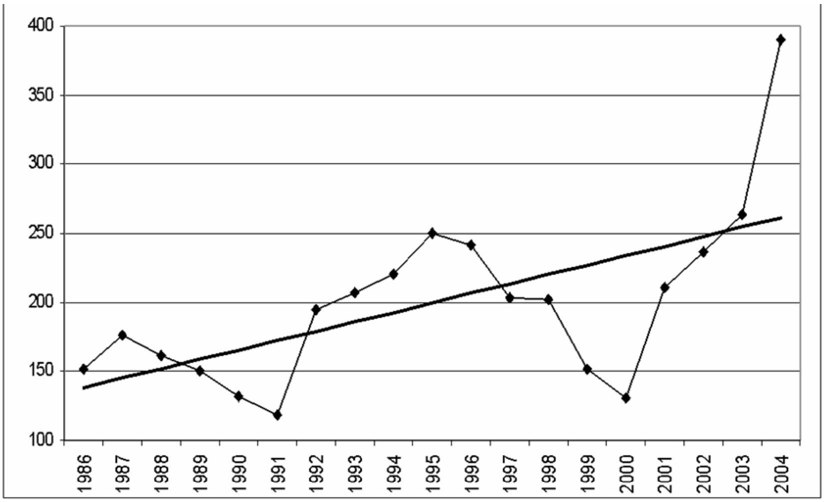

Figure 3. Annual number of dangerous weather events.

TABLE 4. Risk assessment of dangerous weather events and climate anomalies for oil and gas industry.

Dangerous weather event and climate anomaly	**Risk**
Thunderstorm	$3 \cdot 10^{-5}$
Wind speed ≥22 m/s	10^{-5}
Air temperature ≤–30°C	$2 \cdot 10^{-5}$
Air temperature ≤–40°C	10^{-6}
Whirlwind	10^{-7}
Complex:	Fuzzy set method:
Wind speed	High weather and climate related risk (with
≥15 m/s, ≥22 m/s,	confidence 0.48)
≥35 m/s	Medium weather and climate related risk
Air temperature	(with confidence 0.52)
≤250°C, ≤–300°C,	
≤–400°C	

These results are used for new pipelines projecting and existing systems reinforcement. The doubtless favourable consequence of climate change for the exploration in the Arctic is a thinning sea ice. A reduction in sea ice (about 10% over the past few decades) may also mean increased offshore oil exploration.

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PRACTICES, NEEDS AND IMPEDIMENTS IN THE USE OF WEATHER/CLIMATE INFORMATION IN THE ELECTRICITY SECTOR

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Abstract. The energy sector is highly dependent on climate conditions, whatever the particular field of activity, the production means, and the time scale. In developed countries, it is probably one of the most important users of Earth observation products and weather and climate forecasts. Extreme events such as heat waves or cold waves, wind storms or floods can of course have dramatic consequences on the production means or the electrical grid of a country. But "normal" day to day weather variations also have an impact on load level and energy production, transport and distribution management, as well as energy prices. In addition to short-term and medium-term management processes, long-term supply planning and production units dimensioning require climate archive data and future climate scenarios. In order to manage the risks associated with weather and climate conditions on all time scales from a few minutes to a century, reliable weather forecasts and climate information – past, present and future – are therefore crucial to reduce the uncertainty in supply and demand forecasts, as well as market dynamics. Examples based on the French electricity sector are presented, and suggested paths of progress are put forward.

Keywords: Electricity production; demand forecast; weather; climate; power system management

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A. Troccoli (ed.), *Management of Weather and Climate Risk in the Energy Industry*,

1. Some Basics on the Electricity Sector

Energy is a global trillion-dollar sector which includes both non-renewable (oil, gas, coal, nuclear) and renewable (hydropower, solar, wind, geothermal, biomass, …) resources. It covers a wide range of activities, from energy resources exploration, extraction, storage and transport, to electricity production, transport and distribution (GEO, 2005). It is also characterized by an important industrial competitiveness and its influence on political, economic and strategic decisions. Therefore, an optimal and cost effective management of the energy sector is crucial for all nations and the world's economy and development. Electricity is a major component of the world's energy system.

The global production of electricity represents currently about 40% of greenhouse gases emissions, as around two thirds of this production is by fossil fuels. To date, it is estimated that 1.6–2 billion people lack access to electricity, a vital issue for the development of humanity, identified among the Millennium Development Goals of the United Nations (United Nations, 2000). In the context of global warming, it is therefore clear that the energy sector and the production of electricity in particular, have a key role to play in the future development of human societies while ensuring the preservation of the environment.

From 1973 to 2004, the global energy consumption increased by 66% and the electricity generation was multiplied by three (IEA, 2006). According to the International Energy Agency's (IEA, 2008) 2008 Reference Scenario, the world energy demand is expected to expand by 45% between now and 2030, an average increase rate of 1.6% per year, coal being responsible for more than a third of the overall rise. According to this scenario, fossil fuels might account for 80% of the world's primary energy mix in 2030, with oil remaining the dominant fuel; but modern renewable technologies are growing more rapidly, and will overtake gas soon after 2010 to become the second-largest source of electricity after coal.

The electricity sector, like many other economic activities, is obviously sensitive to climatic conditions and water resources, whatever the particular field of activity, the production means, and the time scale, even if this dependence can vary significantly from one country to another. The volatility of climatic variables is indeed the same magnitude as that of other phenomena (the euro-dollar conversion rate, oil prices, ...) and should therefore be considered with the same importance as the financial indices in the process of risk management (Marteau et al., 2004). Moreover, the rising use of renewable energies in the future, necessary to mitigate climate change effects, will make energy production and distribution more and more dependant on climate conditions (IPCC, 2001).

This paper aims at giving an overview of the main relationships between weather, climate and the electricity sector, and at pointing out the current and future needs of weather, water and climate information. It is organized as follows: we first describe, as a representative example, the French electricity system and the main constraints on its management. We then examine the main operational processes which depend on climate conditions and explain how weather and climate information are taken into account. Climate crisis and adaptation to climate change are then addressed. Particularly important gaps and needs are then discussed. These needs are summarized in the last part, in which we emphasize major challenges.

2. Management of a Power Production System

A power production system can be viewed as a complex ensemble of processes, interacting with each other. In France, Electricité De France (EDF) has a very diversified fleet of production, consisting of thermal (nuclear, coal, fuel and gas) power generation plants, together with renewable energy sources, mainly hydro power, but also a rising number of wind, biomass, geothermal, solar production units (see for example, http://energies.edf.com/accueil-fr/edf-and-power-generation-122160.html).

As electricity cannot be stored, it is necessary to ensure a strict balance between production and consumption at any moment on the scale of a country. Many processes affect this balance: maintenance scheduling, network, inventory and stocks management, demand forecasts, forecasts of production from renewables and others (see Figure 1). The various production units and the whole system have different technical and legal constraints to respect; for example, from the technical point of view, a hydro-power unit can be switched on in a few seconds, and can therefore be used to face peak demand that has not been forecast accurately; on the contrary, thermal units (fuel, coal) need a few hours to reach their optimal power and can only be used if the corresponding demand has been forecasted in advance. From the legal and environmental point of view, hydro-power units must for instance be managed in coordination with other users of water resources: if the energy production is the priority in fall and winter, irrigation and tourism become important in spring and summer, and power producers have to ensure minimum river flows to allow for other activities. Of course, environmental rules also apply in order to preserve the biodiversity. Liberalization of the electricity markets has led to an increase in the volatility of both clients and prices, which reinforces the complexity of the whole optimization problem.

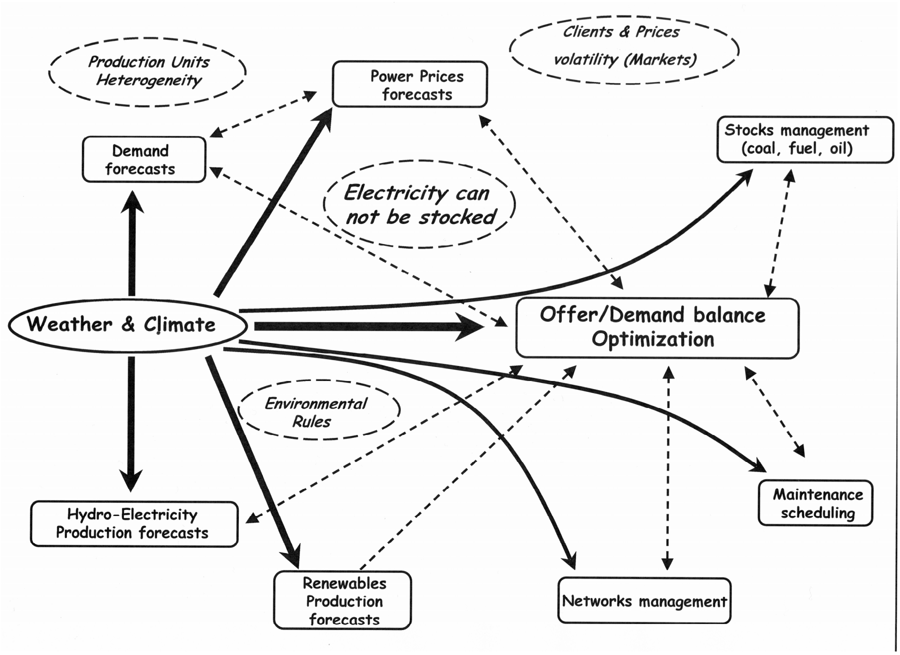

Figure 1. Schematic view of the offer/demand balance process and its links with weather and climate.

Weather and climate conditions have an impact, directly or indirectly, on most of these processes. Depending on the time scale at stake, different sources of weather and climate information are used, as shown in Figure 2. In situ and remote observations are used for monitoring and to produce very-short term forecasts (e.g., for severe weather events). For real time operations, from a few hours to a few days, weather forecasts are taken into account in operational models. For longer time scales forecasts and long-term planning (network development, new units building, siting and dimensioning of new facilities, decisions of investments), the most common information used is observed data, but climate projections are also used to assess uncertainties in the frame of climate change.

3. «Business as Usual» Weather and Climate Information for the Electricity Sector

The way in which weather and climate information is taken into account is now examined in two key processes at stake in the management of an electrical system.

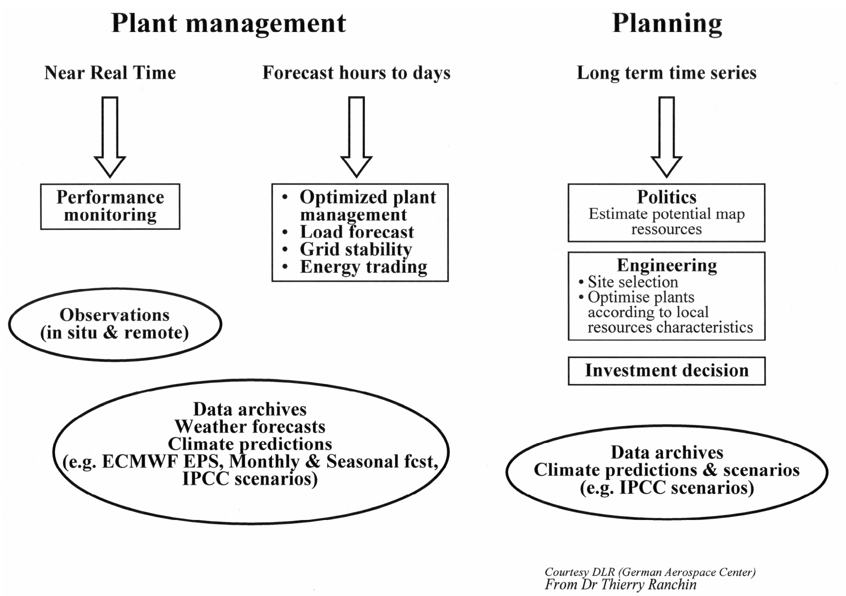

Figure 2. Data and forecasts types used in the electricity sector (Courtesy of DLR – Deutsches Zentrum für Luft- und Raumfahrt e.V., German Aerospace Center).

3.1. DEMAND FORECASTS

Air temperature is the most important parameter for electrical systems in many countries, because it controls an important part of the demand variability. Cloud cover also plays a role, but to a lesser extent.

Figure 3 from RTE, the French grid operator, shows the day-to-day temperature and its deviation from climate normal, as well as consumption in France, in March 2005. There is a clear relationship: when temperature decreases, consumption increases, and vice versa. As a rule of thumb, in winter, an extra anomaly of −1°C on average over France leads to an increased consumption of about 1,700 MW, mainly for heating; this is more than the production capacity of the most powerful nuclear reactors, or the equivalent of around 850 wind turbines (considering an average capacity of 2 MW). Similarly in summer, high temperatures imply a growing demand for cooling and air conditioning needs, though to a lesser extent. It is estimated that an extra anomaly of +1°C implies an over consumption of 400 to 500 MW. Demand forecasts, and hence temperature forecasts are therefore very important first to ensure the availability of production to face demand, on any time scale, but also to manage the system in the most profitable way. In the USA, electricity generators save $166 million annually using 24-h temperature forecasts to improve the mix of generating units that are available to meet electricity demand (Teisberg et al., 2005).

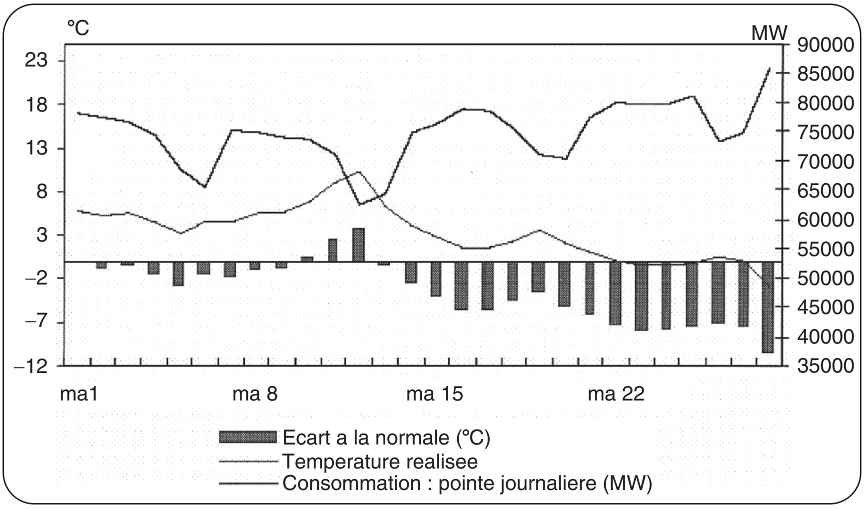

Figure 3. Influence of temperature on electricity demand in France in March 2005. Temperature and temperature anomaly (lower curve and bars, left axis) and power demand (upper curve, right axis).

To predict consumption in France at 1–2 week lead-times, EDF uses deterministic and probabilistic forecasts from Météo-France and ECMWF. These temperature forecasts are incorporated into operational tools, especially demand and electricity prices forecasting models. For longer time scales (>14 days), only climatological data are used, either in the form of climate normals or numerous observed yearly time series, but no dynamic predictions are taken into account. Monthly and seasonal climate forecasts, as that of ECMWF, Météo-France, the UK Met Office and other institutes could of course be useful to improve demand forecasts, and they are currently investigated as part of research projects.

Demand forecasts is probably the field in which the use of climate information and weather forecasts is most developed in the electricity sector. However, there is still much to do, from the providers' side to improve the forecasts themselves and the way they are designed to meet the needs; from the users' side, emphasis must be put on a better understanding of probabilistic information and the implementation of methods to integrate them into operational decision making processes.

3.2. HYDRO-POWER PRODUCTION FORECASTS

Hydro-power is very important in many countries, and particularly in France. The first reason is that it allows electricity to be produced in a few seconds, offering the possibility to face unanticipated peaks in demand at short notice. Secondly, the water stored in big reservoirs can be seen as a stock of electricity, which can be optimized in the year in order to manage the whole system in a safe and profitable way. Last, but not least, hydro-power is the most developed renewable energy source for power production, and should play a key role in the next decades to address the major issue of climate change. But the water resource, which is linked to precipitations (rain and snow) and air temperature, is very variable from 1 year to another. Figure 4 shows the daily variations of the French hydro-power production capacity in 2003 together with the 10%, 50% and 90% percentiles of the 1948–2000 period. In 2003, the rainy winter was followed by a dry and warm spring, which led to an early and quick melting of the snow pack in mountainous areas. The summer was then very hot and dry, so that the production capacity was one of the lowest ever recorded, before important rains and floods allowed the reservoirs to be well filled during fall. In addition to their direct influence on hydro power production, low levels and high temperature of water can cause trouble to thermal production of electricity; for the plants along rivers, the water is also used to cool the systems. If the water level is too low and/or the temperature too high, the cooling capacity can be reduced, with possible consequences on the production, as was the case in summer 2003 on the Rhône river in France.

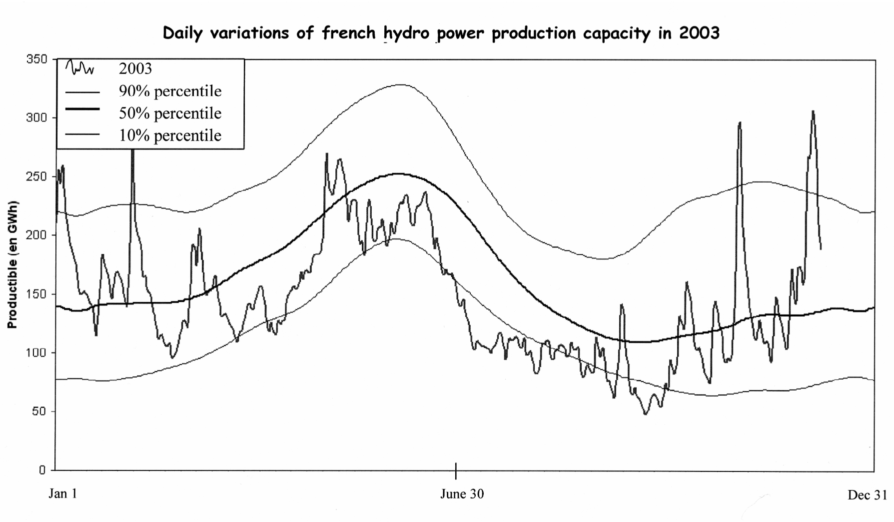

Figure 4. Yearly hydro-power production capacity in France, climatologic 10%, 50% and 90% percentiles and 2003 data.

As hydro-power is used mainly to face peak demand, its management is very important for the whole production system. Precipitations (rain and snow) and temperature forecasts hence need to be as accurate as possible.

Currently, EDF uses both deterministic and probabilistic forecasts of weather parameters, combined with post-processing methods such as analogs which allow to improve the forecast quality. These forecasts together with observations that provide the initial states of the system, feed hydrological models, to forecast hydro-power production capacities, on the local, regional and national scale.

For longer lead times, from weeks to months, current models use initial states provided by observations and past time series of air temperature and rain for the period of time to forecast. This method allows us to estimate how the current stocks of snow and water would evolve if we were to have the same temperature and rain conditions that have been observed in the past. It gives rather good results, notably in spring because future inflows are greatly conditioned by the snow stock to melt during the warming in spring; but this approach is of course limited when inflows do no depend so much on initial conditions, as is the case in autumn, when inflows are determined mainly by precipitations. Moreover, using past time series as predictors for the near future is based on the assumption that future atmospheric conditions were already met in the past. This, of course, is not true, especially in the case of extreme events that were never met before, as was during the 2003 summer heat wave and drought.

For time scales from a few days to a few months, reliable forecasts of precipitations and temperature, if they bring more information than climatology, would therefore be more useful than using past data. Once again, as hydro-power is used notably to face peak demand, the economic value of monthly and seasonal forecasts of temperature and precipitations for these applications would be very important.

4. Extreme Events and Climate Change: How to Revisit the Needs of Information about Weather and Climate?

As seen above, “normal” day-to-day weather variations have impacts on load level, production capacity, transport and distribution. But extreme events such as heat or cold waves, wind storms or floods can of course have severe impacts on production means and electrical grids. There have been many examples of extreme climatic events, causing both casualties and huge economic losses in the energy sector in the last decades. Such examples are listed in the GEOSS 10-Year Implementation Plan Reference Document (GEO, 2005). Reference papers, case studies and evaluations of overall socio-economic impacts of high-weather events are also available on the WMO Madrid 2007 Conference web site (WMO, 2007). In France and a large area of Europe, the Lothar and Martin storms of December 1999 caused 91 casualties and important physical damages to power grids and forests. The overall losses were estimated to be around $19.2 billion US dollars, of which 14.2 insured. The extreme drought and heat wave that hit Europe in the summer of 2003 had enormous adverse social, economic and environmental effects, such as the death of thousands of vulnerable elderly people, the destruction of large areas of forests by fire, and effects on water ecosystems and glaciers. It caused power cuts and transport restrictions and a decreased agricultural production. The losses were estimated to exceed €13 billion (UNEP, 2004). In France, the very low river flows and increased water temperature, had consequences on the cooling of nuclear reactors; EDF had either to reduce the power production, or to ask for an exceptional exemption from the legal requirements about the temperature of water returned to rivers after it was used to cool the production units. Moreover, the national demand increased with respect to normal summer conditions, because of an extra need for air conditioning and refrigerators which led to a 50% decrease in power exports. The overall cost of the heat wave for EDF was estimated to be around €330 million. The electricity sector is, in fact, prone to most extreme weather events: droughts and floods affect the hydro-power production, storms and wires icing affect transport and distribution networks, heat and cold waves can increase the demand dramatically in periods where the production capacities can also be reduced by weather conditions, as was the case in summer 2003.

If the recent extreme weather events can not be attributed with certainty to climate change, it is very likely that future climate changes will impact the electricity sector, as all others (IPCC, 2001). The changes in mean, variability and extreme of weather parameters will of course impact the demand, the production and the networks. But the increasing use of renewable energies, which is desirable to mitigate the effects of climate change, will particularly make energy production and distribution increasingly dependent on climate conditions (IPCC, 2001).

Adaptation to climate change is possible through several kinds of actions, at different time horizons. First, after extreme events, action plans can be set or reviewed, in order to reduce future exposures to risk; modifications in the organization can reduce the sensitivity to risk. For example, after the summer 2003 heat wave in France, the nuclear plants maintenance planning was reviewed so that reactors located on the coasts are not stopped in summer, as they are not sensitive to river flow and temperature; the coordination between the different actors operating facilities on the Rhône river was also enhanced and improved. Crisis staff training enhancement, promotion of information towards the public and stakeholders at all levels and, of course, improvements in optimization tools can also help in better managing future events.

Weather, water and climate information are therefore very important to help the energy sector to react to climate events and to adapt to climate change. High quality observations for the relevant parameters with long enough time series are necessary; they are used to characterize the recent trends and to estimate the near future evolutions. In particular, statistical methods for the evaluation of extremes, that take into account the non-stationarity of the observations (Parey et al., 2007), have been developed to allow relevant estimations of recent trends and future changes. In addition to observations, climate projections with different scenarios are used to estimate the possible changes in demand, and in the dimensioning parameters of future facilities, as production units are designed to run for 40 to 60 years or more. Using most recent climate projections together with relevant statistical methods to estimate the future trends in means and extremes of weather parameters, power companies therefore use more than the current common rules to dimension their future infrastructures and build their industrial and financial strategies. For existing plants, climate change scenarios are also used to modify some characteristics, in order to anticipate water scarcity, improved needs for cooling and network reinforcements for instance.

Many actions can be made and many decisions can be oriented with relevant information about the recent past and future climate. The need for data and projections is clear, but we should emphasize the fact that dialog between climatologists and people from the electricity sector is at least as important; the knowledge of limitations and uncertainties of climate projections is indeed fundamental when translating the climate information into business applications.

5. Some Gaps, Needs and Requirements

Despite the fact the energy sector is already one of the most important users of weather, climate and water information, there are still many ways to progress, in order to better meet the needs, and facilitate the communication between providers and users of climate data (Dubus, 2007).

One important field of research concerns the use of probabilistic forecasts, which are still not yet fully exploited in application models. In France for example, improved short-term probabilistic forecasts of river flows are required to better manage the security of the hydraulic system. The main limitation in the use of ensemble forecasts comes from the difficulties end users have to deal with probabilistic information. A special emphasis should therefore be put on this point in the next years, in particular to encourage communication and discussions between National Meteorological and Hydrological Services (NMHSs) and the users. Many forecasting products already exist that may answer, at least partially, end-users questions, but they are either not known by the users, or not perfectly designed to the concerned applications. Some weather parameters or events, which may not be very well forecasted by models, however are very important for the energy sector. Therefore, even if the forecasting scores are low – but better than that of the sector's current practices – their value may be important. Such opportunities in using weather forecasts can only be identified if close relationships are developed between providers and users of climate information.

A second important need for the electricity sector is to have coherent approaches for the different lead times. For example, medium term demand forecasts currently use ensemble forecasts of temperature from 1 to 14 days, but, on longer time scales, historical data with a different number of scenarios are the common rule. The question here is how to couple short and medium term forecasts with historical time series on longer time scales? Improving the consistency between these two time horizons is a big challenge, with both technical and financial consequences. Seamless predictions as those proposed by ECMWF (Vitart et al., 2008) will certainly offer solutions to that problem, especially if communication between NMHSs and users is developed.

Standard weather and climate observations are not necessarily adequate for many applications, especially the management of renewable energy production. For example, solar and wind power production models require respectively surface irradiance and wind speed and directions at the turbine's hub height (around 100 m); this data is not currently available. New satellite data and tailored observational products, defined between providers and users, would therefore be of great value for the development of renewable energies. Other applications, as detailed in the recommendations by Working Group 2 (Chapter 23, this book) during the workshop will certainly provide the electricity sector with valuable information in the near future. Programs such as those developed in the frame of GEOSS or GEMS will be very useful in helping monitoring and forecasting systems to trace atmospheric constituents important for climate and air quality; in particular, the tools developed in these projects will be useful for the electricity sector to reach its objectives in the context of the European policy for sustainable development.

To address the major challenge of greenhouse gases emissions reduction in the next decades, renewable energies should be developed on a large scale. If climate change projections at the end of the twenty-first century are important to estimate the future evolutions of their potential production, the main concern probably remains on intermediate time-scales (2020–2030). The operating period of such investments (wind farms, photovoltaic production units) are indeed of the order of 15–30 years and estimations of the relevant weather parameters on the same time scales are thus very important in the business plans. Current projects on decadal predictions, and the requirements for IPCC AR5 scenarios are in phase with these needs, and a careful coordination between the climate community and renewable energies operators will be beneficial for the development of these energy types.

6. Summary and Conclusions

The electricity sector is sensitive to climatic conditions. Many processes are involved in the operational management of its energy production and its policies for development and long term investments.

For the operational management, temperature and cloudiness strongly influence consumption. Climatic parameters also have an impact on production, particularly for renewable energy sources: hydro-electric power (rain, snow, temperature), solar power (irradiance and cloud cover) and wind power (wind). But classical means of production (oil, coal, gas, nuclear) are also impacted by the need for cooling the production units (water temperature and river flows). In the long term, electrical transport and distribution networks must be designed to withstand extreme weather events (wind, accretions on the lines, temperature, water level in rivers, etc.) Therefore, the dependence of the electricity sector on climate must be addressed on all time scales, from long-term planning to real time operations.

By 2030, investments needed to meet the World projected demand in electricity are estimated to be around $14 trillion, half of which for developing countries (IEA, 2008). Reducing risks linked with those investments and then to the management of energy systems is therefore crucial. Weather, climate and water information have a major role to play in this context. Vital issues are an environmentally responsible and equitable energy management, a better matching of energy supply and demand, a reduction of risks to energy infrastructure, a more accurate inventory of greenhouse gases and pollutants and a better understanding of renewable energy potential. This can be done by acting in three directions (Rogers, 2007; Lazo, 2007); the first is to improve data and forecasts; the second is to improve the communication and the third to improve the decision-making processes. If the information currently available is insufficient either in terms of quality or availability to be applied in operational processes, improving the weather, water and climate information will add value for the users. But currently available information may be underutilized, and then progress is needed in the provider-user communication and in the integration of the information into the decision-making processes. Many challenges are still to be faced to bridge the gaps between users and providers of weather, water and climate information in the electricity sector, as in other sectors (Dubus, 2007). Among those challenges is the importance to recognise that the investments in research, necessary to improve scientific and technical capabilities, should be seen as an investment rather than an expenditure. While this statement may seem evident for the electricity sector, there is much more to do to raise awareness of the general public and decision-makers.

In addition to its relationships with several operational centres and research institutes, EDF relies on a strong partnership with Météo-France, the French National Weather Service. This partnership is based both on common research projects with the Centre National de Recherche Météorologique, Météo-France's research centre, and on commercial contracts for the provision of data and forecasts. Coordination teams have been formally set in place, and meetings with feedback and event review mechanisms regularly take place. This organization has proven very efficient both to increase the quality of communication and mutual understanding, and without impinging on confidentiality concerns. This example could be followed by other companies. In developing countries in particular, upstream communication between providers and users of weather, water and climate information should be specially emphasized, in order to rationalize the investments in observing and forecasting services, as energy and electricity will be a major component in their development.

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LARGE-SCALE VARIABILITY OF WEATHER DEPENDENT RENEWABLE ENERGY SOURCES

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Abstract. The fluctuation of photovoltaic and wind power generation is directly related to the weather variability. In this study, 8 years of data from a weather model were used to simulate the spatial and temporal characteristics of photovoltaic and wind power generation in Europe. Imbalances in the power system between photovoltaic (PV) plus wind power generation and consumption are investigated in a full (energy) supply scenario. Two different approaches in spatial aggregation are analyzed (i) unlimited cross-border power flows to simulate *one* European control zone and (ii) no cross-border power flows, i.e. deviations between generation and consumption are balanced on a regional level. On all investigated time scales the fluctuation of imbalances can be reduced by 50% in a common European control zone, i.e. power flows smooth out spatial differences in PV and wind power generation on a European wide grid very effectively. Consequently, less energy from storage facilities is required to meet imbalances, e.g. storage losses are reduced by about 50%. The optimal mix between PV and wind energy in the power system depends on the time scale. While on the monthly time scale roughly 40% of PV is favourable to minimize the variance of imbalances, the optimal share of PV is only 20% on the hourly time scale, because of the strong impact of the diurnal cycle on PV generation.

Keywords: Renewable energy sources; wind power; photovoltaic; power supply system; climate change

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A. Troccoli (ed.), *Management of Weather and Climate Risk in the Energy Industry*,

1. The Role of Renewable Energies in the Future Power Supply System

It is expected that the worldwide primary energy demand will increase by 45% and the demand for electricity will increase by 80% between 2006 and 2030 (WEO, 2008). The rather conventional International Energy Agency states that Renewable Energy Sources (RES) will play a significant role in the future power supply system in order to reduce CO2 emissions (IEA, 2008). Also policymakers started to look at climate change as a global threat since the Intergovernmental Panel on Climate Change (IPCC, 2007) makes it undoubtedly clear that the current warming of the Earth is related to the extensive release of greenhouse gases from fossil fuels.

Most of the western industrial countries take the responsibility and role to lead the discussion of climate protection. European Union (EU) heads of state and government officials committed in March 2007 to set a binding target for 20% of the EU’s total energy supply to come from renewables by 2020 (6.5% in 2007). Furthermore they set a firm target of cutting 20% of the EU's greenhouse gas emissions by 2020 relative to 1990. As a side-effect, RES will reduce Europe’s dependency from natural gas, crude oil imports and will help to phase out the use of nuclear power, which is disliked by the majority of Europeans (World Energy Council, 2007).

During the last decade the market for wind power, photovoltaic and biogas grew faster than expected. Increasing prices for fossil fuel and the aim of developed countries to become more independent on energy imports will further boost the deployment of RES. It is expected that the price of energy from RES will continue to decrease considerably and that they will become competitive in the very near future (EWEA, 2009).

RES can be divided into three categories with respect to their relationship with weather/climate variability:

- Geothermal and tidal energy are not affected by weather.
- Bioenergies and hydro power from water reservoirs and small hydro are related to weather on the seasonal time scale.
- Wind power, photovoltaic, solar thermal and solar concentrated power sources are directly related to fluctuating weather conditions.

The latter are primarily generating electricity which virtually can not be stored without transfer to a different form of energy. Relevant long-term and large-scale storage solutions are pumped-hydro and Compressed Air Energy Storage (CAES) in salt caverns. Batteries (also in electro-mobility) and flying wheels have rather low storage capacities and might be used for short-term storage with high efficiency.

Disregarding geothermal and tidal energy, RES are powered directly or indirectly by the sun, i.e. the 'fuel' for RES is free. Only 0.01% of the solar energy received by the Earth must be made available by RES to meet the world's primary energy demand.

The inherent problem with fluctuating RES generation is the fact that power generation and demand must be balanced at any time in a power system. Nowadays interconnected power systems are very large. Hence the variability of wind and solar power generation can be smoothed to a large extent over almost the whole of Europe since most European countries are part of the UCTE (Union for the Co-ordination of Transmission of Electricity) transmission network. Nevertheless, it is essential to increase the (market) value of fluctuating and non-controllable wind and solar energy relative to conventional (fossil and nuclear) power generation. This requires accurate forecasts of PV and wind power generation in order to schedule conventional power plants accordingly to meet the expected consumption. The forecast horizon is typically for the day-ahead (+24–48 h). In the past research in short term wind power forecasting focused on the development of wind power forecasting models and methods (Lange and Focken, 2005; von Bremen et al., 2007). Various Ensemble Prediction Systems (EPS) for wind power forecasting are already developed (Taylor et al., 2009; Pahlow et al., 2008) and tested to facilitate decision making for save integration of wind power in the power system (Pinson et al., 2007; Roulston et al., 2003). However, much more research is required to make better use of operational EPSs. An example is the usage of EPS wind speeds at hub height of wind turbines, a variable that is currently not archived by the European Centre for Medium-Range Weather Forecasts (ECMWF). The market value of wind power can still be increased considerably by using better short-term wind power forecasts (Obersteiner and von Bremen, 2009).

Short-term forecasting of solar power (PV) is much less developed as installed capacities are relatively small compared to installed wind power. In Germany, the country with the highest PV penetration in Europe, about 6.5 GW PV power was installed by the end of 2008 against 23 GW of wind power. Nevertheless the need for solar forecasting will increase in the following years as large-scale PV, solar thermal and solar concentrated power plants will be built.

Results from spatio/temporal variability of wind and solar (here photovoltaic) energy generation in Europe are presented in this study. The analysis of the variability at different time scales is essential to evaluate the opportunities of Pan-European power flows and centralized or decentralized energy storage in a full-supply scenario with renewable energies. In a full supply (100%) scenario wind and PV supply 100% of Europe's annual energy consumption. The very important question: “What is the optimal mix between wind and PV?” is addressed in this study. The discussion about the optimal mix between wind and solar generation is needed to develop the best possible (political) incentives for the deployment of different types of RES.

2. Fluctuating Wind and PV Generation in Europe’s Power Supply System

In terms of (electrical) power it is expected that the major growth in renewable supply will be provided by wind and solar energy. Wind and solar energy are fluctuating resources and can not be scheduled like conventional power plants. However, the variability of wind and solar power decreases with increasing spatial scale of the power supply system as many local fluctuations are balanced by spatial smoothing effects.

In the future temporal smoothing of fluctuating wind and solar power will be achieved with new storage technologies that incorporate very high storage capacities, high efficiency and high discharging power. The combination of wind and solar has the potential to further reduce temporal variability on longer time scales (e.g. seasons).

The future power supply system with high penetration of renewable energies requires sustainable reinforcement of the transmission system and the usage of all existing storage capacities including the construction of new units. It is essential to analyse weather-related fluctuations of wind and solar energy generation over a long period and a large area (e.g. Europe).

In order to balance the residual load (wind and solar generation minus consumption) in a power system that is powered by almost 100% Renewables cross-boarder transmission and storage are getting very important. Transmission and storage losses must be considered very carefully. At the moment, it is not clear if transmission or storage is economically more advantageous.

Recent studies (EWIS, 2007; van Hulle et al., 2008) dealing with wind power integration and power flows in Europe found that congestion will occur in several cross-border flows (interconnectors) after 2015 if the grid does not get reinforced, e.g. between Germany and France. The capacity credit of wind power in Europe can be doubled in 2020 by trading wind power on a European level compared to national trading (van Hulle et al., 2008). The capacity credit value of wind generation is defined as the amount of conventional generation capacity that can be replaced by wind power capacity, while maintaining existing levels of supply security.

2.1. TIME SERIES OF CONSUMPTION, WIND AND PV GENERATION

Time series of power consumption are available from UCTE for each associated country. Data for Scandinavian countries are obtained from Nordel which is the organization of Nordic Transmission System Operators (TSO). Consumption data for the United Kingdom and Ireland are made available directly by the responsible TSO. Most of the data was already available in hourly resolution, for some countries and periods the hourly consumption had to be reconstructed from typical load profiles.

In this study some countries are divided into different regions. The gross domestic product (GDP) and the population density in the corresponding regions have been used to estimate the power consumption for each region.

Gridded data of a mesoscale atmospheric model is used to generate time series of wind and PV generation. The model downscales 0.5 degrees NCEP analyses to 0.45 × 0.45 degrees of horizontal resolution. The main gain is to increase the temporal resolution from 6 hourly to hourly. Three hourly NCEP forecasts are used as boundary conditions. The data was provided by a private weather service company (WEPROG) for the years 2000–2007.

A model level wind speed close to a height of 100 m has been used to compute wind power production at each grid point using standard wind turbine power curves. The power curve describes the cubic increase of wind power with wind speed. A distinction was made for onshore and offshore grid points with respect to the choice of the power curve.

Figure 1 shows the average wind speed for 50 onshore and 33 offshore regions in Europe. Northern countries and offshore regions are superior to Southern Europe with respect to wind resources. The projected future wind power capacity for each region is determined from the national wind power targets for the year 2020. In countries with more than one region the national target is divided to regional capacities with respect to regional wind resources. The anticipated wind power capacity for Europe is 227 GW. With an average efficiency of 0.3, wind power would generate 19% of Europe's power consumption assuming that the European consumption remains constant to 357.4 GW (average of 2000–2007).

A PV converter model needs the global radiation and the ambient temperature as meteorological input. The global radiation is computed from the net short wave radiation at the surface using the total cloud cover, and the cloud and surface albedo. All variables, parameters and the 2-m temperature (for the ambient temperature) are taken from the mesoscale model.

The annual resource of global radiation is more than double in Southern Europe compared to Northern Europe (Figure 2). In this study the average efficiency of PV is 0.21 which means that a PV converter with 1 MW peak production will generate on average 0.21 MW electrical power. The total installed capacity in Europe is anticipated to reach 68 GW in 2020. Thus, PV would generate 4% of Europe's power consumption.

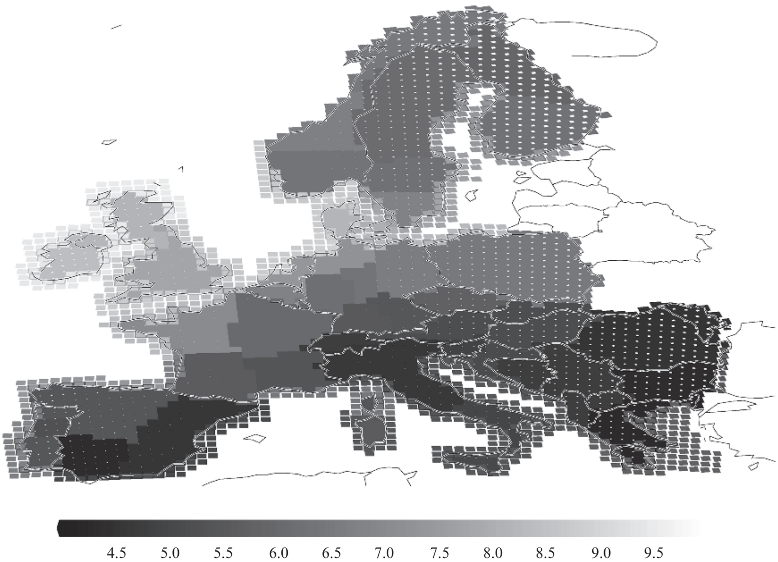

Figure 1. Average wind speed (m/s) in Europe (years 2000–2007).

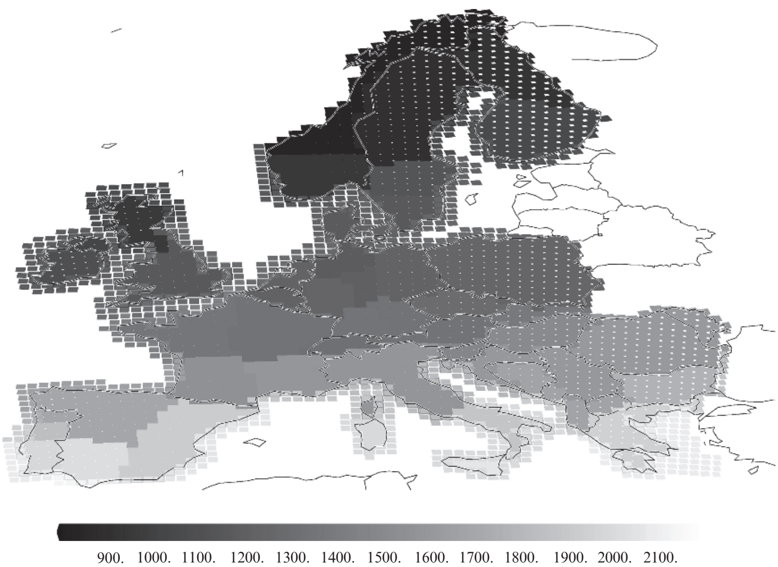

Figure 2. Annual resource of global radiation (kWh/m^2/year) that can be used by PV converters (years 2000–2007).

2.2. SPECTRAL ANALYSIS OF WIND, PV AND CONSUMPTION

For the following analyses in this subsection the time series of wind and PV generation and consumption in the 83 regions are aggregated without (electrical) losses, i.e. a full interconnection with a ‘copper plate’ in Europe exists. The PV and wind power generation in the 83 regions are weighted relative to their installed wind and PV capacity that is expected in 2020. The consumption of all regions is summed up. This type of aggregation is called the “European view” model.

The spectral analysis of wind and PV generation and consumption shows three dominant time scales:

i. Daily: Both wind and PV power exhibit a strong peak in the power spectrum (Figure 3) at the period of 1 day. Wind power (Figure 3a) has a very sharp peak, while the peak for PV (Figure 3b) has also increased power in the wings of the peak at 1 day. This results from the varying length of the day during the year. Note, that the strong peaks at the period of half a day and less are an artefact to represent the cycle of the diurnal irradiation using sine and cosine functions. The reason for the strong diurnal cycle in wind speed is that during the day the thermal stratification of the atmosphere gets less stable (due to an induced sensible heat flux from the surface into the atmosphere) and consequently the wind speed at hub height decreases. Wind power generation is about 2.7% lower during the day (6-18 UTC). On the other hand the wind speed increases during the night when the thermal stratification is becoming more stable due to radiative cooling of the surface. The consumption shows also a very pronounced peak for 1 day (Figure 3c). The average consumption during the day is about 8.2% higher than the daily average, i.e. the PV can be used cut the peak in consumption during the day.

ii. Synoptic: The synoptic time scale (2–10 days) is connected to passing weather systems. This is most pronounced in Northern Europe when cyclones with large kinetic energy are crossing. It can be seen that in the synoptic range the spectral power of wind power is much higher than of PV. Consumption has a very strong weekly period.

iii. Seasonal: The seasonal cycle is very pronounced for PV and wind power generation and consumption. In the winter months (DJF) the consumption is increased by 11% and wind power is increased by 32.2% while PV is reduced by 34.1%. During summer (JJA) the consumption is 9.1% below the average, wind power is decreased by 33.6% and PV generation is 28.2% higher than the average.

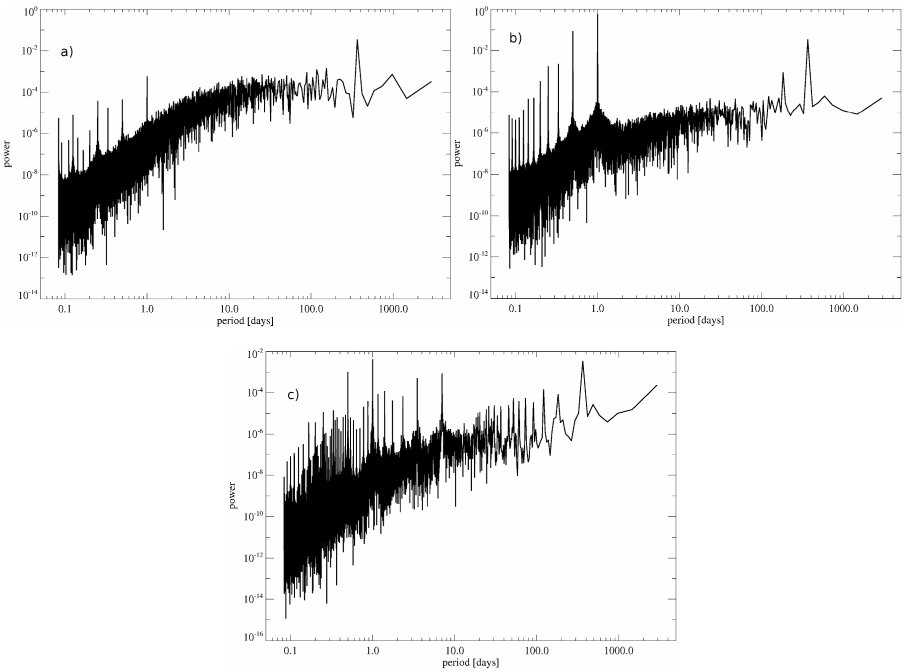

Figure 3. Power spectrum of (**a**) normalized wind power and (**b**) PV power generation in Europe. In (**c**) for the consumption.

2.3. POWER BALANCING BETWEEN PV AND WIND POWER GENERATION AND CONSUMPTION

Imbalances between RES generation and consumption must be balanced at any time. The imbalance is also called residual load which is defined as generation minus the consumption (load). In case of an excess of generation, the generation must be stored or reduced. Reducing RES generation means to curtail wind farms and PV power, i.e. wasting energy. In case the consumption is higher than the current generation, either stored energy must be released or additional generation units must be activated. The activation of additional generation units requires that several units are operated in stand-by or in part-load. Both options are not economical for large fossil powered generation units. Nuclear power plants can not be used as they require lead times for scheduling up to 1 day. The power of small-scale gas-powered units can be increased very quickly, thus they are ideal to fulfil this kind of service. They run either with natural gas or gas from (renewable) biomass plants.

Two types of mass storage technologies for electrical energy are operated at the moment. One is compressed air energy storage (CAES), which stores compressed air in salt caverns. A typical facility is operated in Huntorf, Germany, and has a capacity of 580 MWh. This capacity equals 6.7% of Europe's daily consumption. The maximal power is 290 MW and the overall efficiency is $\eta_{eff} = 42\%$.

A second mass storage for electrical energy is pumped hydro. Around 220 facilities are operated in Europe with a total power output of 43 GW. The capacity of a modern large pumped hydro facility is around 8,000 MWh, which equals 90% of Europe's daily consumption. Pumped hydro facilities are mainly used as tertiary control reserve (minute reserve), i.e. to balance deviations in consumption and generation in the time frame of 2–60 min. The total efficiency of pumped hydro power is about $\eta_{eff} = 80\%$.

At the moment the future of hydrogen as a mass storage for power is not certain. Currently no large-scale hydrogen storage facility exists as the efficiency is only about 29%. The goal is to increase it to around 46%.

The German TSO EON-Netz envisages that for short-term balancing of RES fluctuations, storage facilities with a power of up to 25% of installed RES capacity are necessary. This estimate is not based on a full supply scenario and therefore does not include storage capacities to substitute low RES generation in specific weather conditions or even seasonal fluctuations. Hence, much higher capacities are needed in a full supply scenario.

Figure 4 shows average wind and PV generation per month normalized with the (constant) installed capacity for 2020. The annual amplitude of wind power generation is much stronger than for PV. The load (capacity) factor increases from 0.2 in summer to 0.45 in winter. In several years the peak is very pronounced (either January or February). The PV load factor increases from 0.12 in winter to 0.28 in summer. However, the annual cycles of wind and PV are coherent, i.e. the lack of PV production in winter is balanced by increased wind power and low wind power generation in summer is compensated by high shares of PV.

The smaller the imbalances (residual load) from month to month, the less stored energy is required. In the optimal case, PV and wind power capacities are adjusted in a way that their total generation equals the consumption in each month. In order to find the ratio (optimal mix) between PV and wind power capacity that best fulfils this requirement, the fluctuation of the residual load is computed as the standard deviation of the monthly time series and is supposed to be small. In general, the standard deviation of the residual load time series is called variance of the residual load or variance/variability of the imbalances.

The share of PV (s_{PV}) is defined as the generated PV energy relative to the total of wind and PV energy. Note that s_{PV} is not the ratio with respect to installed capacity but with respect to generated energy. s_{PV} is now varied between 0 and 1 to minimize the variability of the imbalances. The results of this analysis are shown in the following section.

In preparation to this analysis, the time series of wind and PV power are scaled to a full-supply scenario, accordingly. A full supply with only wind power requires an installed capacity of 1,186 GW. The average load factor is 30%. A full supply with only PV power requires 1,714 GW of installed PV, while the average load factor is 21%.

2.4. VARIABILITY OF THE RESIDUAL LOAD

The variance of the residual load is a measure of activity to balance the power supply system. In general, the variability should be small to cut the costs of imbalance power. In this section the dependency of the variability on the share of PV (s_{PV}) in the power system is investigated for different time scales, e.g. monthly, weekly and daily.

Two models for the spatial aggregation of RES generation and consumption are applied. The first model is the "European view" that is described at the beginning of Section 2.2. All 83 regions are fully interconnected by a "copperplate", i.e. regional imbalances will immediately be compensated with other regions. As a result there will be either a general excess or demand for energy.

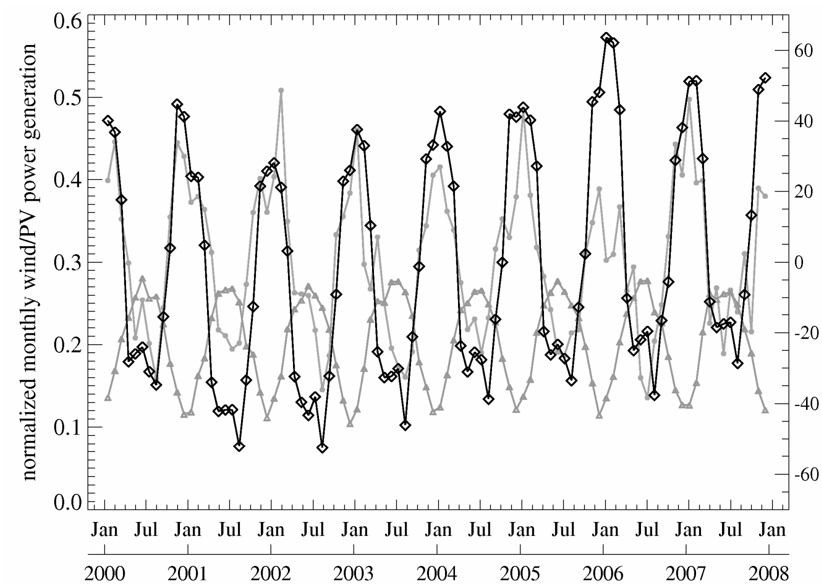

Figure 4. Monthly generation of PV (triangles) and wind power (bullets) in Europe. The generation is normalized with the installed capacity. The anomaly of consumption is plotted with diamonds and refers to the right axis (GW). The average consumption is 357 GW.

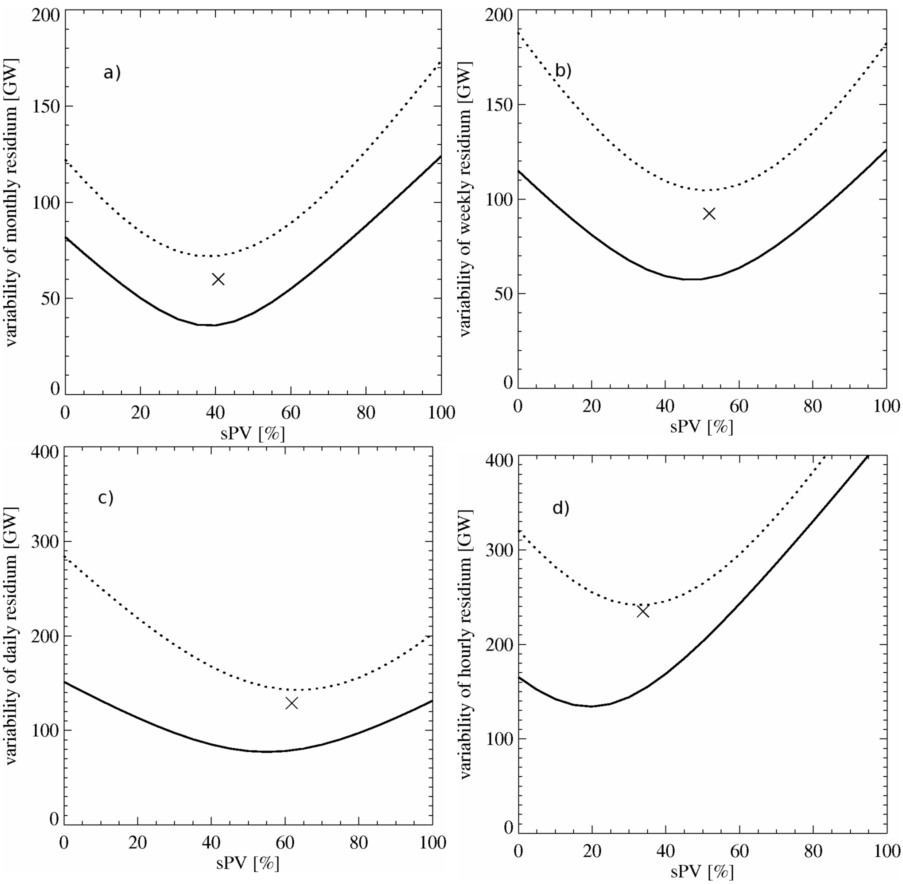

Figure 5. Variance (expressed as standard deviation) of the residual load depending on share of PV (s_{PV}) for a full supply scenario. The residual load is averaged to (**a**) monthly, (**b**) weekly, and (**c**) daily values. In (**d**) the original hourly resolution is used. Two spatial aggregation models are applied: "European view" (solid line) and "regional view" (dotted). The cross in each graph indicates the location of the optimal share of PV and the variability of the residual load when the share of PV is optimized in each region individually.

The second aggregation model is the extreme that no power flows between regions exist and that each region is responsible to balance its own fluctuations in the residual load. This is called the "regional view". For the final result for Europe, all regional results (standard deviations) are summed up as it is required to treat them individually.

2.4.1. *Monthly Time Scale*

The variance of the residual load strongly depends on the share of PV s_{PV} (Figure 5). The total of all regions ("regional view") is minimal when each region has 40% of PV generation (s_{PV} = 40%) (Figure 5a, dotted line). To the left of the minimum the signal of wind power production (high in winter and low in summer) is predominant and adds more variability to the residual load. To the right of the minimum the signal of the annual PV generation (low in winter and high in summer) is predominant. In order to overcome the disadvantage of this analysis that no regional diversification of s_{PV} is possible, the lowest variability in each region and the corresponding value of s_{PV} is stored when varying s_{PV} for that region. The map of s_{PV} for European countries is shown in Figure 6 for monthly (Figure 6a) and hourly (Figure 6b) imbalances.

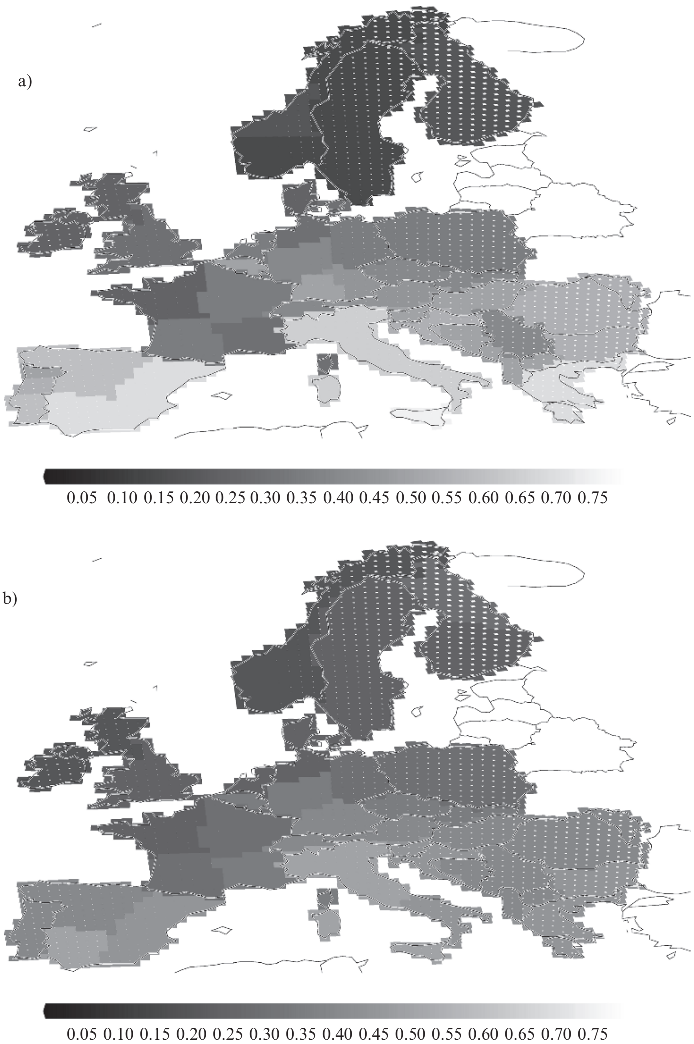

Figure 6. Optimal share of PV (s^0_{PV}) that minimizes the variability of the imbalance (residual load) for each region on a monthly (**a**) and hourly (**b**) time scale (a).

In southern countries the share of PV is considerably higher than in northern countries (Figure 6a) to minimize the variance of the residual load. Highest values are 70% in Southern Spain. The highest share for wind power is favourable in Scandinavia (s_{PV}= 0.15).

The total variability (standard deviation) of imbalances for all regions is 60 GW when considering the optimal shares of PV (s^0_{PV}) in each region (Figure 5a, cross). The overall share of PV for Europe is 40%.

Figure 5a also shows the variability of imbalances for the "European view" (solid line). It is about 50% lower than the minimum of the "regional view" and also considerably lower than the optimum of the "regional view". Cross-border power flows reduce imbalances between generation and consumption very effectively (spatial smoothing). The minimum is at s_{PV}= 40%, i.e. in an European wide balanced power system the same amount of PV is generated than if each region reaches its own optimum on PV generation (s^0_{PV}).

It is worth noting that the inter-monthly variability of imbalances in a purely PV powered generation system (s_{PV} = 100%) is considerably higher (123 GW) than in a purely wind powered system (s_{PV}= 0%, 80 GW, Figure 5a).

2.4.2. *Weekly and Daily Time Scale*

Figure 5b and c show the variability when averaging the residual load over weeks and days, respectively. The minimal inter-weekly variability of imbalances is obtained at higher shares of PV (~50%) compared to the minimal inter-monthly variability (Figure 5a). The variability itself has increased when averaging over shorter time periods. In contrast to Figure 5a it can be seen that the inter-weekly variability in a pure PV or wind power system has the same size. The variability in the "European view" is only 50% of the variability in the "regional view".

The inter-daily variability is further increased (Figure 5c) and the share of PV has moved to 55% for the "European view" and to 60% for the "regional view". Apparently, PV is getting more important in the power system when looking at fluctuations on shorter time scale. This is confirmed by the fact that in a pure wind power system the variability of imbalances is higher than in a pure PV powered system ("European view").

2.4.3. *Hourly Time Scale*

The diurnal day/night cycle causes that PV generation varies very much throughout the day (see strong peak in Figure 3a for period 1 day). The variability of imbalances reaches very high values in a pure PV powered power supply system (Figure 5d). The minimum variability occurs for s_{PV}= 20%

for the “European view” and for s_{PV}= 30% in the “regional view”. The latter value is identical to the share of PV (s^0_{PV}) when optimizing s_{PV} for each region individually (see cross in Figure 5d). The minimum variability for the “European view” is half the variability when cross-border balancing is not permitted (“regional view”). The level of variability of the imbalance is consistently increasing with shorter averaging periods. Compared to monthly values (Figure 5a) the minimum variability in the “European view” has increased by a factor of three.

The share of PV in the system decreases (share of wind power increases) in order to obtain the lowest variability of imbalances with increasing time scale (Figure 5). It can be concluded that wind power introduces more fluctuations in the power system on shorter time scales (compared to PV). However, this does not apply when looking at hourly values (Figure 5d). The day/night cycle in PV generation introduces large imbalances. Hence it is superior to have only 20–30% of PV in the system. The implication of the diurnal PV generation on imbalances is discussed in Section 2.6.

2.5. STORAGE LOSSES

Deviations (imbalances) between current RES generation and consumption need to be balanced with reserve power, which can be negative or positive. Supplying negative reserve power in a full supply scenario requires curtailment of RES units while positive reserve power requires extra power from fossil units or from storages. As discussed in Section 2.3 the best efficiency for large-scale storage (e.g. pumped hydro power) is about 80%.

In the following analyses the time series of the residual load (hourly values) was evaluated. The required energy from storages is given by the integral over all negative values. In order to account for storage losses the annual demand from storage is multiplied by the reciprocal of the storage efficiency. Figure 7 shows these storage losses relative to the annual energy consumption. The lowest storage losses (about 3.8% of the annual energy consumption) occur when 20% PV is in the system (“European view”). The losses are almost doubled in the “regional view” and the optimal share of PV moved to 30%. A qualitative comparison to Figure 5d shows that storage losses are proportional to the variability of imbalances.

In a European wide control zone only about half the storage losses will occur compared to balancing being a regional requirement. However, transmission losses are considerably higher in a European wide control zone, and future analyses must show the order of magnitude of these losses. In a following analysis a final conclusion can be made too which extent transmission or storage can be justified.

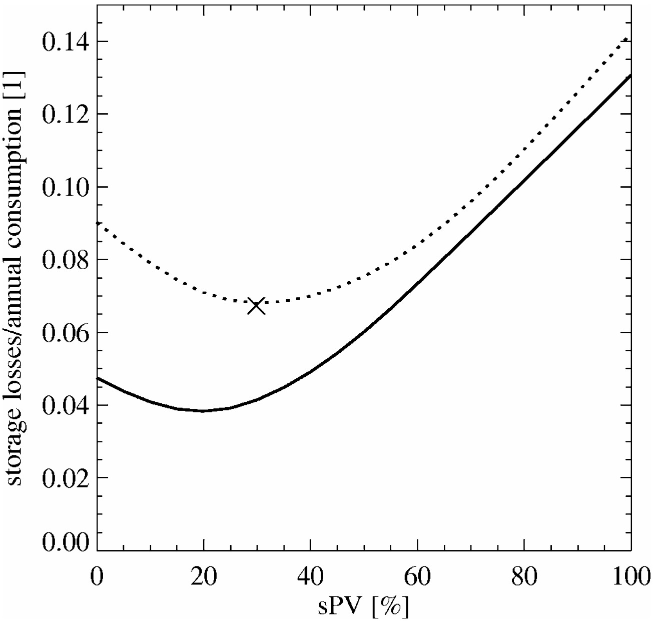

Figure 7. Storage losses relative to annual energy consumption depending on share of PV (sPV) for a 100% RES scenario and storage efficiency ηeff = 80%. Two spatial aggregation models are applied: "European view" (solid line) and "regional view" (dotted). The cross indicates the location of the optimal share of PV and the variability of the residual load when the share of PV is optimized in each region individually.

2.6. OPTIMAL SHARE OF PHOTOVOLTAIC

The analysis on the variability of imbalances (Figure 5) has shown that the optimal share of PV depends (i) on the spatial design of the power supply system ("European view" vs. "regional view") and (ii) to a much larger extent on the time scale. On the time scale of months about 40% of the generation should be based on PV while the hourly fluctuations are smallest when PV contributes only 20%. Thus, simple recommendations can not be given. The European map in Figure 6 shows considerable differences in shares of PV to minimize monthly (Figure 6a) and hourly (Figure 6b) fluctuations. For example s_{PV} is 70% in the East of Spain to minimize imbalances from month to month and 45% when minimizing imbalances on the hourly scale. The possible range is getting even wider looking at fluctuations from day to day as Figure 5c suggests a European penetration of 60% PV. For eastern Spain 90% of PV would lead to the smallest fluctuations (not shown).

It can be concluded, that the optimal mix between wind power and PV can only be determined when different time scales are considered at the same time. A technical solution would be the use of very efficient short-term storage facilities to bridge the lack of PV during the night. The required storage capacities would be relatively small and the optimal share of PV in the power supply system would increase compared to the results of the hourly time scale.

3. Summary

Renewable energy sources (RES) like photovoltaic (PV) and wind power generation fluctuate following the weather. Thus, utilizing RES requires knowledge on spatio-temporal characteristics of RES generation in order to determine the smoothing effect of spatial distributed RES. Long time series of gridded weather model data are needed to simulate RES generation for large domains.

In this study the optimal mix between PV and wind power to meet Europe's power consumption (in a full-supply scenario) is investigated by computing imbalances in the power system. Imbalances are defined as the difference between PV plus wind power generation and consumption. Hence, imbalances require either the use of conventional power or the use of storage facilities to meet the consumption. The standard deviation of the time series of imbalance (residual load) is used to characterize the variability of imbalances. A low variability is favourable as little action for balancing is required.

It was found that wind power generation anomalies have a strong correlation to consumption anomaly on the monthly scale. Wind power and PV anomaly are anti-correlated, i.e. wind power increases during winter months while PV decreases and vice versa.

Two different approaches in spatial aggregation are analyzed (i) unlimited cross-border power flows to simulate *one* European control zone ("European view") and (ii) no cross-boarder power flows, i.e. deviations between generation and consumption are balanced on a regional level ("regional view"). On all investigated time scales the fluctuation of imbalances can be reduced by 50% in a common European control zone, i.e. power flows smooth out spatial differences in PV and wind power generation in a European wide grid very effectively. Consequently, less energy from storage facilities is required to meet imbalances, e.g. storage losses are reduced by about 50%.

The optimal mix between PV and wind energy in the European power system depends on the time scale. While on the monthly time scale roughly 40% of PV is favourable to minimize the variance of imbalances, the optimal share of PV is only 20% on the hourly time scale, because of the strong impact of the diurnal cycle on PV generation. It can be concluded, that the optimal mix between wind power and PV can only be determined when different time scales are considered at the same time. A technical solution would be the use of very efficient short-term storage facilities to bridge the lack of PV during the night.

For an economic evaluation if storage or transmission is more important in a 100% RES scenario for Europe, it is necessary to distinguish different storage types (short and long term) and to quantify storage and transmission capacities. The need for research in this area is overwhelming.

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MODELLING AND FORECASTING ENERGY DEMAND: PRINCIPLES AND DIFFICULTIES

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Abstract. We give a brief description of how energy demand can be modelled as a function of calendar data, meteorological data and economic variables. The principles of energy demand models are presented and a brief overview of commonly used mathematical methods is given. For each method advantages and disadvantages are described. Some examples illustrate difficulties that may be encountered when using meteorological data in energy models. These difficulties are discussed and we propose some steps weather services could take to facilitate the use of meteorological data in the energy sector.

Keywords: Energy demand; forecast; modeling; non-linear

1. Introduction

The energy sector is one of the most weather sensitive sectors of the economy. Areas that are strongly influenced by weather and climate and their respective influence factors are:

- Demand: temperature, solar radiation, humidity, wind speed
- Renewable energy production: accumulated precipitation, wind, solar radiation
- Operational risk: cooling of thermal power stations, logistics, transport of fuel
- Price: Demand, production, operation

The operational risk is mainly influenced by extreme weather events like heat waves during summer, severe storms or extreme snow fall. Energy prices change as a function of demand and production. Thus weather only

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influences prices indirectly. In this article we'll focus on direct relationships between normal weather and climate variability and the energy sector. We'll discuss principles and methods to model and predict energy demand and to a lesser degree the renewable energy production.

Energy demand (electricity, gas, district heating) is highly influenced by weather and climate, with the most important factor being temperature. During winter a drop of the temperature by 1°C causes an additional power request of about 1.8 GW in France.

The influence of weather and climate on renewable electricity production is obvious. Accumulated rainfall influences the reservoir content for electricity production. Wind speed is the determining factor for wind power and solar electricity production depends directly on solar radiation. Although the total volume of renewable electricity production represents only a few percent of the total electricity production in Europe it can be an important factor locally. For example in the north-east of Germany the installed nominal wind power outruns the total demand for that region. Thus modelling and short term predictions of renewable energy production become crucial for safe and economic grid management. This point will become even more important with the increase of renewable energy production. The European Commission has set a target for renewable energies to provide at least 20% of the electricity production in Europe by 2020.

Furthermore renewable energy production strongly influences electricity prices. It is estimated (Eric Stein, Senior Meteorologist and Weather Derivative Trader, RWE Supply & Trading GmbH, Essen Germany, 2008, personal communication) that 1 GW of wind power production in Germany causes a drop of the electricity prices at the German spot market of about 1 EUR/MWh. In total the installed nominal wind power in Germany is about 23 GW which translates into potential price changes of up to 20 EUR/MWh due to wind power. At the beginning of 2009, the month ahead future prices in Europe were around 60 EUR/MWh and 80 EUR/MWh for base and peak periods, respectively (Tendance carbone, February 2009). This illustrates how significant the influence of wind on power prices in Europe can be.

In Section 2 of this paper we outline the principles of modelling and predicting energy demand. In Section 3 we present different algorithms and give a very brief overview of their respective advantages and disadvantages. In Section 4 we present some examples and in Section 5 we discuss difficulties related to meteorological data. The conclusions in Section 6 finalise the paper.

2. Modelling Energy Demand

The most important factors that influence energy demand on time scales ranging from a few hours up to about 1 year are

- Calendar data: time of the day, day of the week, public holidays, bridge days, school holidays, daylight saving time, …
- Meteorological data: temperatures, solar radiation, humidity, wind speed, …
- Economic factors: economic growth, production plans of companies

On these time scales the importance of calendar data and of meteorological data is comparable. The influence of economic factors on energy demand becomes only visible on longer time scales or in extreme situations such as during the current economic crisis (Tendance carbone, February 2009).

The following graph shows hourly electricity consumption for a region in France, covering a period of 11 months from January to November (Figure 1). The strongest signal we can identify is a seasonal signal. The electricity demand in winter is about 50% higher than in summer. This is mainly due to the air temperature. It must be said, that the situation in France is a bit special, since many households use electric heating. In other European countries the difference between summer and winter is less pronounced, but the seasonal signal remains nevertheless dominant. In winter we observe a significant amount of variability on synoptic time scales (low consumption at around time step 2000, high at around time step 2500, etc.) whereas in summer almost no variability is present on these time scales. This indicates that temperature variability at low temperatures causes significant demand variability, whereas temperature changes in summer have less influence on the electricity demand.

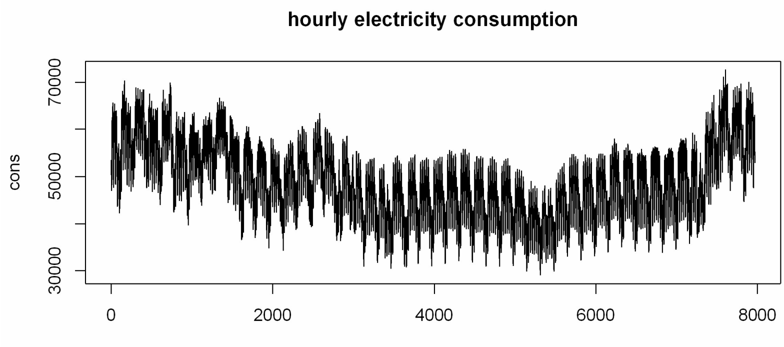

Figure 1. Hourly electricity consumption for a region in France over a period of 11 months, January to November. One time step represents 1 h.

The second strongest signal is the daily cycle, closely followed by the weekly cycle. Those two signals have almost the same amplitude as the annual cycle. Between time step 5200 and time step 5500 we see a drop of demand during 2 weeks which can be explained by the main vacation period in France (beginning of August). A closer look to the data reveals also an interaction between the weekly cycle and the annual cycle. During summer the amplitude of the weekly cycle is more pronounced than during winter. The same holds for the vacation period. During the first weeks of August (time step 5200 to 5500) not only the demand in general is lower but also the amplitude of the weekly cycle is reduced.

This example shows that a range of different data types, like calendar data, temperature, vacation, etc. influence energy demand. The functional relationship is non-linear and there are more or less complex interactions between different data types. Since no simple deterministic laws that relate the predictor variables (calendar data, meteorological data and economic variables) on one side and energy demand as the target variable on the other side seem to exist, it is necessary to use statistical models. A statistical model "learns" a quantitative relationship from historical data. This process is called "training". During the training process quantitative relationships between the target variables (variables that have to be predicted) and the predictor variables are determined from historical data. Data sets must be provided for which the predictor variables and the target variables are known.

From these example data a mathematical model is determined. This model can then be used to compute the values of the target variables as a function of the predictor variables for periods for which only the predictor variables are known.

To run a prediction, the model that was found during the training process is used to compute from the known predictor variables for the prediction period the unknown target variables. Hence, in order to run a prediction, forecasts of the values of the predictor variables must be available. If we use meteorological data as predictor variables we need forecasts for those meteorological variables. These forecasts must be as coherent as possible with the historical meteorological data that were used during the training process. We will come back to this point later in Section 4 in this paper.

A wide range of statistical modelling algorithms is used in the energy sector. They can be classified according to three criteria:

- Linear/non-linear
- Univariate/multivariate
- Parametric/non-parametric

The separation between linear and non-linear methods is straightforward. The best known example of a linear algorithm is the linear regression.

A univariate model uses one single predictor variable to explain a single target variable. Several target variables can be treated with a univariate approach by modelling separately the influence of each predictor variable on the target variables. In this case the interaction between target variables is not taken into account. A fully multivariate approach fits a single model to explain the behaviour of several target variables as a function of several predictor variables. Interactions between predictors and targets are taken into account.

In parametric models the type of the functional relationship between predictors and targets is prescribed and only the coefficients in this functional relationship are fitted during the training process. A simple example is a non-linear regression of the form $f(x) = a \cdot x^2 + b \cdot x + c$. The functional relationship is prescribed as a quadratic function in x and only the coefficients a, b, and c have to be determined. The type of the underlying function is not questioned. This can be a very good approach, especially if some a-priori knowledge about the underlying dynamics of a system is available and integrated into the prescribed functional relationship. However, if no a-priori knowledge about the underlying functional relationship is available, the best modelling approach is a fully non-parametric model. The structure of the model is entirely determined from the data used during the training process.

3. Modelling Algorithms

In this section we present some commonly used methods to model and forecast energy demand. We give a very brief description of each method and discuss advantages and disadvantages. At the end of this section we draw some conclusions and we present the method we have chosen for modelling energy demand.

3.1. ANALOGOUS METHOD

This is simply a method of finding in a data base with historical data a situation that is similar to the one that has to be predicted. A set of explanatory variables is defined and similarity between situations is measured with these variables. Let's assume we want to run a prediction for a Tuesday, with a mean predicted temperature of +3°C. In that case the algorithm is simply looking in a data base for another Tuesday with a mean temperature close to +3°C and the historical consumption data for that day are used as a prediction.

For a long time this method has been the reference method for energy demand predictions and surprisingly it is still widely used. The advantage of the method is that it is easy to understand, the results are easily interpreted and it is relatively easy to implement.

However the disadvantages are numerous. Although the implementation of the method seems to be straightforward, it becomes very quickly rather complicated if the number of criterions increases. If for instance hourly temperatures are used instead of daily mean temperature the measures of similarity are no longer so obvious. With an increasing number of explanatory variables, the probability to find no data set that is similar according to all criteria increases. This becomes even more critical for extreme – and hence rare – situations. A Tuesday with +3°C is easily found; but what about a Friday that is a bridge day or a normal Wednesday with 35°C (in France)? Furthermore this method does not interpolate. That means if we do not find a perfect match we cannot use similar situations close to the one we are looking for.

A possible extension of this method is to search for similar situations and adapt a linear regression model that is trained on the let's say 20 best fits that were found. In this way at least the last point in the list of disadvantages is eliminated.

Despite its conceptual simplicity the method can be very expensive in terms of computational time. With an important number of criterions and hence a relatively big data base the computational time for a single 1 day forecast can easily go beyond 15 min, even on a powerful machine (Dirk Heinze, Managing Director of Aktif Technology GmbH, Germany, 2007, personal communication).

This method is non-linear since it takes the full dynamics of the historical data into account. Furthermore it is non-parametric and depending on the implementation it can be uni- or multivariate.

3.2. MULTIVARIATE LINEAR REGRESSION

Multivariate linear regressions are widely used in the energy sector. They are simple to implement, fast, reliable and they provide information about the importance of each predictor variable and the uncertainty of the regression coefficients. Furthermore the results are relatively robust. Regression based algorithms typically work in two steps: first the data are separated according to categorical variables (e.g. calendar data) and then a regression on the continuous variables (meteorological data) is done. This approach works fine as long as the relation between energy demand and the continuous variables – in general temperatures – is indeed linear.

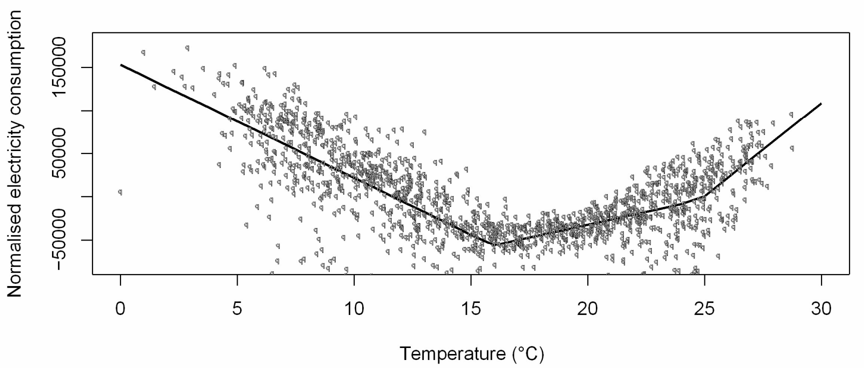

Figure 2. Normalized electricity consumption in Spain, daily values.

As can be seen in Figure 2 the relationship between daily energy demand and temperatures in Spain is at best piecewise linear. In this simple case with daily data and a single predictor variable it is easy to split the whole domain into three sub-domains and to fit three different regressions.

However, such an approach requires a manual intervention. If a multivariate regression is performed the identification of knots (splitting points) is no longer straightforward and the piecewise linear approach becomes very complicated, if not unfeasible.

As the name already indicates the method is multivariate and linear. Furthermore it is parametric since the functional relationship is prescribed and only coefficients are fitted.

3.3. SUPPORT VECTOR REGRESSION

Support vector (SV) machines (SVM) were first introduced by Vapnik and co-workers. A detailed description of the SV method would be far beyond the scope of this paper. For a detailed description we refer to the literature (Vapnik, 1995; Vapnik et al., 1996; Tay and Cao, 2001; Smola and Schoelkopf, 1998).

The basic idea is to find a function f(x) such that the deviation between f(x) and the actual corresponding target variable y is at most ε. This problem is similar to a regression but it is formulated as a minimisation problem under constraints:

$$f(x) = \langle w, x \rangle + b$$

$$\text{minimize} \quad 0.5 \, \| w \|^2$$

$$\text{subject to } \begin{cases} y_i - \langle w, x_i \rangle - b \le \varepsilon \\ \langle w, x_i \rangle + b - y_i \le \varepsilon \end{cases}$$

<,> denotes a dot product. In the above equations x represents a vector of predictor variables and w is a normal vector representing the regression hyperplane[1]. Slack variables ζ can be introduced to cope with otherwise infeasible constraints of the optimisation problem (for details see Smola and Schoelkopf, 1998). In that case only points with a difference y-x outside [-ε, ε] contribute to the cost function of the optimisation problem. Deviations outside this interval are penalised in a linear fashion (Figure 3).

This algorithm can be generalised to non-linear regressions by pre-processing the training data x by a map Φ into a high dimensional feature space such that the problem becomes again linear in that feature space. Then the standard SV regression algorithm is applied. This direct approach is feasible for simple low dimensional problems but becomes infeasible for complex problems with higher dimensionality. However, the mapping can be done implicitly via kernels. The linear SV algorithm only depends on dot-products; hence it suffices to know the dot-product between mapped vectors. The value of the kernel $K(x_i, x_j)$ is equal to the inner product (dot product) of two vectors mapped into feature space, that is $K(x_i, x_j) = \langle \phi(x_i), \phi(x_j) \rangle$, hence the use of kernel functions allows to compute the required dot product in arbitrary dimensionality without having to compute the map explicitly. Smola and Schoelkopf (2003) show that a Kernel function must fulfill certain conditions in order to correspond to a dot product in a higher dimensional feature space. We refer to this article for a detailed description of the SV regression method.

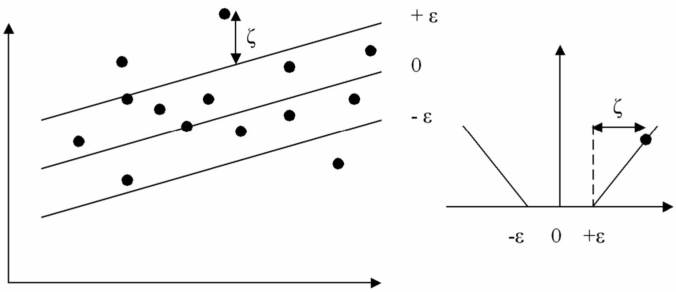

Figure 3. Soft margin loss setting corresponds for a linear SV machine (after Smola and Schoelkopf, 1998).

[1] A multivariate regression can be interpreted as a hyperplane in a multidimensional space. This hyperplane can be defined by its normal vector.

The principle of non-linear SV regression is to map the original space onto a high dimensional feature space and to do linear SV regression in that feature space. As pointed out in (Smola and Schoelkopf, 1998, 2003; Tay and Cao, 2001) SV regression has become a very powerful and competitive non-linear regression method. It has been successfully used in predicting financial time series and in optical character recognition.

We tested SV regression to model energy demand. The quantitative results were satisfying, but the method is computationally expensive and the results are difficult – if not impossible – to interpret. It seems that the method is less prone to overfitting than for example artificial neural networks, but, as for neural networks, the algorithm is like a black box and gives no further insight into the underlying dynamics of the system. The choice of the kernel is another issue. The results of the regression can be rather sensitive to the choice of the kernel function and to the tolerance parameters ε and ζ.

The method is non-linear, multivariate, and non-parametric. Hence SV regression is a very general method that can be applied to (almost) arbitrary problems without a prior knowledge of the underlying dynamics.

3.4. NEURAL NETWORKS

Artificial neural networks (ANN) have been widely used in modelling energy demand. We will not give a description of the theory behind ANNs. For details we refer to the vast amount of literature that is available on the subject. In a very schematic way the method is inspired by the functioning of a brain, although compared to a brain the method is of course very much simplified. The ANN algorithm uses step functions (or close approximations of step function) as a basis to approximate a functional relationship.

As SV regression, ANN represents a multivariate, non-linear, non-parametric regression method. The algorithm is very flexible and in principle can be used for all kinds of problems. In the field of energy demand modelling results are in general good and in some cases excellent. Over the past 10 year or so, ANN-based methods have become a sort of reference in the energy sector. New or alternative methods are usually benchmarked against neural networks.

Beside their strengths there are also important disadvantages. First of all training an ANN system can be computationally extremely costly. Training an electricity day-ahead ANN model with a 30 min time resolution over a period of 1 year may easily take several hours on a normal personal computer. Thus developing new models becomes a time consuming and expensive task. Due to the substantial amount of computational time it is in most cases not possible to re-train a model in operational mode every day.

Typically the model is frozen for a month or so and the training is done once a month during a week-end. In most cases this works fine, however, if important changes happen during the period the model was frozen the results can become rather poor. Models based on neural networks work very much like a black box. It is very difficult to interpret the results and the method does not easily provide further insight into the underlying dynamics of the system that is modelled. The quality of a prediction with a neural network is very sensitive to the design of the network. The structure of the network should be adapted to the dynamics of the system of interest. If the network is well adapted results are in general excellent. However, if the structure is not well suited results can be extremely poor. The use of neural networks requires a high level of expertise and a good understanding of the functioning of the system of interest and of the neural network itself. A last and very important point is the fact that neural networks are prone to overfitting. To avoid this problem rather long time series of historical data are required and even then the user must pay attention not to fall into the "overfitting trap".

To summarise, neural networks can provide excellent modelling and forecasting results but they demand a high level of expertise from the user. Their use is relatively cumbersome and they do not give any insight into the dynamics of the system of interest. This explains why opinions on the use of neural networks in the energy sector are mixed. On one side there are users who are absolutely in favour of neural networks, on the other side many potential users shy away from using this relatively complicated method operationally.

3.5. MULTIVARIATE ADAPTIVE REGRESSION SPLINES

Multivariate Adaptive Regression Splines (MARS) is a non-linear, multivariate non-parametric regression method that was first introduced by J. Friedman in 1991. Detailed descriptions of the MARS algorithm can be found in Friedman (1991) and in Hastie et al. (2001). The MARS algorithm divides the modelling space into subspaces and fits in each subspace a separate simple model subject to the constraint that the complete solution is continuous at subspace boundaries. The "simple" models for each subspace are multivariate polynomial models. The maximum degree of the polynomials can vary. In most cases multi-linear models are used. The advantage compared to higher order models is that the danger of overshooting of the solution is very much reduced. In the multi-linear models or higher order polynomial models the maximum degree of interaction can be set by the user. A purely additive model is obtained if the maximum degree of interaction is set to 1. Higher degrees of interactions can be used but the complexity and hence the computational cost increases dramatically with the degree of interaction. For practical use a degree of interaction higher than 2 is very rarely used.

The plot on the left in Figure 4 shows an example of a one-dimensional non-linear non-parametric fit using the MARS algorithm. The thin black line and the dots represent the observational data, the thick black line shows a simple MARS fit to the data. The only predictor variable that was used was the index value indicated on the x-axis. The model determines automatically the best position of the knots and the equation for each linear sub-model.

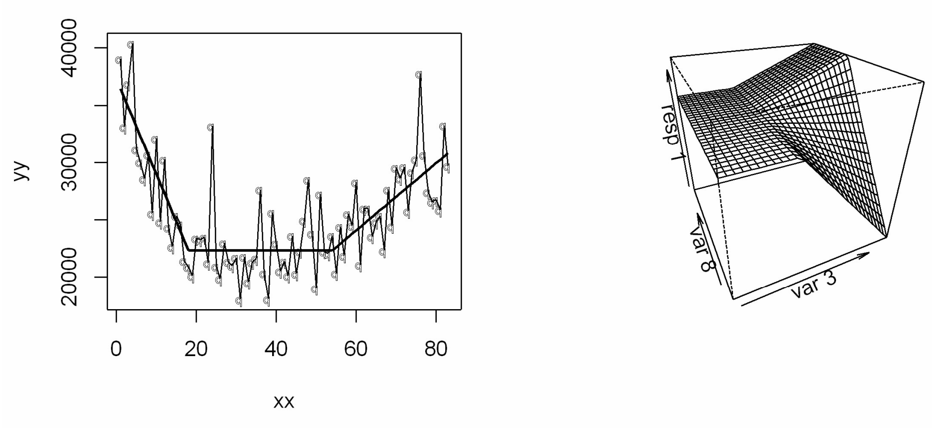

Figure 4. Examples of MARS model fits.

Another example of a simple one-dimensional MARS model was shown in Figure 2: the solid line represents the MARS model that was fitted to the data. In these simple one-dimensional cases the same result easily could have been obtained with a piecewise linear model and manually specified knots. In contrast to such a piecewise linear regression finding the number of knots and their position is part of the MARS algorithm. In a higher dimensional space it would be difficult – if not impossible – to find a proper data representation manually.

The plot on the right side of Figure 4 shows a model for one target variable (vertical axis) dependent on nine predictor variables. The maximum degree of interaction was set to 2. The plot visualizes how the target variable changes as a function of the predictor variables 3 and 8, while the other variables are kept constant. In this case it would have been very difficult to define the necessary number of subspaces and the positions of the respective boundaries manually and to adapt for each subspace a multivariate linear model. In an even higher dimensional space a manual approach becomes completely unfeasible.

As long as the maximum degree of interaction stays small (1 or 2) the MARS algorithm produces very reliable and robust results. Relatively small training data sets are sufficient to find a stable model and MARS has much less tendency to overfitting than ANN methods. Furthermore MARS is computationally extremely efficient. Training electricity day-ahead MARS models with a 30 min time resolution over a period of 1 year takes about 30 s or less. We ran benchmark tests between MARS and ANN for electricity models. The quality of the results obtained with the two methods was comparable, but MARS was typically between 100 and 300 times faster.

MARS becomes difficult to use when the degree of interaction between predictor variables is higher than 2. Computational time increases dramatically and the results are no longer very robust. Furthermore overfitting becomes a real issue. In such cases ANN or SV regression are probably more appropriate.

3.6. CONCLUSIONS – MODELLING ALGORITHMS

We have tested all the algorithms presented in this section for a wide range of applications in the energy sector and we selected the MARS algorithm. MARS yields very good modelling results, comparable with the best neural networks we have tested and it is much easier to use. The algorithm is extremely quick, the results are robust, and overfitting is encountered less often than with other non-linear algorithms. A MARS model is very easy to interpret and in principle the formulas describing the final model can be written down explicitly, even though they might be rather complicated. The algorithm yields also a ranking of the importance of each predictor variable, it indicates the presence of interactions between predictor variables and it automatically rejects predictor variables that do not contribute to explaining the target variables. Thus MARS is not only a good modelling method but also a very powerful analysis tool.

As with other non-parametric methods MARS cannot calculate confidence intervals on the model. Cross validation and similar techniques have to be used for that purpose. This is a disadvantage compared to parametric regression models, but the superior flexibility and the ease of building a model largely outweigh this shortcoming. MARS is not well suited for highly non-linear models that require a high degree of interaction even in the subspaces in which individual models are fitted. Examples of such applications are automatic text recognition or optical character recognition. Fortunately in the energy sector such problems seem to be extremely rare and so far we have not encountered them.

All statistical modelling algorithms have difficulties with linearly dependent or almost linearly dependent input variables. To overcome this problem it is possible to combine the MARS model with a projection on empirical orthogonal functions (EOFs). This is a commonly used trick in statistical modelling. Papers on EOF regression (also known as principal component regression or PCR) can be easily found and we will not give a description here. In the remaining part of this paper all examples shown are done using MARS.

4. Examples

In this section we present three examples of energy demand modelling. The first two examples deal with short term predictions, up to 1 day lead time. The third example shows a seasonal forecast for electricity consumption in France.

4.1. SHORT TERM ENERGY DEMAND

Day-ahead forecasts of the electricity demand are the principal tool for scheduled energy interchange and for day-ahead electricity trading. Predictor variables are calendar data and meteorological data. A short term deterministic weather forecast is transformed into a short term electricity demand forecast. The required time resolution is between 10 and 30 min and the lead time is typically 1 day.

As a first example we present results of a prediction model for a day-ahead electricity demand for a region in France. As predictor variables the model uses the day of the week, public holidays and bridge days, school holidays, daylight saving, and hourly temperatures. Furthermore the model uses an autoregressive term to capture internal inertia which is important when heating plays an important role.

Data were available for a period of 11 months from January to the end of November. The model was trained from January to October and the forecast skill of the model was tested for November. The test was carried out as if the model were used in daily operational mode. Each day the model was trained using all available data up to “yesterday” and a forecast for “tomorrow” was carried out. However, instead of predicted meteorological data we used observed values. Thus the test represents a real operational forecast situation but with “perfect” meteorological forecasts.

In a second test we trained the model only once using data up to the beginning of the test period and all predictions during the test period were carried out with the same frozen model (see Figure 5). The black line represents the observed hourly electricity consumption. The dashed and the dotted line show the forecast results with the daily updated model and with the frozen model, respectively. The differences between the two forecasts are not big, but with the exception of a few days, the updated model (dashed line) systematically outperforms the frozen model slightly. The root mean square errors of the updated and of the frozen model are 2,002 and 2,062, respectively. The explained variances over the test period of the updated and the frozen model are 91.4% and 90.7%. These differences are not big, but in all cases we have tested the updated model systematically outperforms its frozen counterpart.

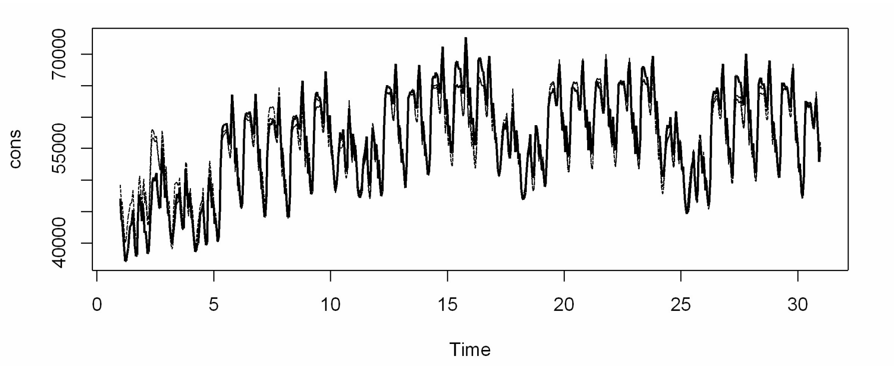

Figure 5. Observed hourly electricity consumption (solid bold) over a month, prediction with daily update of training (dashed) and prediction with frozen model (dotted). The x-axis represents the day of the month, the y-axis shows the consumption; the units are of no relevance.

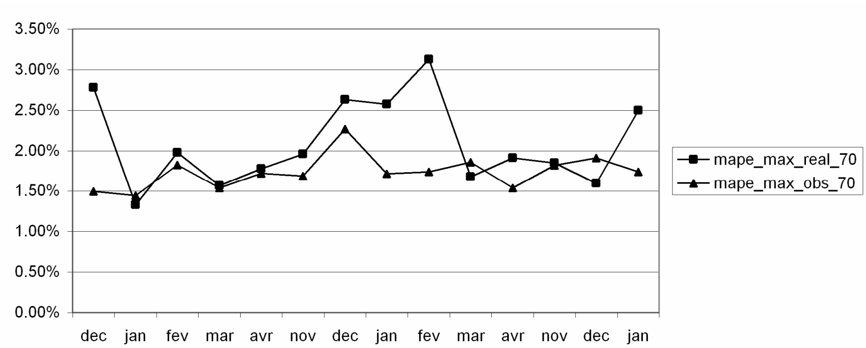

Figure 6. Monthly mean average percentage error (MAPE) for the operational forecasts (squares) and the results of the monthly control run (triangles); only the months December to April (cooling period) are presented for the period December 2006 to January 2009.

Our second short term prediction example emphasises the importance of quality control of the input data and of their consistency. This model is in operational use and it provides a prediction of peak electricity load every week day at 8.30 local time for a city in the southern hemisphere tropics with about 150,000 inhabitants. The major part of electricity consumption is due to air-conditioning and cooling (supermarkets, breweries, etc.). The outside temperature is of course the most important predictor variable but wind speed plays also an important role: for a given temperature the peak load during the day is significantly higher at low wind speed. The model uses observed temperatures and wind speed and observed electricity consumption up to 8.00 local time and a prediction for the maximum temperature during the day. The forecast system is run fully automatically. Each Monday the input data of the previous week are manually quality controlled. The model is re-trained every day. Thus for the daily training the operational model uses quality controlled data up to week-1 and non-quality controlled data during the current week. Once a month a control run for the previous month in quasi operational mode, i.e. with a daily updated model, is carried out. In contrast to the operational forecast this control run uses only quality controlled data and instead of predictions for the daily maximum temperature it uses the observed maximum temperature. A comparison of the results of the control run with the operational forecasts allows quantifying the combined negative impact of errors and inconsistencies in the data and of the forecast error for the daily maximum temperature (see Figure 6).

In most cases the error measures for the operational forecast (squares) and for the control run (triangles) are quite close together. In these cases the discrepancy between the two can be mainly attributed to the meteorological forecast error for the daily maximum temperature. But there are also periods when the difference between the operational forecast and the control run is very significant. In those cases we could trace the reason back to inconsistencies and errors in the data that were used for training. Especially in February 2008 the difference between operational forecasts and the control run was very substantial. The error of the operational forecast was almost twice as big as the error of the control run. The reasons were missing meteorological data and occasional inconsistency in the temperature data. This example emphasises how important the quality of the input data can be.

4.2. SEASONAL FORECASTS

Seasonal forecasts cover lead times from a few weeks up to a few months. Grid operators, energy traders, carbon traders and energy distributors show increasing interest in this type of forecasts. In contrast to short term forecasts medium range energy forecasts do not aim at predicting individual events. The goal is to forecast changes in the probability distribution of certain events. The most promising approach is to transform probabilistic climate forecasts into probabilistic energy demand forecasts and to apply probabilistic skill score measures and decision making methods (e.g. relative operating characteristics). We ran a comprehensive study together with

Electricité de France (EDF) on the predictability of electricity demand in France on seasonal time scales.

The skill of seasonal temperature forecasts in Europe is known to be relatively low, but it is nevertheless significantly better than zero (e.g. Dutton, this volume). In this study we investigated whether this weak signal can be exploited to predict quarterly anomalous electricity consumption in France. Over a period of 42 years (1960 to 2002) temperature anomalies of individual members of seasonal ensemble predictions over France of the DEMETER project (www.ecmwf.int/research/demeter) were transformed into predictions of the electricity consumption. Each prediction covered a lead time of 6 months and the ensemble predictions were initialised beginning of February, May, August, and November of each year. The transfer model was based on the MARS algorithm. The data – meteorological data and consumption data – were homogenized to ensure a coherent data set over the whole 40-year period. As "observational" meteorological data we used a combination of ERA-40 re-analyses (www.ecmwf.int/research/era) for the period 1960–2001 and of the operational ECWMF analyses for 2002. To obtain seasonal forecasts that are coherent with our observational data we computed predicted temperature anomalies with respect to the Demeter climatologies. These anomalies were then added to the climatology of our "observational" data.

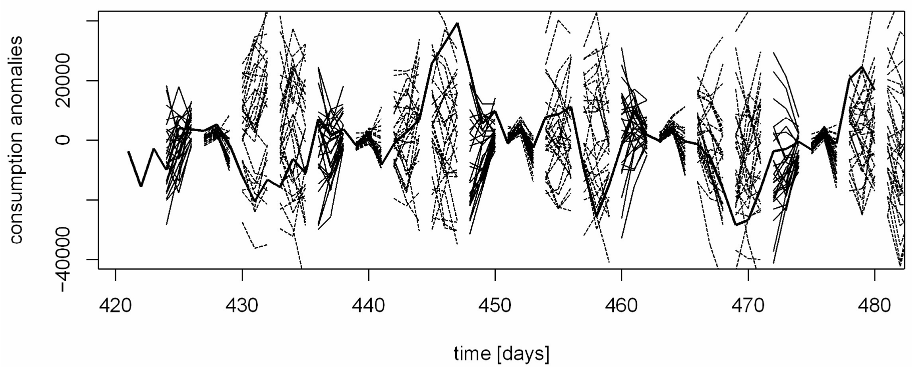

Figure 7. Individual forecast ensembles over an arbitrary period of 5 years, representing the verification periods L1 to L3 for forecasts initialized in February (solid), May (dashed), August (dotted), and November (dash-dotted). The bold line represents a 3-months running average of the observed electricity consumption anomaly.

The transfer model was run with a daily time step, thus fully taking into account the calendar data. For the skill verification daily results were averaged over 3 months. The first month of the forecasts was not used. This yields for each ensemble forecast three verification periods, covering lead times from 2–4 months (L1), 3–5 months (L2), and 4–6 months (L3).

In Figure 7 the individual forecast ensembles, averaged over 3 months are shown. Each thin line contains three points, representing the verification periods L1 to L3. We can see a strong seasonal signal of the forecast quality. The predictions launched in May (dashed) follow very closely the observed data; whereas those initialised in November (dash-dotted) hardly show any predictive skill. This subjective assessment is confirmed by objective probabilistic skill measures (Figure 8).

We used the relative operating characteristics (ROC) to measure the skill of our probabilistic forecast system. The diagonal in the graphs above represents the performance of a forecast system with no skill (i.e. pure chance). The thin curves represent the skill measured over the L1 verification period for different events (see Figure caption). The further these curves are above the diagonal, the better is the performance of the forecast system. The ROC curve of a perfect forecast system would start at the lower left corner (0,0), hit the upper left corner (0,1) and go straight to the upper right corner (1,1).

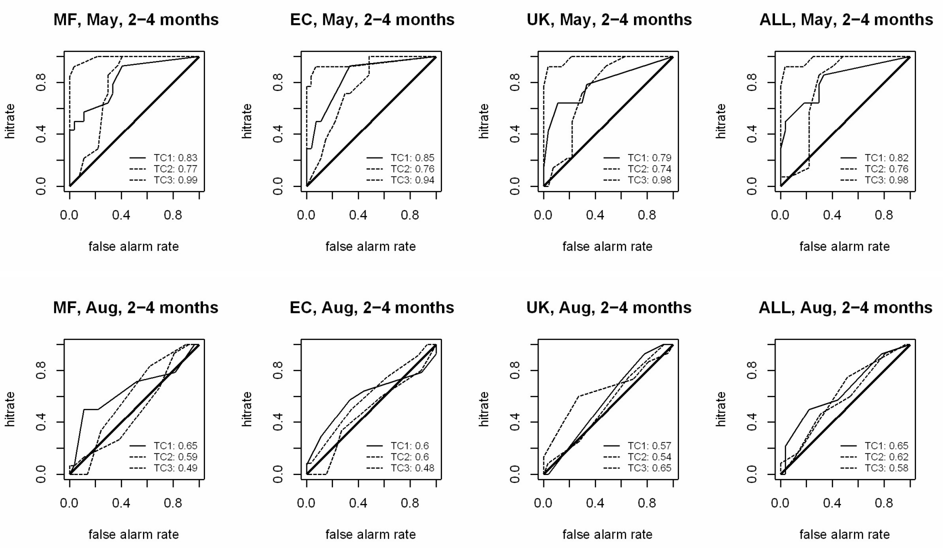

Figure 8. ROC curves for 2 to 4 months lead time for forecasts initialised in May (upper panel) and August (lower panel) using the seasonal climate forecasts from Météo France (MF), the European Centre (EC), the UK Met Office (UK) and a combination of those three (ALL). The events tested were consumption in the upper tercile (TC1), middle tercile (TC2), or lower tercile (TC3). The numbers in the legend represent the area under the ROC curve.

As we can see the forecasts launched in May are not far away from a perfect forecast system. This is easily understood by the fact that during the verification period for those forecasts (June to August) the temperature anomalies play only a very minor role and the most important factor is simply the number of working days during the verification period. Since the number of working days is perfectly predictable the energy consumption forecasts for that period show an extremely high skill. One must keep in mind that the period we analysed ends in 2002. Up to the year 2003 the number of air conditioning systems in France was relatively low and hence the electricity consumption did not change much as a function of temperature in summer. However, this has dramatically changed since summer 2003 which was extremely hot in France and other parts of Europe.

For the forecasts initialised in August the situation is different. The verification period (2–4 months lead time) is September to November, and during this period the temperature strongly influences the electricity consumption. Thus the uncertainty in the seasonal temperature predictions is transferred to the energy demand prediction. Nevertheless we still observe ROC curves that are clearly above the diagonal, which means that the use of seasonal forecasts to estimate electricity consumption in France provides some gains also in autumn. During spring and winter the skill is comparable to the skill in autumn (not shown here).

5. Difficulties Related to Meteorological Data

In the previous sections we showed how meteorological information is transformed into energy consumption forecasts. A statistical model is trained on historical data to obtain a quantitative relationship between influence variables (amongst others meteorological data) and energy consumption. This relationship is then used to transform meteorological forecasts into energy consumption forecasts.

The importance to use time series of meteorological data that are coherent in time is evident. Furthermore it is equally important to use forecasts that are coherent with the data that were used to train the statistical model. A difference of statistical characteristics between historical data – that were used to train the energy model – and the forecast data – that are to be transformed into an energy prediction – will immediately translate into a change of the statistical characteristics of the energy forecast relative to the observational energy data. Since we are dealing in most cases with non-linear transfer models the effect of inconsistencies in the input data onto the prediction result is difficult to estimate. We found the strongest negative impact of this type of error in wind energy production models and in models to predict peak load.

To avoid such inconsistencies we usually train the statistical energy model with analysed meteorological data, obtained from the same numerical model that is used to produce the meteorological forecasts. With this approach we may loose some local information that could be obtained from in situ observations, but at least the characteristics and the error structures of the data used during the training process are coherent with those used to produce a prediction.

In the case of wind energy production modelling, we combine the actual production model with a spatial downscaling model. In a first step the wind data from a numerical weather model are statistically downscaled to the location of the wind farm and these downscaled data are then used in the production model. To ensure coherence between training and prediction, this procedure is applied in the same way to the training period (with analysed data) and to the prediction period (with predicted data).

6. Summary and Conclusions

Energy demand depends on different types of influence variables. These include calendar data, meteorological data and economic variables. Depending on the time scale one is interested in, the relative importance of each data type changes. On short to long range time scales, ranging from hours up to 1 year, the most important influence factors are the calendar data (day of the week, public holidays, vacation, …) and the meteorological data (temperature, solar radiation, wind speed, humidity, …).

Since there are no fundamental physical laws that relate energy demand to the influencing factors it is necessary to use statistical models to simulate and to predict energy demand. Such models are trained on historical data. The resulting relationship is then stored and it can be used to transform predictions of the influencing variables into predictions of energy demand. A wide variety of statistical methods is used in the energy sector and we gave a brief description of the most commonly used, together with their respective advantages and disadvantages.

We pointed out the importance of the coherence of meteorological time series, used in energy demand models. Changes in the statistical characteristics of such time series translate directly into changes in the results of the energy demand models. Our experience shows that many users of meteorological data sets in the energy sector are not aware of this problem. They mix in-situ observations and numerical model output without any correction. It would be a big help for the users in the energy sector to provide data sets such that historical data and prediction data are as coherent as possible:

- Short time scales: Provide data sets such that historical data and predicted data are coherent. They should be produced with the same numerical model in analysis mode and in forecast mode. In a second step these data sets could be run through a statistical adaptation process to make them even coherent with in-situ observations. These data sets should be updated at least once a day and the time resolution should be at least 3-hourly.

- Long range: Provide re-analysis data sets. The reanalysis should be continued in near real time. Statistical adaptation and coherence between reanalysis/analysis and forecasts (from short term to seasonal) probably can be left to the user. These data sets are probably mainly used by experienced users who have a sufficiently strong background in climate analysis to adapt the data to their specific needs.

These two steps would facilitate the use of meteorological data sets for energy sector operational needs.

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CAN WE TRUST LONG-RANGE WEATHER FORECASTS?

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Abstract. Long-range weather forecasts are widely used in the energy industry, but too often their properties and limitations are not understood well enough. This chapter reviews the characteristics, methods and reliability of long-range weather prediction, and makes recommendations regarding its use. Despite their limited skill, long-range forecasts can still be a valuable tool for managing weather risk provided the necessary caution is exercised.

Keywords: Long-range weather prediction; seasonal forecast; weather risk management; energy weather; weather forecast quality

1. Introduction

What does 'long range' actually mean in weather prediction? In the energy sector, the appellation 'long range' commonly refers to time horizons of one to several years. In weather prediction however, the definition of 'long range' is based on the notion of atmospheric predictability. Figure 1 shows the skill of eight competing forecasts of daily average surface temperatures at one location (London Heathrow, United Kingdom) produced by purely atmospheric (i.e. the evolution of oceans is not predicted) numerical prediction models. In this case, skill is measured in % through comparing the accuracy (errors) achieved by the forecasts with that obtained using seasonal normal temperatures obtained from climatology through the period considered (6 months). Positive (negative) skill means that the forecasts are more (less) accurate than simple seasonal normal temperatures.

It can be seen that in this case none of the forecasts on Figure 1 has positive skill beyond day 9. With other weather variables like surface wind speed or daily accumulated precipitation, forecast skill usually drops faster than with daily average surface temperature. In all cases though, information

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on the initial state of the atmosphere at the start of the forecast fades away rapidly as a result of inexorable error growth and contamination. Because of this 'memory loss', exact knowledge of the atmosphere's initial state becomes irrelevant after about 2 weeks or less depending on the degree of predictability of the situation, and as a result predictions of daily weather fluctuations produced by atmospheric models are not more accurate than long-term climatology.

However, persistent forcing from the Earth's surface can have long-term effects on the *average* state of the atmosphere, like e.g.:

- The patterns of sea-surface temperature anomalies in the North Atlantic (North Atlantic Oscillation tripole), in the tropical Pacific (El Niño/La Niña), or in the North Pacific (Pacific Decadal Oscillation)
- The extent of snow cover over Eurasia

Some predictability of average weather conditions can therefore be gained by including these non-atmospheric factors in the forecast. The *long range* refers to time horizons from one to several months (e.g. seasonal) where average weekly or monthly weather conditions still enjoy some predictability. The *short* and *medium ranges* refer to time horizons of 1–2 days and from 2 days to 2 weeks, respectively. In these ranges, transient weather systems such as storms, fronts and anticyclones can be predicted by models, but uncertainty as to their intensity and timing increases rapidly. Because of this, it is more suitable to communicate forecasts using confidence intervals or probabilities, more particularly so in the medium range and beyond. The transition time window between 2 weeks and 1 month is often designated as *extended medium range*. Climate forecasts attempt to predict the response of the earth climate system to long-lasting environmental changes such as global increases in greenhouse gas concentration in the atmosphere and the depletion of the tropical rain forest. They look at time horizons from one to several decades. Although these forecasts are becoming increasingly relevant for long-term decisions in the energy sector (see e.g. EP2, 2008), climate prediction will not be considered in this chapter.

In order to correctly interpret and use the information provided by long-range forecasts, users of these products should be well aware of what makes them inherently different from the more common short- and medium-range forecasts. These differences are highlighted in Table 1.

The reader should always keep in mind that the purpose of long-range forecasts is definitely not to predict the weather that will be observed at some distant time in future (e.g. on some day next month) in future. Its goal is rather to enlighten the user on a range of plausible weather scenarios which

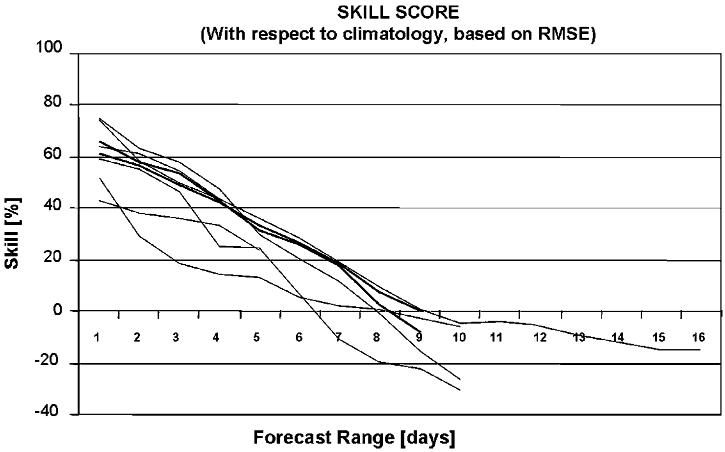

Figure 1. Skill scores of a set of eight competing forecasts of the daily average temperature at London Heathrow. Positive (negative) skill scores indicate that the forecasts are more (less) accurate than long-term climatology. Accuracy was measured by calculating root mean squared errors (RMSE).

are consistent with observed or projected patterns of temperature anomalies above the earth surface. In order to better appreciate the limitations of long-range forecasts, is also important to have a smattering of how such forecasts can be produced. The main techniques used in long-range weather prediction are discussed and exemplified in Section 2. Issues with long-range forecast communication and skill will be examined in Section 3 and Section 4 is devoted to conclusions and recommendations.

2. Outline of Methods for Long-Range Weather Prediction

There is no space in this chapter to discuss the many methods available in detail, but these can be classified in three basic categories: the method of analogues, statistical models and dynamical models.

2.1. THE METHOD OF ANALOGUES

2.1.1. *Method*

This method is the cheapest and quickest to realise, which explains why it is also the most popular approach to produce a view on the weather in the long-range. Basically, it consists of selecting past situations that were similar initially to what is currently observed and see what sort of scenarios unfolded in the weeks/months that followed. It can be seen as a 'naïve' form of ensemble forecasting using past observed scenarios as members. The method of analogues can somehow be paralleled with an experienced forecaster making inferences on future weather based solely on cases from the past and not on dynamical or physical thinking. Mechanisms like ocean-atmosphere interactions are not described statistically or explicitly by means of a model, but are believed to be included implicitly in the past scenarios themselves. This method is therefore essentially empirical. Of course, statistical techniques may be used to detect/enhance any interesting pattern(s) and/or summarise the results, e.g. cluster analysis (i.e. group scenarios into possible families) or extract mean, percentiles or anomalies from the distribution of scenarios.

TABLE 1. Comparison of short- and medium-range forecasts vs. long-range forecasts.

Short and medium range	Long range
Transient weather systems (e.g. storms, fronts, anticyclones) have some predictability	Transient weather systems are no longer predictable
Forecasts are able to pick up the day-to-day variability of weather variables (temperature, pressure, wind speed and direction, precipitation, etc.)	Forecasts predict overall/average conditions or a range of possible outcomes over an extended period of time (month, season)
Deterministic (one single scenario only) and probabilistic (distribution of possible scenarios, confidence intervals for predicted values of weather variables)	Should be probabilistic
The *surface* of the ocean is important, but its state evolves very slowly and does not change significantly over the forecast period (only the atmosphere does)	The state of the ocean changes and must be predicted *over a significant depth*. In order to achieve this, coupled ocean-atmosphere models are used instead of purely atmospheric models
Intensive quality control is made possible by the availability of frequent forecasts and observations, and by the existence of many established verification methods	Quality assessment is more problematic due to reduced forecast/observation frequency and less suitable verification methods
'Mature' operational models	'Young' models with limited track record, often experimental

The main criticism that can be made against the method of analogues is that usually it does not contain a scientific understanding on the mechanisms involved in the forecast. This absence of model constitutes a severe limitation to forecast improvement. Another weakness of the method is that it is heavily dependent on what is meant by ‘similar’. Furthermore, when selecting analogues, some balance must be found between two antagonistic constraints: the sample of analogues must be sufficiently large and at the same time the analogues must be close enough. The criteria used to choose the analogues as well as the sample size should always be mentioned when communicating the forecast.

2.1.2. *Example*

An example of forecast obtained through the method of analogues and its verification are presented in Figure 2. The divisional temperature dataset from the US National Climatic Data Centre (NCDC, 1994) was used in this case. The map on the left shows the distribution of mean surface temperature anomalies (in °F) predicted over the United States for the winter of 2008–2009 (from December to February, or DJF). This forecast was made at the end of August 2008 using 11 past cases with similar neutral to weak El Niño conditions between 1950 and 2007. The plotted mean anomalies suggest that, on average, such conditions are consistent with a cooler regime across the north and eastern half of the United States and possibly a warmer regime over central areas.

The map on the right shows the mean surface temperature anomalies that were actually observed during the winter of 2008–2009. The sign of observed anomalies was predicted correctly over the north, much of the northeast, and over some of the central of the US. However, the sign of the anomalies was not well predicted over the south and much of the southeastern quadrant (expected negative, observed positive). Note that the

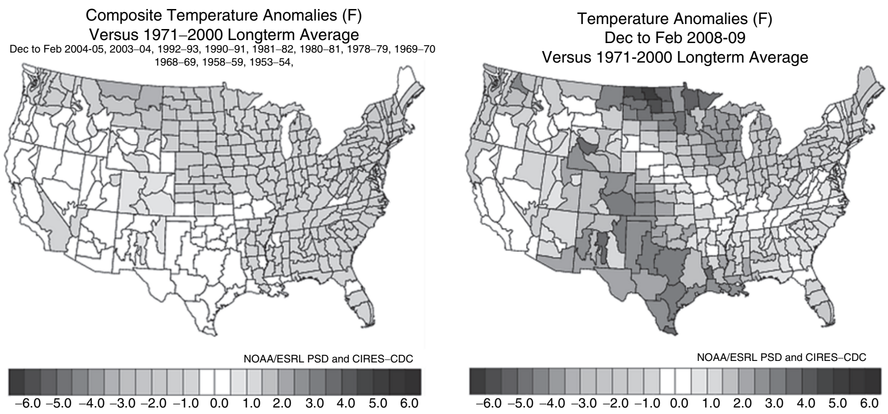

Figure 2. Mean surface temperature anomalies over the continental United States as predicted by the method of analogues (*left*) and observed (*right*) for the winter of 2008/09. Source: NOAA/ESRL Physical Sciences Division.

predicted mean anomalies are often quite small compared to the observed. This is mainly due to the averaging process over all 11 cases, which smoothes out extremes. Users should be aware that forecasts obtained through averaging a number of scenarios (e.g. ensemble mean) typically under-predict significant anomalies. Because climate is not stationary, it is also important to specify which reference climatology has been used. In this case, the mean temperature anomalies were calculated relative to 1971–2000 long-term averages.

As mentioned earlier, a significant drawback of the method of analogues is that it is a kind of 'black box' that does not 'explain' the forecast. The forecasting methods discussed below use models to overcome this problem.

2.2. STATISTICAL MODELS

2.2.1. *Method*

Variations in average weather conditions can be forecasted quantitatively using statistical relationships between one or a set of several chosen explanatory variables (predictors) and a dependent variable to be predicted (predictand), e.g.:

- Use sea-surface temperature (SST) anomalies in the North Atlantic and/or the extent of the snow cover over the North-American and Eurasian continents to predict the state of the North Atlantic Oscillation (NAO) during the following winter (Rodwell and Folland, 2002; Saunders and Qian, 2002; Saunders et al., 2003).
- Use the states of the Atlantic Multidecadal Oscillation (AMO), the Quasi-biennial Oscillation (QBO) and El Niño Southern Oscillation (ENSO) to forecast the frequency and intensity of Atlantic hurricanes (Klotzbach, 2007).

The main advantage of statistical models is that they can offer a scientifically sound methodology to produce long-range forecasts that is still relatively cheap to develop, maintain and run. Another significant advantage is that many of these models are documented and discussed in the scientific literature. Their focus is mainly regional (e.g. Western Europe, North America).

The significance and physical interpretation of statistical relationships must be treated with particular care. For example, measures of association like correlation do not necessarily imply causality. A good statistical model should contain statistical relationships that reflect connections or links believed to take place between key physical processes.

A point worth noting about the statistical modelling approach is that it is essentially based on linear thinking whereas weather and climate processes are subject to non-linear interactions. Dynamical models, which are more suitable to deal with non-linearity, will be dealt with in the next subsection.

2.2.2. *Example*

Winter climate over the North Atlantic and European sector is modulated by a phenomenon known as the North Atlantic Oscillation (the NAO, see http://www.ldeo.columbia.edu/NAO/, for more details). In the United Kingdom, the Met Office has used a statistical model that uses the SST anomaly pattern over the North Atlantic in May to predict the average state of the NAO for the next DJF winter (Rodwell et al., 1999; Rodwell and Folland, 2002). In November 2005, the onset of a cold spell in Europe triggered a considerable rise in UK wholesale gas prices. The main factor which had made energy markets particularly sensitive was the expectation by the Met Office that a negative phase of the North Atlantic Oscillation (NAO) would favour colder-than-usual conditions in northwest Europe over the winter. The Met Office had stated that their system was able to correctly predict the sign of the NAO two times out of three, which is a slight advantage over random guesses. For instance, one might reasonably expect that a prediction based on tossing a coin will be correct roughly 50% of the time. The dashed line in Figure 3 shows all Met Office (UKMO) hindcasts/forecasts of the winter NAO index from 1948/49 until 2008/09 (61 consecutive DJF winters). The solid line shows the observed indices. It can be seen that the sign of the NAO index was correctly predicted for the winter of 2005/06 (larger circles), though the expected amplitude (–0.86) was twice as large as the observed (–0.42). Despite this apparent success, there are also some winters where the UKMO forecast fails badly. The predictions appear to follow the same trends (low-frequency signal) as the observations, but there is no convincing evidence that they manage to capture the year-to-year variability (high-frequency signal) of the observed indices. Therefore, the claim that the Met Office statistical model provides a useful forecasting advantage is questionable.

Alternative forecasts of the winter NAO index are shown in Figure 4. These forecasts were not produced using a statistical model, but much more simply by predicting the moving average of the observed NAO indices of the two most recent winters (MA-2). Mathematically, MA-2 is good for picking up the trends in observed NAO indices while being unable to realistically reproduce their variation from 1 year to the next. For the winter of 2005/06, the negative sign of the NAO index is also predicted correctly by MA-2, but more accurately (–0.24) than by UKMO.

The statistics presented in Table 2 compare the performances of the two forecasting systems over the period 1950/51–2008/09. The reader is referred to Jolliffe and Stephenson (2003) for an exhaustive discussion of the verification metrics used. The results suggest that the Met Office statistical model does not really provide a clear advantage because the forecasts it produces do not perform better than those obtained through a simple moving average.

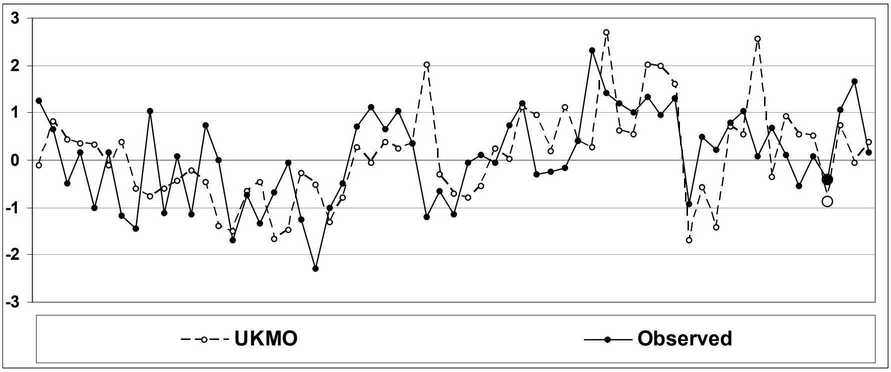

Figure 3. Time series of observed (solid line with black circles) and UK Met Office predicted (dashed line with white circles) winter NAO indices from 1948/49 (first on the *left*) until 2008/09 (last on the *right*). The larger circles to the right highlight the winter of 2005/06. Source: UK Met Office.

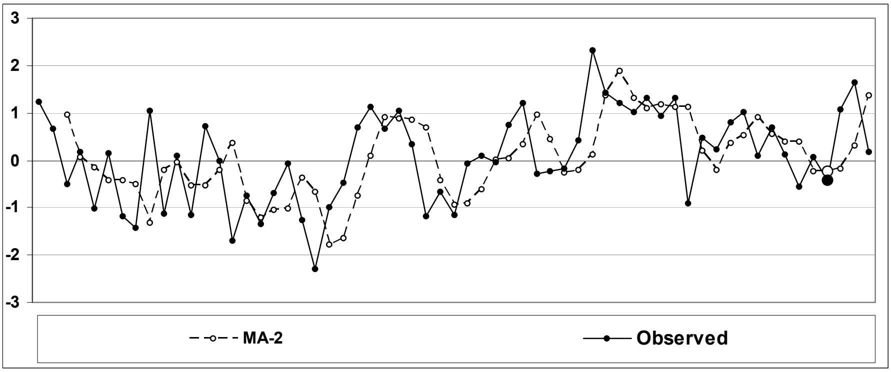

Figure 4. Time series of observed (solid line with black circles) and MA-2 predicted (dashed line with white circles) winter NAO indices from 1950/51 (first on the left) until 2008/09 (last on the right). The larger circles to the right highlight the winter of 2005/06.

TABLE 2. Performance statistics of the winter NAO index forecasts produced by the Met Office statistical model (UKMO) and by moving averages over two winters (MA-2). The scores that perfect forecasts should achieve are also indicated (Perfect) to facilitate interpretation.

Predicted attribute	**Verification metric**	**Perfect**	**UKMO**	**MA-2**
Sign	Proportion of correct forecasts	100%	68%	69%
Sign	Odds ratio skill score	1.00	0.63	0.68
Sign and amplitude	Mean squared error	0.00	1.07	0.89

2.3. DYNAMICAL MODELS

2.3.1. *Method*

This 'number-crunching' approach, which has been made possible thanks to the availability of ever more powerful supercomputers, consists of running numerical simulations of global coupled ocean-atmosphere models. These very complex models attempt to mimic the behaviour of the atmosphere-ocean system in a way that is consistent with the laws of physics. Because of all the technology and research efforts involved, this method is by far the most expensive. However, it also offers the greatest scope for improvements as models get more sophisticated. Much work has been done recently to obtain better simulations of key patterns such as El Niño and the Madden-Julian Oscillation. Long-range forecast models are mainly developed, run and maintained by national or international weather agencies in collaboration with academic institutions.

Given the considerable levels of forecast uncertainty present in the long range, producing one single forecast from one model does not make much sense. Instead, ensembles of forecasts are run, each individual member starting from slightly different initial conditions (different dates). Ensembles run from different models (a.k.a. multi-model ensembles or super-ensembles) like EUROSIP attempt to gauge the additional uncertainty due to model imperfection. The resulting forecast distribution provides quantitative information on forecast uncertainty that can be translated e.g. in probabilities or confidence intervals. The horizontal resolution of long-range forecast models is coarser (>100 km) than that of short- and medium-range forecast models (<100 km), so downscaling techniques are required for regional applications and extremes (e.g. weather generators).

Dynamical models and associated methods are extensively documented in the peer-reviewed scientific literature.

2.3.2. *Example*

Tercile probabilities are commonly used to summarise the forecast distribution in a way that is relevant to users in the energy sector. Each temperature forecast falls in one of three climatologically equiprobable categories labelled as 'below normal' (the lowest third of the climate distribution), 'above normal' (the upper third of the climate distribution), and 'normal' in-between. Probabilities of terciles can then be estimated from the proportion of forecasts counted in each of these categories. The seasonal forecasting system of the European Centre for Medium-range Weather Forecasts (ECMWF) routinely produces probabilistic forecasts of terciles for the monthly mean temperature out to a horizon of 7 months. The performance of these forecasts over Southern England has been gauged for all three terciles from a set of 252 hindcasts. The statistic used in this case is the ROC skill score (ROCSS). This metric measures the overall ability of the forecasts to discriminate between event and non-event (maximise the hit rate and minimise the false alarm rate). The score is 1 for perfect forecasts (hit rate of 100% and false alarm rate of 0%), and 0 for forecasts that are not more informative than climatology (i.e. always forecasting a probability of 33% for each tercile). Once again, the reader is referred to Jolliffe and Stephenson (2003) for more details on the ROCSS. The results shown in Figure 5 indicate some modest skill in the first month, which dwindles rapidly at longer lead times.

3. Current Issues with Long-Range Weather Forecasts

The examples given in Section 2 prompt to some issues with the communication of long-range weather forecasts as well as in the interpretation of their skill.

3.1. COMMUNICATION OF FORECASTS

Weather forecasts should always be presented to users in formats that are fit for purpose. Long-range forecasts are inherently uncertain and so the level of confidence that can be placed in them constitutes crucial information to the decision maker. Forecast uncertainty can be conveyed to users by means of confidence indices, confidence intervals and probabilities. The forecast and its uncertainty must preferably be quantified so that the user can assess their quality in an objective manner. In spite of this, a large number of long-range forecast products available on the markets are based on a single consensus scenario (e.g. the case presented in Section 2.1) with no or little verifiable information on uncertainty or on alternative scenarios. Users

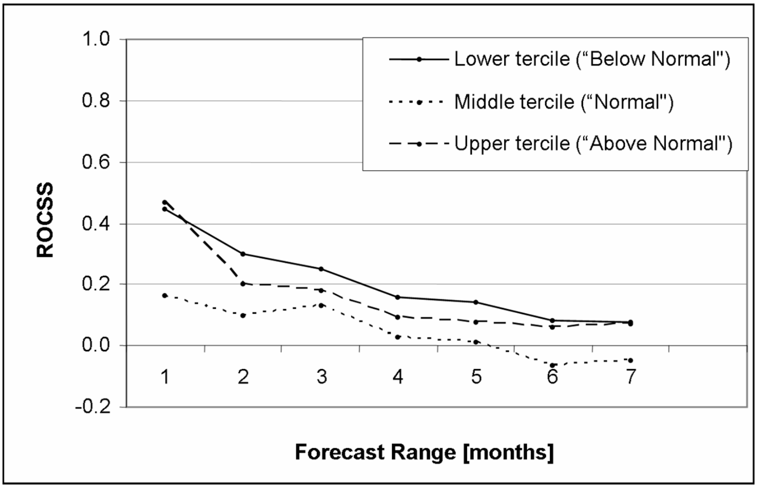

Figure 5. ROC skill scores of a set of 252 ECMWF probabilistic seasonal hindcasts of terciles for the monthly mean temperature over Southern England out to 7 months.

should also keep in mind that consensus scenarios are typically obtained through averaging, so they tend to under-forecast or even remove significant events that can be detected in the scenarios that have been averaged to produce the consensus.

In a risk management perspective, probabilistic products offer more value because they allow users to treat forecast uncertainty as information that allows economically optimal decisions (Jolliffe and Stephenson, 2003, Chapter 8). Nonetheless, many users may still be deterred by the difficulty to understand and process probabilistic information, by the negative connotation of probability implying ignorance, and by some reluctance to transfer the ‘Yes/No’ decision stage from the weather forecaster to the user (Mailier et al., 2008).

3.2. SKILL OF LONG-RANGE FORECASTS

In 2006, the hedge fund Amaranth lost $6 billion and collapsed after speculating wrongly that a very active hurricane season would disrupt the US oil production in the Gulf of Mexico with soaring natural gas prices as a result (Dealbreaker, 2006). Their bet was based on long-range forecasts published in December 2005 and April 2006 by Klotzbach and Gray (2005, 2006). The high level of confidence placed in their predictions was due to Dr Gray’s successful forecasts in 2002, 2003, 2004 and 2005. This story along with the case discussed in Section 2.2 illustrates how forecast performance results can be misinterpreted. The example of Subsection 2.2 also recalls that a forecasting system deemed skilful by meteorologists may turn out to be less attractive for practical applications. This aspect is too often neglected in the weather forecasting industry. For instance, predictions based solely on ensemble means are popular as they tend to score best in terms of accuracy because they minimise forecast errors. However, they smooth out potentially crucial features like extreme events.

Finally, the example of Subsection 2.3 demonstrates that the typical skill of long-range weather forecasts is not particularly high. All the methods tend to perform best in situations with strong persistence in sea-surface temperature anomalies (e.g. El Niño/La Niña), which is not always the case.

4. Conclusion

Because of the chaotic nature of the atmosphere, long-range weather forecasts will never achieve the same level of detail and confidence as short- and medium-range forecasts. Users in the energy sector must take this fact into account so that they can adjust their trust and base their strategies on realistic expectations. Long-range forecast products based on obscure (unpublished or undisclosed) methods should always be treated with suspicion.

Any claim of skill should not be taken at face value. The meaning of "skill" is strongly user-dependent and metrics used to assess skill should be chosen carefully so that they are appropriate for the user application. Even when the methods of forecasting appear to be scientifically sound, useful skill is often modest in the mid-latitudes, particularly so in Europe. However, the limited reliability of long-range forecasts should not discourage their users in the energy sector. Indeed, careful usage of these forecasts can still make them a valuable tool for managing weather risk, and meteorologists need feedback from energy users in order to make these forecasts more useful for industrial applications.

ACKNOWLEDGEMENTS

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STORM PREDICTION RESEARCH AND ITS APPLICATION TO THE OIL/GAS INDUSTRY

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Abstract. The accurate prediction of storms is vital to the oil and gas sector for the management of their operations. An overview of research exploring the prediction of storms by ensemble prediction systems is presented and its application to the oil and gas sector is discussed. The analysis method used requires larger amounts of data storage and computer processing time than other more conventional analysis methods. To overcome these difficulties eScience techniques have been utilised. These techniques potentially have applications to the oil and gas sector to help incorporate environmental data into their information systems.

Keywords: Storm tracks; ensemble prediction system; eScience; oil and gas industry

1. Introduction

Storms are a major natural hazard, causing vast amounts of damage and loss of life around the globe (see below). It is therefore vital that they are predicted accurately by Numerical Weather Prediction (NWP). The quality of the forecasts is improving all the time, because of very large worldwide investments in supercomputing and in satellite technologies for new global observing systems. How can the results of these investments be used profitably by the oil and gas sector?

High quality forecasts of severe weather are essential to the management of oil/gas operations both on and offshore. In 1982 a North Atlantic storm, known as the Ocean Ranger Storm, caused an oil rig located near Grand Banks, Newfoundland to capsize and resulted in the tragic death of the

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entire crew of 84 workers. Hurricane Katrina and other hurricanes in the Gulf of Mexico have led to repeated disruption of the oil and gas industries located there, and similar disruptions are faced regularly by operators elsewhere in the world. Accurate and up to date forecast information delivered in understandable ways to operators is therefore crucial to avoiding disasters and minimising disruption in the future.

Oil and gas consultancy Schlumberger (http://www.slb.com) have recognised the importance of accurate weather forecasts and environmental information in general. Their most recent (2008) annual report reflects the business consequences of these risks and states:

> "The prices for oil and natural gas are subject to a variety of additional factors, including: … weather conditions."

> "Environmental compliance costs and liabilities could reduce our earnings and cash available for operations."

> "Severe weather conditions may affect our operations."

Other oil and gas companies and operators note similar risks to their operations in their financial statement. Schlumberger Information Solutions (SIS, http://www.slb.com/content/services/index_sis.asp) are currently funding storm prediction research of the Environmental Systems Science Centre (ESSC), University of Reading in the UK in order to see if they can develop tools that can tailor the new information obtained from this research to their clients.

The storm prediction research being funded by SIS makes use of the storm identification and tracking software of Hodges (1995, 1999). This software has been used in numerous studies to explore both the current and future climate of extratropical and tropical storms (e.g. Hoskins and Hodges, 2002, 2005; Bengtsson et al., 2006, 2007a, b, 2008). More recently the method has been applied to forecast data to explore the prediction of extratropical storms by NWP (Froude et al., 2007a, b; Froude, 2009). The approach provides detailed information about the prediction of various properties of storms, such as their position, intensity, growth and propagation speed.

NWP models are integrated from a best estimate of the current atmospheric state, known as an analysis. This is obtained by statistically combining different types of observations (e.g. satellite, weather balloons, aircraft) with a previously obtained numerical forecast by a process known as data assimilation. Since the observations will contain errors and are unevenly distributed around the globe, an analysis will always contain errors. Due to the chaotic nature of the atmosphere (Lorenz, 1963) these errors grow rapidly throughout the forecast, making it impossible to accurately predict the weather at higher forecast times.

Recent and current work has focussed on a particular type of forecast system known as an Ensemble Prediction System (EPS), which aims to take this uncertainty into account. A set of multiple forecasts (ensemble members) are run from slightly different initial states. One of the forecasts is known as the control and is started from the analysis and the initial conditions for the other ensemble members are obtained by applying small perturbations to the analysis. Since forecast models themselves are also not perfect sometimes the model is also perturbed during the forecast integration.

The study of Froude et al. (2007b) explored the prediction of storms by the European Centre for Medium Range Weather Forecasts (ECMWF) and National Centers for Environmental Prediction (NCEP) EPS (Buizza and Palmer, 1995; Molteni et al., 1996; Buizza et al., 2007; Toth and Kalnay, 1993, 1997). It showed that the ECMWF EPS had a slightly higher level of performance than the NCEP EPS and highlighted a number of benefits ensemble prediction offers over single deterministic forecasts in the prediction of storms (such as providing early warnings). As a continuation of this study Froude (2009) explored the regional differences in the prediction of storms by the ECMWF EPS. The results of this study are discussed in Section 2 of this paper.

Current work is using the storm tracking approach to analyse and compare nine EPS from different operational centres. The data for this is being obtained from the THORPEX Interactive Grand Global Ensemble (TIGGE, http://tigge.ecmwf.int/) archive. The first objective of this paper is to present a selection of results from the above discussed work and to describe how this type of information could be useful to the oil and gas sector.

Analysing EPS data using the storm tracking software requires large amounts of data processing and storage. This motivated the use of eScience methodologies, which use distributed computing with distributed data resources to help reduce both the computation time and the storage required to perform the analysis (Froude, 2008). The second objective of this paper is to discuss how eScience techniques are being used to help with the research and how they could potentially be used to help integrate environmental information into Schlumberger's information systems.

This paper continues by describing the storm prediction research in Section 2 and is followed by a description of the eScience techniques used to perform the research in Section 3. The paper finishes with a final summary in Section 4.

2. Storm Tracks and Ensemble Prediction

In this section a brief description of how the storm tracking techniques is applied to ensemble forecast data to investigate the prediction of extratropical cyclones by EPS is given. For further details the reader is referred to Froude et al. (2007b). Some results will then be presented to illustrate the type of information that can be obtained from the method and their application to the oil and gas sector are discussed.

2.1. STORM TRACKING

For a given EPS, the extratropical cyclones are identified and tracked along the 6-hourly forecast trajectories of each of the perturbed ensemble members and the control forecasts in both hemispheres using the automated tracking scheme of Hodges (1995, 1999). Before the cyclones are identified the planetary scales with total wavenumber less than or equal to five are removed (Hoskins and Hodges, 2002, 2005) so that the cyclones can be identified as extrema without being masked by the larger scale flow. The data are also reduced to a resolution of T42, to ensure that only the synoptic scale features are identified. Vorticity features, at the 850-hPa level, exceeding a magnitude of $1.0 \times 10^{-5}\ s^{-1}$ are identified, as positive extrema in the northern hemisphere (NH) and negative extrema in the southern hemisphere (SH), and considered as cyclones. Once the cyclones have been identified the tracking is performed, which involves the minimization of a cost function (Hodges, 1999) to obtain smooth trajectories (storm tracks). Only those storm tracks that last at least 2 days, traveled further than 1,000 km and had a majority of their lifecycle in 20°N–90°N or 20°S–90°S are retained for the statistical analysis. The tracking is also performed on the analysis data of the same time period to generate analysis storm tracks to use for the verification of the forecast storm tracks.

2.2. EXAMPLE STORM

Figure 1 shows the tracks and intensities of hurricane Dennis predicted by the European Centre for Medium Range Weather Forecasts (ECMWF) EPS published in Froude (2009). We note that although this storm clearly originates as a tropical cyclone, it spends a majority of its lifetime in the extratropics and is therefore included in the extratropical analysis. There is a large level of uncertainty in the forecast of this storm as can be seen from the large spread of the ensemble forecast. For the storm's track, some of the ensemble members that lie to the left of the storms analysed track (which is shown in black in Figure 1) travel as far as the west coast of Mexico, whereas ensemble members that lie to the right travel into eastern Canada, with one almost reaching Greenland. The mean forecast storm track from the ensemble provides a reasonably accurate prediction of the storm's track, lying just a little to the left of the truth. It is also more accurate than the control forecast, which lies further to the left. One advantage of an EPS is that in general the mean forecast will provide a better forecast than the single control forecast (Leith, 1974; Toth and Kalnay, 1993, 1997).

There is also a large spread (and uncertainty) in the predicted intensity of the storm. The growth of the storm is underpredicted by the ensemble forecast, as can be seen from the slope of the mean curve compared with that of the analysis curve between day 0 and 4 in the figure. The control forecast also underpredicts the growth of the storm.

The study of Froude (2009) showed that in general storms that originate in the tropics, such as hurricane Dennis above, are more difficult to predict accurately than those that originate in the extratropics. Dynamically tropical storms are very different to extratropical storms; although they can reach far higher intensities and cause far more damage, they are much smaller in spatial scale. This makes them more difficult to predict without higher resolution models. Information concerning the difficulties and uncertainty in predicting tropical storms could be very important for managing operations in the Gulf of Mexico and similar regions severely affected by tropical storms.

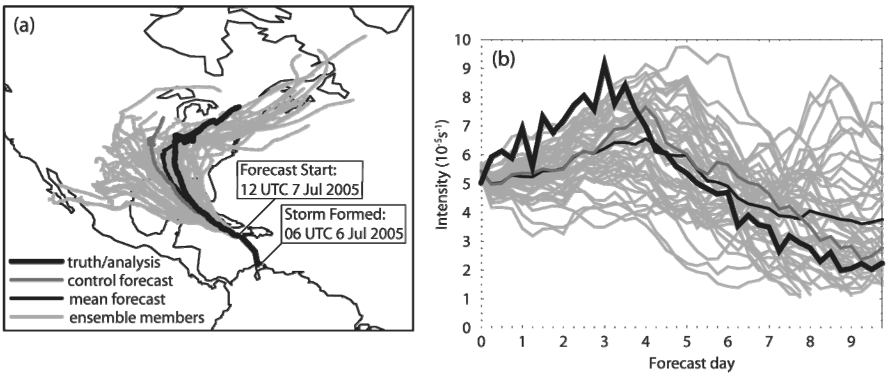

Figure 1. Tracks (**a**) and intensities (**b**) of hurricane Dennis predicted by the ECMWF EPS forecast started 1200 UTC 7 July 2005, from Froude (2009). The ECMWF analysed track and intensities are also shown (in black).

2.3. STORM PREDICTION STATISTICS

In order to generate statistics comparing forecast storm tracks with analysed storm tracks for a large number of storms it was necessary to have an automated objective method of determining which forecasted cyclones correspond to which analysed cyclones. This was achieved using a matching methodology (Froude et al., 2007a, b). For the results presented in this paper, a forecast track was said to match an analysis track (i.e. considered to be the same storm) if the following criteria were satisfied:

i) At least 60% of their points overlapped in time, i.e. $100 \times [2n_m / (n_A + n_F)] \geq 60\%$ where n_A and n_F denote the total number of points in the analysis and forecast tracks respectively and n_m denotes the number of points in time that occur in both the analysis and forecast tracks.

ii) The *geodesic* separation distance between the first four points in the forecast track, which coincide in time with the analysis track, and the corresponding points in the analysis track must be less than 4°.

The matched forecast tracks can then be used to generate statistics. In the studies of Froude et al. (2007a, b) a variety of different matching criteria were considered. Although the choice of matching criteria had a considerable impact on the number of forecast tracks that match analysis tracks, the statistics generated from the matched tracks were unaffected. In this chapter we therefore only present the results obtained with the above criteria. For further details of the matching method please see Froude et al. (2007b).

2.4. INTENSITY AND PROPAGATION SPEED BIAS

Figure 2 shows the bias in intensity and propagation speed of storms predicted by the ECMWF ensemble members, in different regions of the extratropics, for the 1 year time period of 6 Jan 2005–5 Jan 2006. For the intensity, a positive value corresponds to the storm intensity being overpredicted by the forecasts and vice versa. For the speed a positive value corresponds to the storms moving too quickly in the forecasts and vice versa.

Figure 2 shows that storm intensity is generally overpredicted by the ensemble forecasts over the oceanic regions (Atlantic, Pacific and Indian) and underpredicted over the land based regions (Eurasia and North America). The predicted speed of the storms is consistently too slow over all regions, but the bias is larger over the Atlantic in the NH. This will affect the predicted time in which a storm will strike in a certain place. In general a storm will strike earlier than predicted by the forecast. It is important that this and other biases of forecast systems are taken into account when deciding what action needs to be taken in response to the prediction of a storm. For example, suppose a very severe storm is heading directly for an oil platform/rig and the decision must be made to stop operations in preparation for when the storm strikes. If storms generally strike earlier than predicted by the forecasts, operations should be stopped some time before

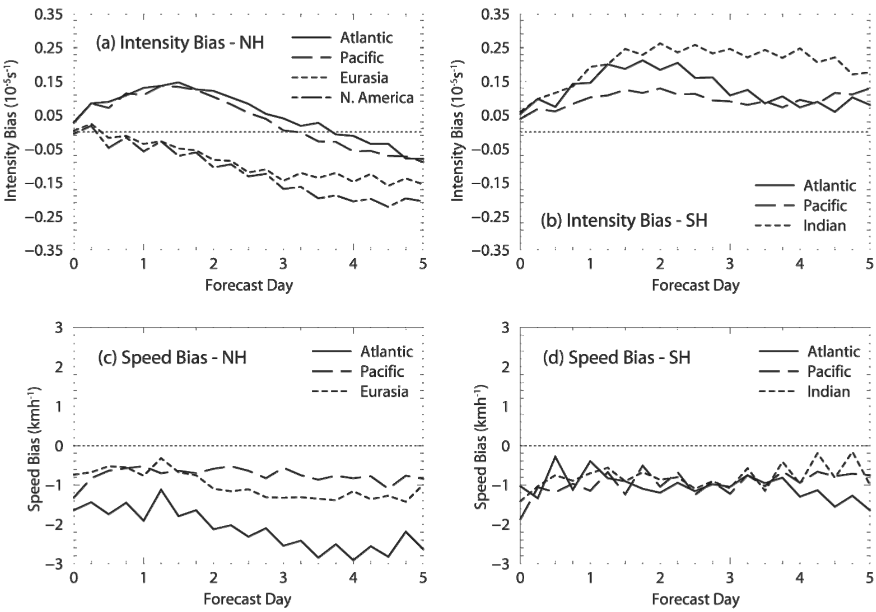

Figure 2. Bias in predicted intensity in (**a**) NH and (**b**) SH, and in propagation speed in (**c**) NH and (**d**) SH of the ECMWF ensemble members for the period of 6 Jan 2005–5 Jan 2006, from Froude (2009), for different regions.

the storm is forecast to strike. The amount of time before should depend on the size of the bias. Operations located in regions with larger biases should be stopped earlier than those in regions with smaller biases. Stopping operations is clearly very costly and so this needs to be balanced against the risk of potential damage that could be caused by an oncoming storm.

2.5. DIFFERENT ENSEMBLE PREDICTION SYSTEMS

Ensemble Prediction first became operational in 1992 at both ECMWF and NCEP (Buizza and Palmer, 1995; Molteni et al., 1996; Toth and Kalnay, 1993, 1997). Nowadays a large number of the major operational weather centres run an EPS. As mentioned in the introduction, data from nine different EPSs, obtained from the TIGGE archive, are being analysed with the storm tracking approach. Figure 3 shows the ensemble mean error in storm position and intensity for each of the different EPS for the 4 month period of 1 Feb 2008–31 May 2008. The ensemble mean error is calculated by determining the mean track/intensity from the ensemble member storm tracks and then calculating the error between this and the corresponding analysis storm track/intensity (see Froude et al., 2007b for further details). All the EPSs were verified against the ECMWF analyses so the results for

ECMWF may be subject to some positive bias in the earlier part of the forecast. In the future we hope to be able to perform the verification against analyses from the other centres, but we currently only have access to the ECMWF analyses at the 6 hourly frequency required for the storm tracking.

Figure 3 shows that there are large differences between the different EPS. In general EPS with smaller/larger errors in position have smaller/ larger errors in intensity. However, NCEP has a larger error in intensity in relation to the other EPS than it does for position. Further analysis of the TIGGE data (not shown) indicates a lot of differences in the ability of the different EPS to predict storms. For example the ECMWF EPS has a small bias to overpredict the intensity of the cyclones, whereas the UKMO has a bias to underpredict them. Like the ECMWF EPS, all of the EPSs under-predict cyclone propagation speed, although some centres have larger biases than others.

This type of information would potentially be useful to the oil and gas industry when deciding which forecast system (or systems) to use for decision making concerning operations. For example if an intense storm is expected to strike in a region where oil/gas operations are being carried out, it may be more important to know the timing of the storm to high accuracy than the exact intensity when deciding when to shut down operations. In this case it would be better to use a forecast system with higher skill in predicting the propagation speed of the storms than the intensity. If several different EPSs are used, then the question of how best to combine the information they provide in order to get the best estimate of position, intensity, timing etc. would need to be addressed.

3. Storm Tracks and eScience

As discussed in the introduction, the storm track analysis of EPS requires large amounts of data processing and storage. In this section some of the eScience techniques used to help overcome these difficulties are discussed.

Froude (2008) developed a web application to allow users to run the storm tracking software directly from a web browser with remote datasets and using distributed computing. Users are currently able to compute storm tracks from the NCEP re-analysis (Kalnay et al., 1996) and NCEP EPS (Toth and Kalnay, 1993, 1997) datasets. A list of jobs can be constructed and executed across multiple computers to reduce computation time. The progress of each job can be monitored and once completed; the computed storm tracks can be downloaded and plotted in a web browser. Froude et al. (2007b) made use of the web application to help reduce the amount of data storage required and to help reduce the computation time involved in the processing of the NCEP EPS data.

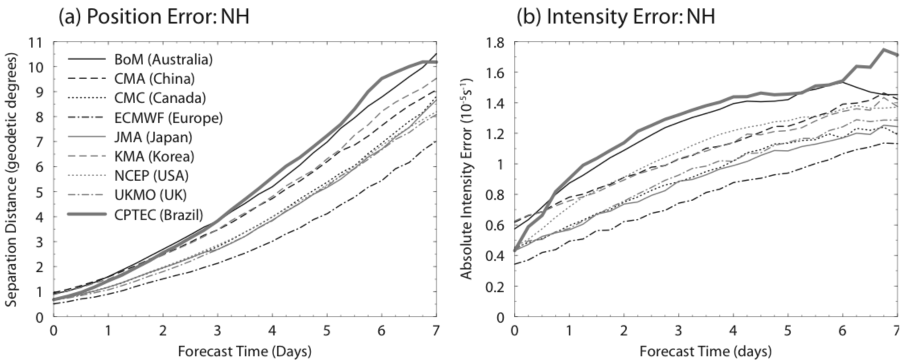

Figure 3. Ensemble mean error in (**a**) position and (**b**) intensity of storms in the NH extratropics for the period of 1 Feb 2008–31 May 2008 for the different EPS.

The web application was written using Java Servlets/Java Server Pages (Hall, 1999). It accesses the remote data using the Open-source Project for a Network Data Access Protocol (OPeNDAP, http://www.opendap.org). OPeNDAP allows data to be accessed over the Internet. OPeNDAP also has a sub-sampling facility, so that a specific part of a data file can be requested. This allows the user to download just the parts of the data they require, rather that downloading the entire data file. The storm tracking program was modified to work with OPeNDAP. It can now be used to compute storm tracks from remote datasets. The OPeNDAP sub-sampling facility is used to request specific meteorological fields and time periods requested by the user in their job list. This use of sub-setting dramatically reduced the amount of data that are needed to be stored locally. For example, the NCEP EPS data files include a large number of meteorological fields at a large number of different pressure levels. For the storm-tracking analysis only mean sea level pressure or vorticity at the 850 mb level were required. These fields are selected with the sub-sampling facility rather than downloading the entire file.

The web application allows users to submit a list of jobs to the Condor (Thain et al., 2005) pool in ESSC. Condor is a software system that manages a collection of jobs by making use of the computational power of machines over a network. Users can submit a list of multiple jobs to Condor, which chooses where and when to run them. Each job in the user's job list is submitted as a separate job to the Condor pool and is run on a different machine. This allows a much faster throughput than using just a single machine.

The NCEP re-analysis data at the Climatic Data Center (CDC) is stored in yearly files (January–December). The OPeNDAP sub-sampling facility allows users to select a time period within a given year (i.e. the same file). It is not, however, possible to select a period that begins in 1 year and ends in another (e.g. a December–February season) because the data for such a period is split across two file. To overcome this problem, the OPeNDAP aggregation server (http://www.opendap.org/server/agg-html/agg.html) was used. This is a piece of software that can be used to create aggregated datasets by effectively merging individual files so they appear as one large file. The NCEP re-analysis dataset was aggregated so that it could be treated as one large 50 year file rather than 50 smaller 1 year files. The aggregation of the data means that the user is able to run the storm tracking software with NCEP re-analysis data from any time period between 1943 and the present.

Figure 4 shows a flow chart, from Froude (2008), illustrating how the different components of the web application fit together. The user constructs a list of jobs in their web browser (labelled [1]), which is then sent to the server (labelled [2]). The server then submits this list of jobs to the Condor pool in ESSC (labelled [3]). Condor puts the jobs into a queue and then sends the jobs to different computers (labelled [4]) as and when they become available. The program accesses the data using the OPeNDAP protocol. The NCEP EPS data are accessed directly from the OPeNDAP server (labelled [6]), whereas the re-analysis data are accessed via the aggregation server at ESSC (labelled [5]). Once all the jobs have finished running the output from the storm tracking program (labelled [7]) is put onto the server for the user to download or plot. While a set of jobs are running, the user is able to check the progress of each individual job from their web browser. For further details of the web application, please see Froude (2008).

The work discussed in Section 2.4, analysing the TIGGE data sets requires even larger amounts of data storage and processing than the work of Froude et al. (2007b), which made use of the web application. These data are not available via OPeNDAP and so it is not possible to access the data remotely. However, in order to reduce the computation time of this data processing the University of Reading Campus Grid was used. This consists of a Condor pool of approximately 150 Linux machines and therefore dramatically speeds up the data processing. The importance of Condor to this work cannot be overemphasized. Without it, the data processing would have been extremely difficult with the facilities available. Condor was particularly well suited to the processing of the EPS data, since the storm tracking for each ensemble member could be performed on a different computer.

In summary, the storm tracking analysis of EPS data sets requires very large samples of data. Without the use of eScience methodologies, it would not have been possible to store and analyse such large amounts of data. We are currently working with Schlumberger to explore how storm prediction information (and other environmental information in general) can be incorporated into their information systems. This information is potentially

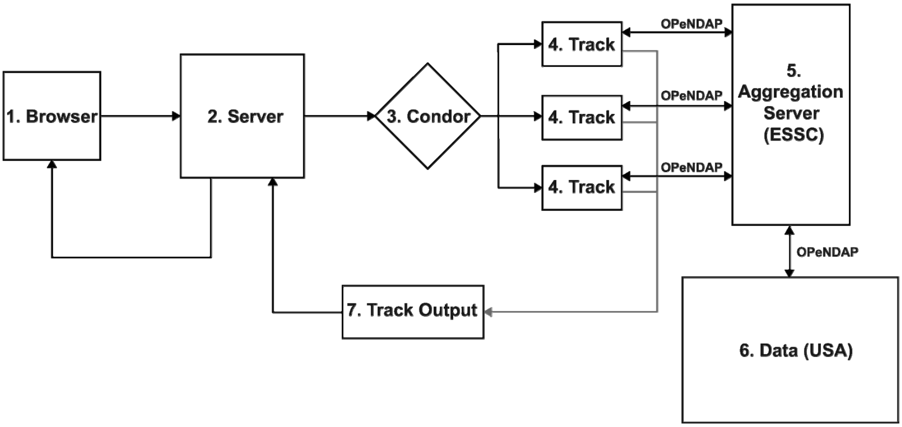

Figure 4. Flow chart to illustrate how storm tracking web application works. Adapted from Froude (2008).

very valuable to the management of operations both on and offshore. It is anticipated that the use of eScience will help with this task considerably.

The eScience technologies discussed in this section could also potentially be useful in other areas of scientific research. The TRACK web application has been used by scientists from the US Navy to study past storms using the NCEP re-analysis data. eScience methodologies, such as those used by the web application, could be useful for operational NWP. For example, distributed computing techniques such as Condor would be ideal for ensemble prediction.

4. Summary

The oil and gas sector, particularly the offshore production platforms, need accurate information on extreme events that may disrupt operations. EPS allow better estimation of extreme events, but analysis shows that there can still be biases in intensities and timing predicted by these systems. Handling the large amount of data in such EPS is also a challenge. While weather forecasts are already essential to safe offshore operations, there is a need for still better analysis of predictions and display of results if the oil and gas sector is to make optimal use of the new environmental information now available.

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WEATHER SENSITIVITY OF ELECTRICITY SUPPLY AND DATA SERVICES OF THE GERMAN MET OFFICE

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Abstract. The topics of this chapter are weather sensitivity related to electricity supply and data services of the National Meteorological Service of Germany (DWD). First, the weather sensitivities of electricity generation (thermal power plants, run-of-river power plants and wind energy plants) are shown. Then, atmospheric influences on overhead lines and underground cables, as well as on transformer and switching stations are examined. Second, the way in which the DWD supports electric companies by offering tailored data is illustrated. One conclusion of the chapter is that the inclusion of environmental parameters (like air and water temperatures, wind speeds, discharge amounts) is of great importance for a number of business actions in electricity companies. In order to ensure efficient research with useful results for electricity companies, the great amount of relevant information (from national meteorological services, planning offices, catastrophe service and as much as possible from companies) needs to be collected and compiled.

Keywords: Weather; climate change; electricity supply; data services; Deutscher Wetterdiens

1. Introduction

Electricity supply is always affected by weather and climate. Therefore, electricity companies have developed various weather and climate risk management tools over the years.

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Nevertheless the current debate about the impacts of climate change on companies has stimulated an increasing public interest concerning the weather sensitivities of electricity suppliers. The content of this chapter is to explore these sensitivities. Secondly, data services of the Deutscher Wetterdienst (National Meteorological Service of Germany; DWD) are presented for important weather parameters in order to better use these services for improved weather risk management. The purpose of this chapter is to contribute to an enhanced transfer of knowledge between energy experts and weather/climate scientists.

2. Generation of Electricity

In this section weather sensitivities of electricity generation will be identified. It is divided in the subsections thermal power plants, run-of-river power plants and wind energy plants.

2.1. THERMAL POWER PLANTS

Weather related interferences occur rarely at thermal power plants (especially coal-fired, gas turbine and nuclear power plants). Hence, the frequency of weather incidents occurs less from material loss, but rather due to several restrictions, such as a diminished operational availability. Some possible impacts are specified below with special reference to Germany (Rothstein and Parey, 2009).

2.1.1. *Water Temperatures and Cooling of Thermal Power Plants*

Thermal power plants need water for their cooling processes. In order to protect bodies of water, legal constraints regulate the water usage of every site. These water quality requirements regulate not only the supply and release but also the evaporation and the warming rate of the body of water in case of low water.

In Germany, basic principles for the assessment of cooling water released into bodies of water have been devised by LAWA[1] (e.g. the maximum allowed warming of cooling water is 10 K). Due to the ecological water protection, 28°C is the limit for cooling water release into a river. To ensure this, regular measurements are taken at every thermal power plant at 30 min intervals (EnBW, 2004).

[1] Bund-Länder-Arbeitsgemeinschaft Wasser; German Working Group on water issues of the Federal States and the Federal Government.

Climate change impacts on thermal power plants result from two possibly simultaneous reasons: legal constraints for both warming and maximum water temperatures, as well as constraints on the amount of water extracted during low water situations to ensure that a minimum discharge is maintained (Rothstein and Parey, 2009).

The cooling method has a considerable influence on the legal constraints for thermal power plants. The various restrictions are often connected and can intensify one another. In certain atmospheric conditions, problems with maximum temperature or low water situations dominate, as was the case in the winter of 2005/2006. Often, as in the hot summer of 2003 in central Europe, high temperatures and low water situations occur together. At the Neckar River (Southwest Germany) the hot summer of 2003 led to the restriction that only power plants with a cooling tower were allowed to operate (LfU, 2004).

Furthermore, the inlet and purification of cooling water at thermal power plants may be affected by weather and climate change. A low water situation can lead to a cooling water shortage in the power plant. The inlet to the corresponding building can be dredged, but this must be requested and decided on a case by case basis (Rothstein and Parey, 2009).

2.1.2. *Sufficient Water Level for Inland Navigation and Coal-fired Power Plants*

Coal-fired power plants can only be operated economically if their location is in close proximity to the coal district or if the supply of hard coal can be shipped cost-effectively via waterways. Three million tons (t) of coal is transported to the different power plants in Baden-Wuerttemberg (South-West Germany) over the Rhine River every year. In comparison with the Ruhr area (North-West Germany), Baden-Wuerttemberg has a serious disadvantage in location due to the higher transport costs of coal (WM, 2004). The risk of extreme water levels, which can degrade the reliability and security of the inland water navigation, adds to the high transport costs (Rothstein et al., 2009).

In order to point out the importance of coal transport, a power plant at the Neckar River is considered more closely. The plant needs more than 200 t hard coal per hour, which adds up to a daily use of 3,000–5,000 t of hard coal. This equals two to four shiploads a day or three to four trainloads, respectively. A trainload consists of 20–25 wagons with 1,000–1,400 t of coal in total. A cargo ship on the Neckar can transport around 1,200–1,600 t. Seventy percent of the coal to the power plant arrives by cargo ship and 30% by train; in the future, however, ships will take a more dominant role. Because of high costs, truck transport is generally not suitable for coal supply (Rothstein and Parey, 2009).

Water-levels have always changed due to climate variability. The debate on climate change has raised the question of whether or not the current strategies that are used by the authorities responsible for management of inland waterways and industrial managers will be suitable to cope with future conditions (Rothstein and Parey, 2009). These questions are dealt with in the framework of the research program KLIWAS,[2] which is initiated by the Federal Ministry of Transport, Building and Urban Affairs.

2.1.3. *Air Temperature and Gas Turbines*

For gas turbine power plants, the net degree of efficiency can be specified at 38%. The efficiency of gas turbines depends primarily on the compressor and the power that is necessary to densify the air that is sucked in. The higher the temperature of the air, the larger the compressor power p:

$$p = c_p T_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{R}{c_p \eta_p}} - 1 \right] \tag{1}$$

The parameters are the specific heat capacity c_p, the ambient temperature T_1, the air pressure at entering p_1 and exiting the turbine p_2, the efficiency of the turbine η_p as well as the specific gas constant R (Kaltschmitt et al., 2006).

An increase in ambient temperature of 10°C causes the turbine output to drop approximately 8–10% (Leopold, 1984). Additionally, gas turbine power plants are particularly affected by air temperatures; they have lower efficiency in summer than in winter.

Water can be added to the air string in order to reduce the efficiency loss incurred by warmer temperatures. Consequently the enthalpy of evaporation lowers the entering temperature (Hermening and Klingemann, 2005). Furthermore, the mass flow in the gas turbine can be increased. As a result the air conditions of a clammy day are artificially created, with its higher gas turbine efficiency in comparison to hot and dry days. Another possibility for increasing efficiency is the use of a heat exchanging device to withdraw heat from the entering air without the use of water (Johnke and Mast, 2002).

Gas-steam power plants are sensitive to ambient temperatures in the same way that gas turbine power plants are. The gas process is more dependent upon environmental influences than the steam process. In a 250-MW-block

[2] KLIWAS – Auswirkungen des Klimawandels auf Wasserstraßen und Schifffahrt in Deutschland; Consequences of climate change for navigable waterways and inland navigation in Germany.

for example, a 30 K lower ambient temperature results in an increased power of 30 MW in the gas turbine but only 3 MW in the steam process (Rothstein and Parey, 2009; Johnke and Mast, 2002).

2.2. RUN-OF-RIVER POWER PLANTS

2.2.1. *Discharge and Generation of Electricity*

The following section refers merely to river power plants in order to keep within the scope of this work. In general, the head (the difference of the water levels) defines the generation of electricity in a run-of-river power plant. The mechanical power of a turbine P_T is calculated under consideration of the degree of efficiency η_T of the turbine, the density ρ_W of the water, the acceleration of gravity g, the water discharge q_W, and the useable head $h_{useable}$ (Kaltschmitt et al., 2006):

$$P_T = \eta_T \rho_W g q_W h_{useable} \tag{2}$$

At extreme low water events the plant may have to be shut down because the turbines function only with a minimum discharge. There is no consistent limit, however, as it depends on the particular power plant. In the German state of Baden-Wuerttemberg, the so called hydro power order ("Wasserkrafterlass") has been regulating the identification of the minimum discharge for small hydro power plants (up to 1,000 kW) since 1993 (LfU, 2005).

With rising discharge the production can be increased until the maximum limit of the turbine is reached. At high water and flood events, the generation of electricity may also be shut down and the weir opened (Kaltschmitt et al., 2006; BUWAL et al., 2004). Here, a consistent limit is missing as well. Moreover, run-of-river power plants work as regulators for flood waves by means of the corresponding adjustment of the weir (Rothstein and Parey, 2009; EnBW, 2005).

Efficiency losses can also occur due to drifting ice and other drifting substances, which are found especially after storms or floods. Rakes, skimming walls, and floating devices are installed for protection against these substances. Their usage is connected with a loss in generation of electricity, but the degree of loss depends on the amount of items stuck in the rakes. On average, they restrict flow by 5–10%. However, at extreme events, like ice drift, storms, or floods, the restriction is much higher; the protection facilities may become damaged and the plant may have to be shut down (Giesecke and Mosonyi, 2005). According to damage statistics, broken rakes, barrages, etc. make up 25% of all the damage taking place at river power plants (Kasper, 1984).

Ice formation is not necessarily a threat for the plant, even if it is a close ice crust, as long as there is a regular discharge beneath the ice. On the contrary, ground-ice and grease ice are more damaging. Reliable forecasts of the ice development and the creation of a close ice crust through a temporary shut-down can be a solution in this case (Giesecke and Mosonyi, 2005).

2.2.2. *High Water/Flood*

All run-of-river hydro power plants (as well as most thermal power plants) are built in close proximity to a river. Therefore, flood control measures are essential as, otherwise, buildings and plant components can get damaged through flow resistance, flooding or sediment discharge (Ritz et al., 2005). There is no consistent threshold value for flood events, since the flooding depends on the actual location of the plant. Hence, for the development of parameters, it is better to stick to common threshold values like the "100-year events" or the "mean high water". It is differentiated between measures that have to be presented to the officials for the authorization of a new plant and such measures that ensure the authorization to operate during the flood events (Rothstein et al., 2008). These measures can not be discussed in detail but instead some basic aspects are covered briefly.

River hydro power plants are designed for a certain mean water quantity. Water levels higher than the mean water quantity lead to the reduction of generation of electricity (just like very low water levels); the plant may have to be shut down in extreme cases. Hence, annual load duration curves for discharge prognosis are of interest for river power plants. The significant question is whether the future yearly discharge will change in comparison to the current rate, and when these differences will occur. Then it can be deduced for the particular power plants when the situation is becoming critical (Rothstein et al., 2008).

2.3. WIND ENERGY PLANTS

2.3.1. *Wind Speed and Generation of Electricity*

The wind power P_W resulting from an air stream depends on the density of the air ρ_A, the wind speed v and the rotor circular area F (Kaltschmitt et al., 2006):

$$P_W = \frac{1}{2} \rho_A v^3 F \qquad (3)$$

The wind speed affects the usable wind power immensely, namely with a power of three. A bisection of the wind speed v then leads to an increase in usable wind power P_W by one eighth.

A defined power output is associated to every prevailing wind speed. At wind speeds higher than 25–30 m/s, wind energy plants are normally switched off to ensure the safety of the plant. As small changes in wind speeds substantially influence the usable wind power, the danger of damage increases as well. The damage symptoms are torn rotors and broken pylons (Rothstein, 2007).

2.3.2. *Mechanical Effects at Wind Power Plants*

The rotor blades of wind power plants are especially prone to mechanical effects (e.g. frost, ice, hail and thunderstorms). Possible consequences are cracks, fractures due to vibration, delaminations, and broken blades. Lightning strikes can even lead to a total loss.

For offshore plants the additional risk of damage comes from storm surges at the foundation, tower and rotor. At mountainous locations over 1,000 m, snow and frost can affect wind power plants more negatively than at locations in a more favourable climate (Rothstein, 2007; GDV, 2005).

3. Transport and Distribution of Electricity

Atmospheric influences on overhead lines, underground cables, transformers, and switching stations are covered in this section. Due to the stronger impacts of atmospheric parameters on overhead lines, these are considered on a larger scale than the other components of the electric mains.

3.1. ATMOSPHERIC INFLUENCES ON OVERHEAD LINES

Overhead lines are affected by atmospheric influences in several ways, such as failures by lightning, wind, additional loads (such as ice or snow), low temperatures, humidity and moisture.

Lightning is divided into direct strikes and induced over-voltage. The latter occurs when lightning strikes close to an overhead line. The high energy resulting from lightning strikes burns the conductor rope and demolishes the isolators, which are protective devices (EnBW, 2004). Additionally, strikes in pylons or underground cables cause a reverse flashover, which can damage transformers and switching devices.

Wind-induced failures depend on the wind speed V_R which, together with height h and air density ρ is used for the calculation of the dynamic pressure q_h (EN 50341-1, 2002):

$$q_h = \frac{\rho}{2} V_R^2(h) \tag{4}$$

A typical threshold for dangerous winds is circa 90 km/h. In addition to the direct wind loads, failures occur when branches or other foreign substances are directed into the circuit by wind. They bypass the conductor rope and cause short-circuits. Moreover, falling trees can damage pylons and conductor ropes especially at the comparatively low overhead lines of medium voltage (EnBW, 2004). Therefore, the density of wood around overhead lines is directly related to the magnitude of failure (Martikainen, 2005). Furthermore, the ropes of overhead lines often swing due to wind. The amplitudes transverse to the rope axis can reach up to half of the conductor spacing so that they can contact and short-circuit. This may cause the stability of the grid to be diminished (Kießling et al., 2001).

Failures caused by ice and snow loads (short additional loads) arise mainly from ice accretion, which is classified as ice from precipitation and ice from fog or clouds. The combination of additional loads and wind is regarded as having the highest impacts on overhead lines (Kießling, 2002). In this case, the ice loads enlarge the surface of the conductor ropes so that there is a greater contact surface for wind. Additional loads alone cause vertical loads as well as higher traction at the conductor ropes. The traction increases with dropping ambient temperatures, because the ropes contract tighter. Strong forces act especially on the pylons. The traction Q_i results from the weight spans L_{W1} and L_{W2} as well as from the ice and snow load I at the grid (EN 50341-1, 2002):

$$Q_i = I(L_{W_1} + L_{W_2}) \tag{5}$$

In the case that the load exceeds the load capacity of the pylons, they can twist or break. Furthermore, conductor ropes can snap. A further danger results from conductor ropes that sag due to ice and snow loads. Ropes could make contact with other ropes or lower lying objects, which causes short-circuits and short-circuits to earth. Particularly affected by sagging are guard wires at overhead lines of high and highest voltage, which do not carry warming electricity as a protection against ice and snow loads. Ice and snow covered trees in close proximity of overhead lines are also a danger when influenced by the wind (EnBW, 2004; Martikainen, 2005). Moreover, the swinging of ropes can also be caused by the changed aerodynamic shape of the grid in comparison to the original cylindrical shape without the ice and snow loads. When the ropes swing for a long time, mechanical overloads of equipment as well as electric arcs can be observed (Kießling et al., 2001). Guidelines regarding the ice loads for pylons were created and partially modified in Germany. The guidelines divide Germany into three different zones (from zone 1, low ice loads, to zone 3, high ice loads).

Further failures are caused by low temperatures, when the functionality of the equipment is reduced through cold and frost or gets damaged (e.g. when the design temperature is under-run). For instance, frost and other weathering signs crack isolators or ropes.

Power losses also occur in electricity transmission and distribution. These are called the corona discharge losses and losses due to high ambient temperatures. The length and sag of a conductor rope is also temperature-sensitive, since the circuits expand with rising temperatures. This aspect is particularly important for the selection and design of the grid and the projection of overhead lines.

Furthermore, transmission networks are exposed to humidity, which can creep into the equipment and lead to corrosion and wasting. In general, it can be distinguished between direct atmospheric influences (e.g. through precipitation or thaw) and results from high water levels (e.g. floods after heavy rainfalls or snowmelt). Frequent damage occurs to metal components degraded by corrosion and fouling at wooden pylons (Martikainen, 2005).

3.2. ATMOSPHERIC INFLUENCES ON UNDERGROUND CABLES AND ON TRANSFORMER AND SWITCHING STATIONS

Underground cables are also affected by atmospheric influences. During the hot summer of 2003 in France a number of failures with underground cables occurred, especially around the Paris area. These failures were analysed and corrected if necessary. Also, a study was produced by EDF that offers recommendations regarding droughts, heat, and the resulting limited conduction capacities. Furthermore, it is considered important to develop regulations for planning. Besides this, cable lines are uncovered, pylon fundaments are washed out, and slumping and mudslides are initiated by rivers bursting their banks. The latter can cause damage to or even breaking of pylons (Rothstein and Parey, 2009; Rothstein, 2007).

The previously described atmospheric influences like lightning and temperature apply to transformer and switching stations as well. Moreover, floods are important because the equipment may be adversely affected. High waters may cause the flooding of transformer stations and their components to silt up, becoming damaged and often completely destroyed (Rothstein, 2007).

4. Data and Services of the Deutscher Wetterdienst

The Deutscher Wetterdienst (DWD) is the National Meteorological Service of the Federal Republic of Germany. It is responsible for providing data and services for the protection of life and property in the form of weather and climate information. One of the main duties of the DWD – embodied in the Law on the Deutscher Wetterdienst – is the provision of meteorological services for the general public or for individual customers and consumers in the fields of traffic, trade and industry, agriculture and forestry, the building industry, public health, and water management, including preventive flood control, environmental protection, nature conservation and science. In fulfilling its statutory tasks, the DWD supports electric utilities and energy supply companies with data, services and expert opinions.

The DWD runs the National Climate Data Centre (NCDC) with its database of climate data for the whole country of Germany. The longest data series dates back to the eighteenth century. Today the observation network of the DWD comprises of about 2,200 stations. Statistical evaluations based on this climate data are the basis of planning purposes and risk management for energy supply companies.

The DWD supports the energy companies, in particular concerning wind power plants, with near real-time meteorological data (temperature, wind speed – mean value or strongest gust) from the manned or automatic weather stations. Providing a continuous supply of power and gas to consumers requires accurate predictions about the quantity of energy from wind energy plants, thermal power plants or solar plants that will be available in the next hours or days. On the basis of numerical weather models, the DWD offers the energy companies short-term forecasts for temperature, wind, solar energy, and precipitation. The local, very short-range numerical weather model COSMO-DE, with a grid length of 2.8 km, is even able to accurately represent shower and thunderstorm events. This high-resolution model belongs to the model chain of the DWD, which consists of the Global Model for the weather worldwide and the local models embedded in it for central Europe and Germany.

Seasonal forecasting is the attempt to provide useful information about the "climate" that can be expected in the coming months. The seasonal climate outlook of the DWD is a seasonal forecasting for 6 months, which is based on numerical weather prediction calculations made by the European Centre for Medium-Range Weather Forecasts in England. Even though this data is less accurate than short-time forecasts, it can be useful to energy companies.

There is quite of lot of cooperation between experts from the DWD, various governmental water and energy management authorities, and power and gas companies to develop and implement special meteorological services. Analysing heavy precipitation events is an important prerequisite even for the energy companies. The KOSTRA catalogue (Bartels and Malitz, 2006; DWD, 2005) contains statistical values of heavy precipitation events for different duration levels and recurrence periods. The values can be interpolated or extrapolated for individual raster cells as well as to average values for larger areas in Germany. Through findings from the KLIWA-project, the DWD further developed the KOSTRA catalogue to include the period 1951–2000 (www.kliwa.de).

Long-term icing measurements have been carried out since 1965 at different stations in Germany. These measurements are carried out in order to improve the knowledge of regional differences, the height dependence of icing (icing climatology), to understand interrelationships between icing and other meteorological parameters, to supply data to special experts, and to produce icing maps of Germany (Wichura, 2007).

Other tools for risk management purposes or planning of the power and gas companies are forecasts for heating or cooling degree days, test reference years, wind data for users of wind energy plants, or maps of the solar radiation for solar plants.

The degree day number (sometimes called heating degree days) is a heating indicator. The heating energy consumption of buildings depends on many factors. They range from the heating and ventilation habits of the inhabitants, the thermal insulation, and the weather. These issues can be dealt with by the help of the degree day number, which is the difference in temperature between the room temperature of 20°C and the daily mean air temperature. When the outdoor temperature decreases, the degree days increase by the same amount as the heating energy consumption rises to keep the room at a temperature of 20°C. The industry uses degree days for the temperature adjustment of energy consumption figures. One of the quantities derived from the degree days, known as the climate factor, is used for issuing energy performance certificates for buildings in the framework of the German Ordinance on Energy Saving. The climate factor can be downloaded from the DWD website (www.dwd.de/klimafaktoren).

The DWD is getting increasingly involved in activities of the Intergovernmental Panel on Climate Change (IPCC) With this know-how and the aid of new results of global and regional climate projections, the DWD is providing advice on issues of climate impact assessment to decision makers in politics, business, administration and industry. In order to be able to assess the impact of climate change on the energy industry and peoples in urban areas, performance models (e.g. microscale urban climate models) will be used to determine how the changes in climate will affect concrete sectors of our society. Climate projections – which describe the development of the climate over the coming decades – are filled with considerable uncertainties, and this is also true of the regional climate models for Germany. The DWD procedure, called ZWEK (a compilation of performance model input data sets for climate impact research), compares existing regional models with the aim of determining the probability and the impact of certain climate changes to be expected in Germany.

An initial application is the description of the future development of the heating degree days. Further calculations will help to answer the question whether, and to what extent, the rising temperatures due to climate change will lower the energy requirement (reduced heating in winter) or enhance the energy requirement (more cooling in summer), especially in urban areas.

5. Conclusion

As shown in the previous sections, many atmospheric and hydrological parameters influence electricity generation, transportation and consumption. The inclusion of environmental parameters (like air and water temperatures, wind speeds, discharge amounts) is of great importance for a number of business actions in electricity companies. Therefore, it is essential for several sub-processes of different business sectors in electricity companies to collect and to analyze this data.

Relevant atmospheric parameters are ground-level air temperatures, wind speeds, lightning strike locations, and rainfall. The most important hydrological parameters are the discharge amount and water temperature.

For some of these parameters (ground-level air temperatures, water temperatures), electricity companies have their own measuring systems from which the data is transmitted to the proper control station. Nevertheless, data services from DWD play an important role for many German electricity suppliers.

An enhanced exchange of data would certainly be useful for the improvement of regional climate forecasts, especially analysis about the occurrence probability of extreme events (e.g. low water periods, intense snowfall at high temperatures), and also accurate predictions regarding the further shift of means due to climate change are required.

In order to ensure efficient research with useful results for electricity companies, the great amount of relevant information (from national meteorological services, planning offices, catastrophe service and as much as possible from companies) needs to be acquired and systematically organised. Subsequently, a GIS-based company-specific risk mapping is possible. Based on this GIS, detailed information can be accessed and connected with information of different regional climate models.

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WATER MANAGEMENT OF A THERMAL POWER PLANT – A SITE SPECIFIC APPROACH CONCERNING CLIMATE CHANGE

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Abstract. In this paper a site-specific approach is presented that aims at the analysis of climate change impacts on the water management of a thermal power plant in order to evaluate and identify possible adaptation measures. On the one hand, a model-based quantification of the impacts of changing air and water temperatures on a cooling system is described. On the other hand, a GIS-based risk management is created on the basis of changing flood water levels.

Keywords: Climate change; electricity production; power plant; water management

1. Introduction

The electricity sector is affected by several meteorological and hydrological parameters, e.g. air and water temperatures, humidity and water levels. Most meteorological and hydrological parameters show significant changes in their recent development (positive as well as negative trends depending on the parameter and season). Due to climate change, these variations are expected to increase in mean or extremes respectively (IPCC, 2007; Jacob et al., 2008). In order to identify suitable adaptation measures, a site-specific approach is chosen that provides detailed information on the impact of changing meteorological and hydrological parameters (air and water temperature, floods) of a specific thermal power plant site in Germany (conventional steam/gas power plants). The impacts are quantified and analysed, so that as a next step, effective adaptation measures can be identified

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and implemented, e.g. an adjusted flood risk management. In the following, the impacts of climate change on power plant cooling systems as well as on flood risks are identified (Chapter 2). Subsequently, the methods and first results of the current study are presented in Chapters 3 and 4.

2. Identification of Climate Change Impacts on Thermal Power Plants

In this section, the impacts of climate change on the water management of thermal power plants are presented. On the one hand, the cooling systems of most power plants are affected, since these are influenced by air and water temperatures. On the other hand, flood risks might increase, which affect the power plant sites along rivers.

2.1. IMPACT OF CLIMATE CHANGE ON THE COOLING SYSTEM OF A THERMAL POWER PLANT

Ambient air and water temperatures influence the electricity production of thermal power plants in different ways: Firstly, the power plant efficiency decreases with high air and water temperatures. The efficiency of a thermal power plant depends on the temperature interval of the steam/gas upstream and downstream the turbine. Since the temperature upstream turbine is limited by material conditions, the steam/gas after the turbine needs to be cooled down as far as possible, if it is not extracted as local or district heat. Due to its high thermal absorption capacity, water is the most effective cooling medium (Kalide, 2005). In water-cooled thermal power plants the steam/gas downstream turbine is conveyed through a condenser where the remaining heat energy is dissipated to a second water cycle. The heated cooling water is either directly discharged into the receiving water (e.g. river) by means of a so-called once-through cooling system or a cooling tower is interposed (mixed-cycle or closed-cycle cooling system) (Kalide, 2005). In comparison to the once-through cooling, the operation of a cooling tower on the one hand decreases power efficiency up to 2–3% due to e.g. increased energy consumption by water pumps or ventilators. On the other hand, the heat discharge into the receiving water is significantly reduced while up to 5% of the cooling water volume is lost through evaporation (Kobus and Bürkle, 1996; Maniak, 2005).

Secondly, the withdrawal of surface water for means of cooling and its discharge back into the receiving water is regulated by threshold values. These are assigned site-specifically by German authorities and regulate e.g. the cooling water temperature, the mixed water temperature after heat discharge or the maximum evaporation loss (Maniak, 2005). The thresholds could be reached more frequently in future, as water and air temperatures significantly correlate and both air temperatures (heat periods respectively) and summer droughts increase due to climate change (IPCC, 2007; Jacob et al., 2008). To prevent the exceedance of the described thresholds, thermal power plants have to reduce the heat discharge into the receiving water by, in the first place, changing the cooling system operation mode from once-through cooling to mixed-cycle or closed-cycle cooling (if technically available). As a last resort, the electricity production has to be decreased or even shut down (Rothstein et al., 2008; Müller et al., 2007). Concerning the studied power plant site, the cooling system operation mode can be switched from once-through to mixed-cycle or closed-cycle cooling. The complex interactions between meteorological and hydrological parameters and the cooling system operation are represented with a dynamic model, which is discussed in Section 3.1. Additionally to the impacts on the cooling system of a power plant, the site itself might be affected as flood risks could increase along rivers. The latter is shown in the following section.

2.2. FLOODS AND THERMAL POWER PLANTS

Most thermal power plants are built along rivers due to their need of high amounts of water for cooling purposes. This can turn into a disadvantage in case of high water levels or floods. Power plants are critical infrastructures since lots of industries, infrastructures and telecommunication depend on electricity. The floods along the River Elbe in the year 2002 and 2006, along the River Oder in 1997 and along the River Rhine in 1993, 1995 and 1999 showed the need for power plants to adapt to flood situations in general.

Power plants in Germany are subject to two different regulations concerning flood protection. The Association of German Engineers (VDI) states a protection level of a 100-year flood for thermal power plants, while the Nuclear Safety Standards Commission (KTA) states a protection level of a 10,000-year flood especially for nuclear power plants (VDI, 2006; KTA, 2004).

Due to climate change, air temperatures and precipitation are expected to increase in Germany, the latter especially in winter (UBA, 2007). Due to the direct influence of increasing precipitation on the river runoff, higher and more frequent floods are expected (Moser, 2006). The German research group KLIWA (climate change and consequences for water management) initiated a research project on 158 gauging stations in Bavaria and Baden-Wuerttemberg. There was no change observed regarding the average runoff, whereas more frequent floods occurred during the winter season in the last decades. An explanation could be a seasonal shift in heavy precipitation from the summer to the winter months (AK KLIWA, 2002). Based on climate projections and the resulting change in runoff, the co-operation project "climate change and consequences for water management" (AK KLIWA) decided to put on a climate change factor which describes a climate-induced extra amount for planning tasks. In order to plan flood protection measures, a so-called design water level or design flood is calculated. It is the highest water level to be expected for certain regions and a certain return period. The design water level at the River Rhine for a 100-year flood needs to be multiplied by 1.15, this means that the new design water level would be e.g. 4.6 m instead of 4 m. The climate change factor is specific to different regions in Southern Germany (AK KLIWA, 2006). The rating of existing as well as the planning of new power plants needs to take into account the climate change factor in order to adapt to future floods. That means the design specifications for the protection against floods need to be revised. Since precipitation will increase in winter, the hazard of flood situations will increase on average as well. When applying the climate change factor to design floods, the amounts of runoff associated with certain return periods rises (AK KLIWA, 2006; Table 1).

TABLE 1. Overview of the climate change factor in Baden-Wuerttemberg, the most relevant return periods for the water management of HQ_2 and HQ_{100} are coloured light grey (LFU, 2005).

T [years]	Climate change factors $f_{T,K}$				
	1	2	3	4	5
2	1.25	1.50	1.75	1.50	1.75
5	1.24	1.45	1.65	1.45	1.67
10	1.23	1.40	1.55	1.43	1.60
20	1.21	1.33	1.42	1.40	1.50
50	1.18	1.23	1.25	1.31	1.35
100	1.15	1.15	1.15	1.25	1.25
200	1.12	1.08	1.07	1.18	1.15
500	1.06	1.03	1.00	1.08	1.05
1,000	1.00	1.00	1.00	1.00	1.00

For the return periods >1,000 years the factor equals 1; $f_{T,K}$ = factor for a certain return period T in a certain climate K

Since thermal power plants are built on different terrain levels, a protection against flooding can never be standardised. Therefore, all flood protection measures are calculated taking into account the return period for floods at a specific site. For example, the height of a dike is calculated using the design flood and the so-called freeboard, the vertical difference between design flood level and dike top (DIN 19712, 1997). The application of this method to site-specific risk management is described in the following Section (Section 3.2.).

3. Methods

Two different approaches are chosen in this study to evaluate possible future effects on water management: on the one hand, a model-based quantification of climate change impacts on a cooling system is chosen. On the other hand, a GIS-based flood risk management is created for a specific power plant site.

3.1. MODELLING CLIMATE CHANGE IMPACTS ON COOLING SYSTEM OPERATION

To quantify the impacts of climate change on the operation of the cooling system of a thermal power plant a model of a cooling system is created using the System Dynamics approach (Software VENSIM®). This approach assumes that dynamical systems, which are characterised by feedbacks and temporal delays, should be analysed by means of dynamical models in order to fully understand the behaviour of the system (Sterman, 2000). The created System Dynamics model allows scenario calculations that show the impact of changing meteorological and hydrological parameters on each part of the cooling system. Hence, e.g. the site-specific probability of reduced electricity production due to the exceedance of statutory thresholds or the possible future changes in gross electrical output can be evaluated.

The database consists of hourly measured data for air and water temperature, humidity, water level, power load, operation mode and cooling water temperature (before and after the cooling tower). Time series with length of approximately 15 years (1993–2008) were provided by the power plant considered in this study. Firstly, missing data and outliers were assessed for each time series. Secondly, the quality of the air and water temperature series was tested with the Standard Normal Homogeneity test by Alexandersson and Moberg (1997). As reference series, measurements of the German Weather Service (DWD) and the State Office for Environment of Baden-Wuerttemberg (LUBW) were utilised (DWD, 2007; LUBW, 2007).

The model relies on the assumptions that the applicable water related thresholds and the future power load remain constant. In order to identify the direct effects of changing air and water temperatures on cooling system operation, another central assumption is a constant electricity price (spot market).

The main input parameter into the model is the air temperature at the power plant site. To simulate the operation of the cooling system until the year 2050, projected air temperatures of the regional climate model REMO (by the Max Planck-Institute of Meteorology, MPI-MET) are used. These are employed as average of nine grid boxes for all of the scenarios calculated by REMO: A1B, A2 and B1 (Jacob et al., 2008; IPCC, 2007; Jacob, 2005). Before simulating cooling system operation under climate change, the results of the REMO control run are compared with the measured data at the site.

Water temperatures are projected using a regression model with daily air temperatures as explanatory variable. To find the best fitting regression function, firstly, a cross-correlation analysis with air and water temperatures is calculated (Schönwiese, 2006). It shows the maximum correlation coefficient at an offset of 3 days. To take this offset into account, a time lag of 3 days is integrated in the model to improve projection quality (Erickson and Stefan, 2000). The daily changes in water temperature are subsequently calculated with a fifth-order polynomial regression. To assess the quality of the water temperature regression model, the correlation between lagged air and water temperature is calculated. The additional input parameters reference water level and relative humidity are estimated with a seasonal cycle, which is created by averaging the available data sets.

A major output variable is the gross electrical output. It is calculated according to the design specifications of the power plant considered here combining them with the parameters cooling water temperature upstream of the condenser and operated load. Furthermore, several parameters specific for the cooling system, like e.g. cooling water temperature at discharge, are computed. Their calculation is based on the design specifications as well. The model parameters are compared with the applicable, site-specific threshold values. If they are exceeded, the cooling system operation is altered. The generalised model structure can be seen in Figure 1.

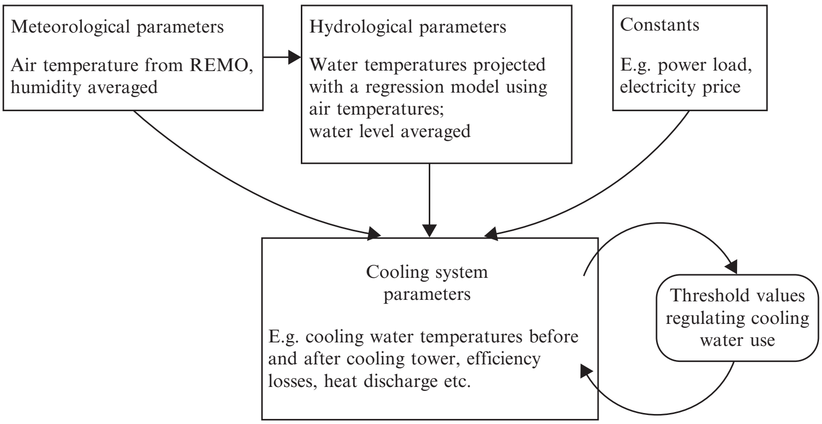

Figure 1. Design of the model for the quantification of the impacts of changing meteorological and hydrological parameter on cooling system use.

3.2. CREATION OF A GIS-BASED FLOOD RISK MANAGEMENT

So far, there is no general concept in Germany for a Geographical Information System (GIS)-based approach of mapping and managing flood risk at a thermal power plant. The advantage of a GIS-based approach is the storage, manipulation and visualisation of all available data of the specific power plant site as well as the legislation and regulations.

According to a scheme by Schmidt-Thomé (Greiving and Fleischhauer, 2006), the four phases of risk management planning are adjusted for the use in a GIS. The four relevant aspects of the scheme of damage assessment are as follow (Büchele et al., 2006):

- Problem analysis: power plant sites are supposed to be protected against flooding. Therefore, all relevant data is collected and integrated into a GIS. This implies the selection of the investigation area as well as the identification and cataloguing of each building in the study area. Furthermore, the design water levels need to be combined with the terrain levels, which can be extracted from a Digital Elevation Model (DEM).
- Assessment of alternatives: different design water levels are illustrated for the different sites. Afterwards a comparison is made.
- Decision-making: based on the illustrated water levels, an individual emergency plan is established and tested. A first assessment of damage according to the degree of utilisation can be provided.
- Implementation: the emergency plan gets implemented at the sites. In this phase, missing protection measures, storage places for mobile protection measures and access routes can be identified within the GIS.

According to this scheme, a standardised GIS-based flood risk management for power plants needs to combine those aspects in order to provide significant background information as well as a practical approach for all types of thermal power plants. The Federal Ministry of the Interior describes risk management as a circle of plan, do, check and act (BMI, 2008). This means that after the preparation of a site-specific plan, implementation is intended. After the occurrence of a flood, the plan needs to be checked whether it worked properly and again, action is needed to improve the plan.

4. First Results

In this section, first results of the site-specific approaches described above are presented. This section is again divided in two parts, i.e. the model-based cooling system analysis and the GIS-based flood risk mapping.

4.1. MODELLING CLIMATE CHANGE IMPACTS ON A COOLING SYSTEM

The available time series contain few missing data or outliers and the tested series are homogenous at the significance level of 95%. Therefore, the quality of the data was deemed satisfactory.

An essential factor for changes in cooling system operation is the evolution of the temperatures in the receiving water. The water temperature regression model (see Section 3.1.) has a good projection quality: the Spearman's correlation coefficient is 0.96 and the coefficient of determination r^2 is 0.92. The result is significant at the level of 99%. The quality of the air/water temperature projection turns out to be acceptable in comparison to other studies, which calculate weekly or monthly water temperatures from air temperatures with coefficients of determination between 0.9 and 0.99 (Pedersen and Sand-Jensen, 2007; Mohensi et al., 1998; Mackey and Berrie, 1991).

The differences between the REMO control run and the available measured data is plotted for monthly mean air temperature over the reference time period 1993–2000 (Figure 2). It becomes apparent that the variations are more distinct in the winter months than during the summer with the exception of the month June.

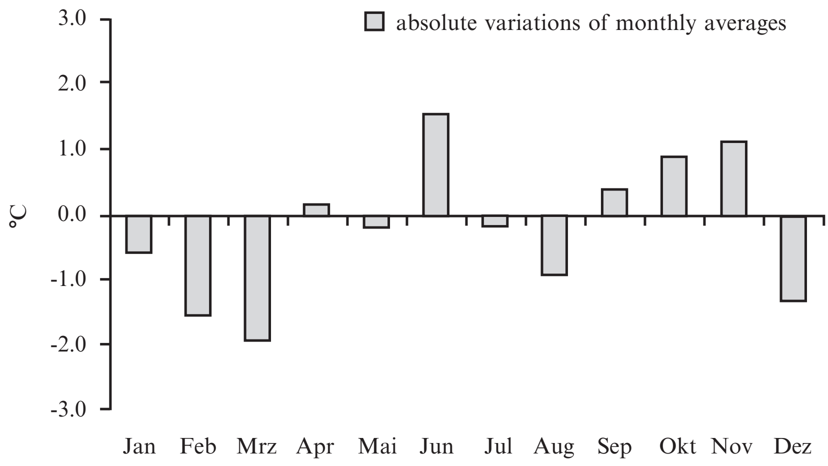

Figure 2. Absolute differences of monthly means of air temperature between the REMO control run and the measured time series for the years 1993–2000.

The results of the water temperature projection until 2050 show an average increase. The change in water temperature in the time span 2021–2050 in comparison to 1961–1990 is 0.8 K for scenario A1B, 0.7 K for scenario A2 and 0.5 K for B1. The average course of the year shows an indentation for the month March and April (Figure 3). This is in accordance with the evolution of the air temperatures for the regarded grid boxes. The standard deviation in the time series increases slightly with 0.2 for scenarios A1B and A2. The exceeding probabilities for high water temperatures change accordingly: The probability for a daily mean water temperature above 22°C increases by 100% for A1B, 76.5% for A2 and 30.2% for B1.

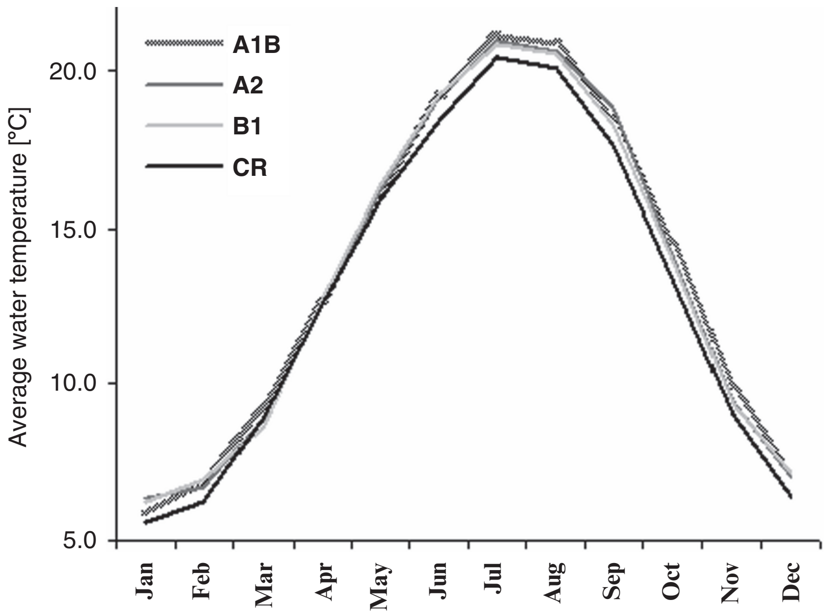

Figure 3. Monthly averages for water temperatures projected from REMO air temperatures for the scenarios A1B, A2 and B1 (2001–2050) and the control run (1961–2000).

The model simulation shows an average decrease in gross electrical output of the power plant considered in this study. The relative decrease comparing the time span 2021–2050 to the control run simulation 1961–1990 is 0.19% for A1B, 0.16% for A2 and 0.09% for B1. The reduction of average gross output is more apparent in summer (0.36% for A1B, 0.18% for B1) than in winter or spring (0.05% for A1B, 0.01% for B1), but still very small (Table 2). The reason for the marginal changes might be the possibility to switch the cooling system operation mode according to the meteorological and hydrological situation (see Section 2.1).

TABLE 2. Relative change in percent of gross electrical output for the scenarios A1B, A2 and B1 for 2021–2050 compared to the control run simulation for 1961–1990.

	Change in A1B in %	**Change in A2** in %	**Change in B1** in %
Spring (Mar, Apr, May)	0.05	0.05	0.00
Summer (June, July, Aug)	0.36	0.28	0.18
Autumn (Sept, Oct, Nov)	0.25	0.23	0.13
Winter (Dec, Jan, Feb)	0.08	0.07	0.06
Year	**0.19**	**0.16**	**0.09**

4.2. MAPPING FLOOD RISK AT AN EXEMPLARY POWER PLANT SITE

In Figure 4 the available data of a DEM, the site and the design water level, which were implemented in a GIS, are displayed. The design water level is calculated to have an overview section through the terrain level, but no real simulation was calculated due to the lack of data. This first visualisation can be used as an overview on the situation at a site and can be easily read even by non-experts.

For responsible persons it is possible to identify dry and flooded areas simply by shades of grey (Figure 4). Darker areas are flooded, which means, that for example a cooling tower might be flooded already whereas the power plant unit is still not flooded and therefore not at risk. Beyond this, a lot of areas are neither flooded nor covered with buildings, so those areas might be possible storage places for mobile protection measures or shelters. Lighter areas that surround the flooded ones are dikes or higher terrain levels. In this case, no modification of the dike is needed since there is no overtopping of the dike to be expected. In case of an overtopping, the GIS could show the areas at risk and therefore the areas that need a modification, for example the heightening of a dike.

As seen in Figure 4, this exemplary power plant does not have to adapt to the current flood level situation. A flood protection was created before the power plant was built. Further calculations might show an increase in the design water level. For this, further maps need to be created in order to assess the water levels site-specifically.

In addition to the maps, a manual for map-making and interpretation as well as a standardised procedure for decision-making in case of an emergency (high water levels) will be established. The responsible persons at the power plant site get the possibility to react to changes in the operating procedure. Power plant sites are obliged to be independent in their planning, so a person in-situ needs the knowledge and the ability to create different maps on his own, especially in case of flooding where the information flow from outside the power plant might be disturbed.

In comparison to an analogue map, mapping within the GIS is fast and includes a high resolution DEM instead of contour lines. An intersection of water levels and the DEM is more accurate. Moreover, background information, e.g. worth of buildings and height of entrances, can be stored and retrieved by selecting them directly. Furthermore, a comparison of terrain and water level reveals the depth of the flooding, so that an analysis, e.g. whether the street is still accessible, can be calculated.

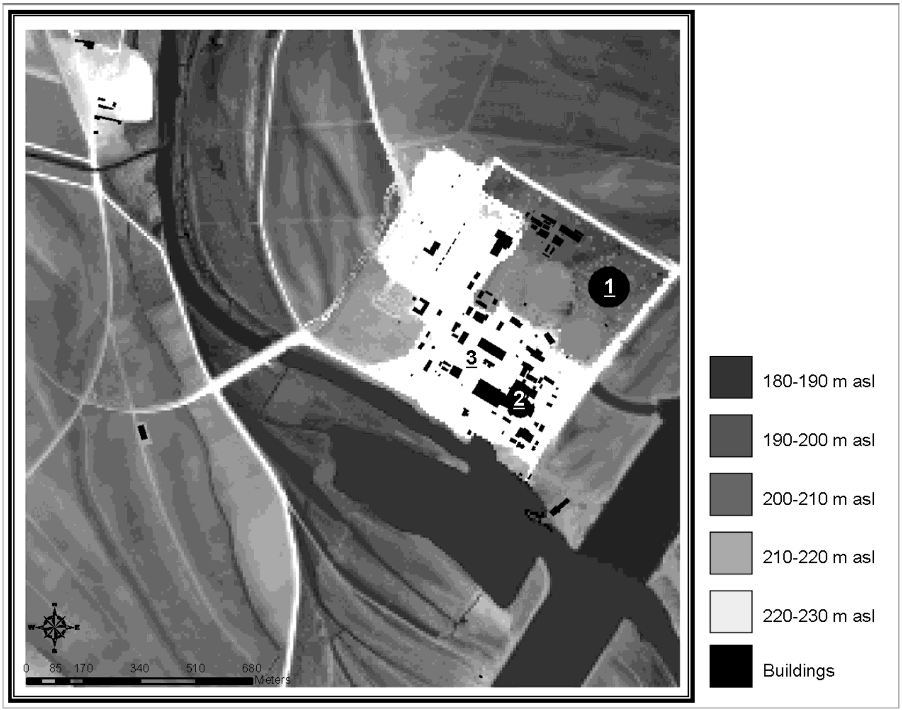

Figure 4. Exemplary map for a thermal power plant. (1) The cooling tower is in a flooded area, the cooling tower pond is already flooded to avoid its floating. (2) The production unit is in a non-flooded area as well as (3) the offices and shops, no damages are expected.

5. Conclusion

The presented site-specific approach, which is used to identify and analyse the impacts of climate change on the water management of a thermal power plant, provides a basis for decision-making concerning relevant adaptation measures. The power plant operators gain insight into the site-specific changes affecting on the one hand cooling system operation and on the other hand their flood risk management.

Regarding the modelling of the climate change impacts on cooling system operation, it can be concluded that the System Dynamics approach is a flexible and powerful tool to analyse the impacts of climate change. The simulation shows that increasing average air and water temperatures result in only very small changes in gross electrical output until 2050. Those changes might become more distinct with intensified global warming until 2100. In the long-term, the scenario calculations provide a basis for site-specific adaptation measures, e.g. future investment decisions for the cooling system can be reviewed taking climate change into account and design specifications can be altered with respect to changing air or water temperatures.

The GIS-based flood risk mapping offers detailed maps to identify dry and flooded areas. These can be used, e.g. to convey the necessary actions in the case of flooding. The combination of maps, which illustrate the emergency, and handbooks or regulations, which describe the procedure in an emergency, is much more comprehensible than the plain description in handbooks/regulations.

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MATHEMATICAL PROGRAMMING BASIS FOR DECISION MAKING USING WEATHER AND CLIMATE INFORMATION FOR THE ENERGY SECTOR

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Abstract. Decision making (DM) problem is of great practical value in many areas of human activities. Most widely used DM methods are based on probabilistic approaches. Well-known Bayesian theorem for conditional probability density function (PDF) is a background for such techniques. It is due to some uncertainty in many parameters entered in any model described functioning of many real systems or objects. Uncertainty in our knowledge might be expressed in alternative form. I offer to employ appropriate confidential intervals for model parameters instead of relevant PDF. Thus one can formulate a prior uncertainty in model parameters by means of a set of linear constraints. Related cost or goal function should be defined at corresponding set of parameters. That leads us to statement of problem in terms of operational research or mathematical linear programming. It is more convenient to formulate such optimization problem for discreet or Boolean variables. Review of relevant problem statements and numerical techniques will be presented as well as several examples. The house heating and air condition optimal strategies responded to different IPCC climate change scenarios for some domains of Russia are considered. Evolving of climate and energy costs should be taken into account in building construction design. Optimal relationship between future expenses for house heating and costs of new house constructions including material costs and its amounts is a subject of discussion. In both considered tasks DM might be performed by means of the discreet optimization algorithms. If the DM variables are all required to be integers, then the problem is called an integer programming (IP). The "0-1" IP is the special case of integer programming where variables are required to be 0 or 1 (rather than arbitrary integers). The IP is a most convenient form for decision maker use. The "1" value means

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that a given scenarios is accepted, the "0" value means that a given scenarios is rejected. To illustrate suggested approach the "branch and bound" technique was implemented to seasonal surface atmosphere temperature ensemble predictions system (EPS) for northern parts of Russia. Aim of this illustrative research was to link the EPS output facility to requirements of particular users.

Keywords: Climate change; energy sector; decision making; operational research techniques; integer programming; branch and bound method

1. Introduction

An overview of key facts and societal challenges related to economic development, future energy demand and the impact that demand could have on the climate system might be found in some documents and papers (IEA, 2003, 2004, 2005; IPCC, 2007). These studies will help further elaborate a business response to the challenges identified in this paper, which will require additional research and consultation.

We cannot know exactly how the world will develop over the next half century, but the scenarios used here fit with the United Nations (UN) development goals of poverty reduction and improved living standards in the developing world. Achieving these goals will require an increase in energy consumption. Although we recognize that a range of human activities has an impact on greenhouse gas emissions and that many of these practices will have to change, the focus of this publication is on the world's use of energy, related impacts and on the decision making in energy sector to optimize relationships between expected benefits and losses (IPCC, 2007).

We have used existing data from the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA) and World Business Council for Sustainable Development (WBCSD) studies. We present it here in a simplified and condensed form to stimulate forward thinking and discussion around the issues facing us as we begin to deal with climate change.

Many paper space (BP, 2003; IEA, 2003, 2004, 2005; Meier, 2001; Von Moltke et al., 2004; WBCSD, 2004a, b, 2006) spent reviewing the different options for meeting green house gas (GHG) reduction targets, including energy supply options (carbon capture and sequestration from coal or natural gas, wind, solar, biofuels), energy efficiency improvements, alternative transportation technologies, and adaptation to climate change. In addition, many studies review the basic science behind climate change, including where significant uncertainties remain: weather forecasting, inter-annual variability, trends in extreme weather events. House heating systems are the substantial energy savers when the DM is based on reliable forecast weather information concerned much shorter time scales (1–7 days).

Projections and examples based on particular global emission levels and eventual CO_2 concentrations in our atmosphere are only set out to illustrate the scale of the challenge. Another issue is to formulate optimization problem in energy sector to minimize GHG emission due to develop scenarios for better proportions between different energy producers and consumers.

2. Climate Change Impact on Energy Sector

The GHG that keeps our planet warm is getting thicker. This is because when we burn fossil fuels and cut down trees we add greenhouse gases to the atmosphere that trap the sun's heat. More heat means more unpredictable weather and other big changes for life on Earth. When we burn fossil fuels – oil, coal and natural gas – to make electricity, heat our homes and offices, cook, or power our cars, the main greenhouse gas carbon dioxide (CO_2) is released. Once released CO_2 can stay in the atmosphere for up to 200 years, heating up the planet.

The latest science from the Intergovernmental Panel on Climate Change (IPCC) – an independent global climate body – says that most of the warming in the past 50 years has been caused by humans. It predicts a temperature rise of up to 6°C by the end of the century. This means dangerous climate change, which we won't be able to avoid unless we act soon. The Kyoto Protocol, which became law in 2005, sets limits on the emissions of greenhouse gases from rich, developed countries like the UK. Many countries have signed up to the Protocol, but not the world's biggest emitter, the US, China, India.

The global economy is dependent upon oil and other fossil fuels, and this dependency (of producers and consumers alike) is fed through international trade. Increasing energy consumption, driven particularly by the rapid growth of emerging economies such as China and India, as well as volatile and rising oil prices and growing concerns over energy security are forcing a re-alignment of the global energy sector. Patterns of investment and technology flows in this sector are shifting in response to the scarcity of reserves, fostering the emergence of new actors and new strategies in the energy business.

The International Energy Agency (IEA) projects that energy demand and prices will continue to soar, with the world set to use 60% more energy in 2030 than at present. Renewable energies such as solar, wind, geothermal and modern biomass are on the rise, with wind power being the fastest growing energy source in the world. However, incentives and investments in renewable energy sources continue to be insufficient to forge a fundamental overhaul of the energy sector.

The prevailing high oil prices encourage non-OPEC production of conventional and non-conventional oil. High oil prices are also likely to encourage the implementation of policies that reduce air pollution and GHG emissions enhance energy security. The higher the price of oil, the greater likelihood that alternative energy technology development will be promoted. Some renewable energy technologies are close to becoming commercially viable, while others occupy niche positions. Although development of renewable energy technologies on a wide-spread commercial basis is not expected in the short-term, high oil prices and technological developments will increase the opportunities for such energy sources.

IPCC's GHG emission scenarios are well known (IPCC, 2007). But the IEA and WBCSD provided more realistic ones due to more experience, deep linkages to industry and competence of their activity for many years (IEA, 2004). Moreover, IEA scenarios are more deeply substantiated by relevant economy research. In contrast IPCC scenarios are based on physical models and provide future evolving not only air temperature, but also some other variables (humidity, precipitation, wind velocity), which are important in more perfect economical models. Pathways to 2050: Energy and Climate Change (WBCSD, 2006) builds on the WBCSD's 2004 Facts and Trends to 2050: Energy and Climate Change (WBCSD, 2004a, b) and provides a more detailed overview of potential pathways to reducing CO_2 emissions.

The pathways shown illustrate the scale and complexity of the change needed, as well as the progress that has to be made through to 2050. Our "checkpoint" in 2025 gives a measure of this progress and demonstrates the urgency to act early to shift to a sustainable emissions trajectory. The WBCSD's principal sources of data for 2002 and 2025 references have been the IEA *World Energy Outlook* (IEA, 2004). While the WBCSD's projections were made in *Pathways to 2050* also build on the findings of *Facts and Trends* (WBCSD, 2004a*)*. Projections for energy consumption by sectors are presented at Figure 1 (energy units – ExaJoules [EJ], one ExaJoule is 278 billion kWh).

There are there main consumers: buildings (house heating and cooling), transport and industry. Transport is expected to follow a sustainable development scenario (at quasi-constant emission level), while two others will enhance energy consumption rate.

Technical progress in energy sectors provides some decreasing in CO_2 emission per unit of produced energy (IEA, 2003, 2005). From 1990 to 2002, economic efficiency improved by 1.4% per year, with only a small improvement in carbon intensity. If the goal is to stay on the indicated pathway to 2050, maintaining this slow decarbonization trend through to 2050 would require a 78% improvement in energy efficiency across the economy, or an improvement of over 3% per year (WBCSD, 2006).

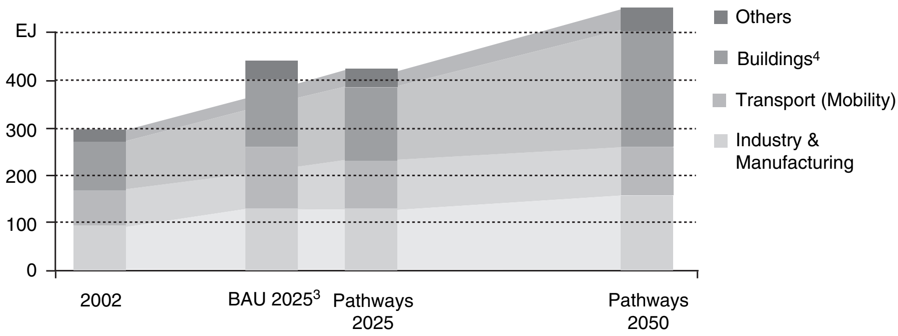

Figure 1. Energy consumption (in ExaJoules (EJ)) by sectors (WBCSD, 2006). (BAU 2025 – "Business As Usual" in 2025).

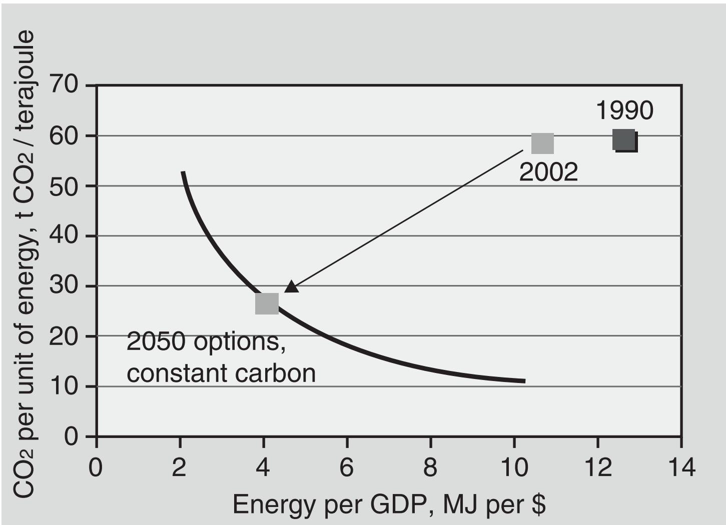

Figure 2. Relationship between carbon emission and produced energy amount for 2050 (WBCSD, 2006), values for 1990 and 2002 presented by single aside points.

Alternatively, with almost no improvement in energy efficiency, energy decarbonization must be some 80%, meaning an almost total renewable / nuclear / carbon sequestration based economy. Tackling both energy efficiency and carbon intensity is necessary. To 2050, an energy efficiency improvement of about 2% per year is assumed for North America, which in turn requires a 1.4% per year reduction in carbon intensity (see Figure 2). GDP – Gross Domestic Product, a measure of the size of the economy; MegaJoules – MJ (A MegaJoule is one million Joules).

To handle with the decision making (DM) one needs some projections of major resource and economic variables. Primary energy (the total energy available from our natural resources, such as renewable, uranium, coal, oil and natural gas, assuming 100% efficient use of those resources) demand should be close to flat after 2025 (Figure 3), while maintaining economic growth (GDP per capita) and catering for growing population (WBCSD, 2006). GtC – carbon Giga Ton (A gigaton is equivalent to one billion tons).

Having in disposal above projections for carbon emission, GDP per capita, and primary energy along with energy distribution between different sectors (building, transport and industry) we are ready to formulate DM problem for optimal scenario to shear energy resources between its sectors.

We will consider mathematical statements of DM problem in next sections. Illustrative examples will be presented in Sections 5 and 6.

3. Decision Making Based on the Mathematical Programming Tools

Decision theory (DT) is theory about decisions. The subject is not a very unified one. To the contrary, there are many different ways to theorize about decisions, and therefore also many different research traditions. This text attempts to reflect some of the diversity of the subject. Its emphasis lies on the mathematical aspects of decision theory.

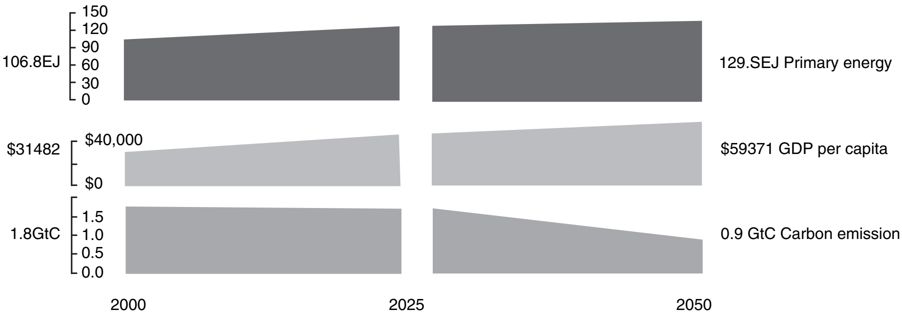

Figure 3. Projected changes in: (**a**) primary energy, (**b**) GDP per capita, (**c**) carbon emission for 2000–2050 (WBCSD, 2006).

Decision-theory focuses on how we use our freedom. In the situations treated by decision theorists, there are options to choose between, and we choose in a non-random way. Our choices, in these situations, are goal-directed activities. Hence, decision theory is concerned with *goal-directed behaviour in the presence of options*.

We do not decide continuously. In the history of almost any activity, there are periods in which most of the decision-making is made, and other periods in which most of the implementation takes place. Decision-theory tries to throw light, in various ways, on the former type of period.

Decision makers divide the decision process into the following five steps:

- Identification of the problem
- Obtaining necessary information
- Production of possible solutions
- Evaluation of such solutions
- Selection of a strategy for performance

A set of above issues are *all sequential* in the sense that they divide decision processes into parts that always come in the same order or sequence. This approach might be criticized in such a way that the decision process can, in a general fashion, be divided into consecutive stages. Some empirical material indicates that the "stages" are performed in parallel rather than in sequence. A more realistic model should allow the various parts of the decision process to come in different order in different decisions.

Bayesian decision theory and relevant algorithms are the most popular tools for the DM (Raftery, 1996a, b). But there is very important disadvantage. One has to introduce a prior probability distribution for a set of the parameters to be estimated (Weakliem, 1999). Classical decision theory, namely Wald's maximin paradigm, is another direction in studies in the DM (Ben-Tal et al., 2006; Kouvelis and Yu, 1997). This general approach to optimization permitted to develop the *mathematical programming* (MP) models (Ecker and Kupferschmid, 1988; Thie, 1988; Kouvelis and Yu, 1997).

3.1. MATHEMATICAL PROGRAMMING

From an analytical perspective (Dantzig, 1949; Kantorovich, 1939, 1966), a mathematical program tries to identify an extreme (i.e., minimum or maximum) point of a function $\mathbf{f}(x_1, x_2, ..., x_n)$, which furthermore satisfies a set of constraints, e.g. $\mathbf{g}(x_1, x_2, ..., x_n) \geq \mathbf{b}$. Linear programming is the specialization of mathematical programming to the case where both, function f – to be called the objective function – and the problem constraints are linear.

From an applications perspective, mathematical (and therefore, linear) programming is an optimization tool, which allows the rationalization of many managerial and/or technological decisions required by contemporary techno-socio-economic applications. An important factor for the applicability of the mathematical programming methodology in various application contexts is the computational tractability of the resulting analytical models. Under the advent of modern computing technology, this tractability requirement translates to the existence of effective and efficient algorithmic procedures able to provide a systematic and fast solution to these models. For Linear Programming problems, the Simplex algorithm, discussed later in the text, provides a powerful computational tool, able to provide fast solutions to very large-scale applications, sometimes including hundreds of thousands of variables (i.e., decision factors). In fact, the Simplex algorithm was one of the first *Mathematical Programming* algorithms to be developed (Dantzig, 1949), and its subsequent successful implementation in a series of applications significantly contributed to the acceptance of the broader field of Operations Research as a scientific approach to decision making.

3.2. LINEAR PROGRAMMING

A Linear Programming (LP) problem is a special case of a *Mathematical Programming* problem (Dantzig, 1949; Gass, 1958; Kantorovich, 1939, 1966).

3.2.1. *Illustrative Example*

Let us consider a simple example of the MP problem formulation (Kantorovich, 1966). Assume that a company produces two types of products P_1 and P_2. Production of these products is supported by two workstations W_1 and W_2, with each station visited by both product types. If workstation W_1 is dedicated completely to the production of product type P_1, it can process 40 units per day, while if it is dedicated to the production of product P_2, it can process 60 units per day. Similarly, workstation W_2 can produce daily 50 units of product P_1 and 50 units of product P_2, assuming that it is dedicated completely to the production of the corresponding product. If the company's profit by disposing one unit of product P_1 is $ 200 and that of disposing one unit of P_2 is $ 400, and assuming that the company can dispose its entire production, how many units of each product should the company produce on a daily basis to maximize its profit?

First notice that this problem is an optimization problem. Our objective is to maximize the company's profit, which under the problem assumptions, is equivalent to maximizing the company's daily profit. Furthermore, we are going to maximize the company profit by adjusting the levels of the daily production for the two items P_1 and P_2. Therefore, these daily production levels are the control/decision factors, the values of which we are called to determine. In the analytical formulation of the problem the role of these factors is captured by modelling them as the problem *decision variables*:

- X_1 := number of units of product P_1 to be produced daily
- X_2 := number of units of product P_2 to be produced daily

In the light of the above discussion, the problem objective can be expressed analytically as:

$$f(X_1, X_2) = 200X_1 + 400X_2 \tag{1}$$

Equation (1) will be called the objective function of the problem, and the coefficients 200 and 400, which multiply the decision variables in it, will be called the objective function coefficients.

Furthermore, any *decision* regarding the daily production levels for items P_1 and P_2 in order to be realizable in the company's operation context must observe the production capacity of the two workstations W_1 and W_2. Hence, our next step in the problem formulation seeks to introduce these technological constraints in it. Let's focus first on the constraint, which expresses the finite production capacity of workstation W_1. Regarding this constraint, we know that 1 day's work dedicated to the production of item P_1 can result in 40 units of that item, while the same period dedicated to the production of item P_2 will provide 60 units of it. Assuming that production of one unit of product type $P_i (i = 1,2)$, requires a constant amount of processing time $T_{1i} (i = 1,2)$ at workstation W_1 , it follows that: $T_{11} = \frac{1}{40}$ and $T_{12} = \frac{1}{60}$. Under the further assumption that the combined production of both items has no side-effects, i.e., does not impose any additional requirements for production capacity of workstation (e.g., zero set-up times), the total capacity (in terms of time length) required for producing X_1 units of product P_1 and X_2 units of product P_2 is equal to:

$$\frac{1}{40}X_1 + \frac{1}{60}X_2 .$$

Hence, the technological constraint imposing the condition that our total daily processing requirements for workstation W_1 should not exceed its production capacity, is analytically expressed by:

$$\frac{1}{40}X_1 + \frac{1}{60}X_2 \leq 1 \tag{2}$$

Note that in equation (2) time is measured in days. Following the same line of reasoning (and under similar assumptions), the constraint expressing the finite processing capacity of workstation is given by:

$$\frac{1}{50}X_1 + \frac{1}{50}X_2 \le 1 \tag{3}$$

Constraints (2) and (3) are known as the technological constraints of the problem. In particular, the coefficients of the variables $X_i (i = 1,2)$ in them, $\frac{1}{T_{ij}} (i = 1,2)$, are known as the technological coefficients of the problem formulation, while the values on the right-hand-side of the two inequalities define the right-hand side vector of the constraints.

Finally, to the above constraints we must add the requirement that any permissible value for variables $X_i (i = 1,2)$ must be nonnegative since these values express production levels. These constraints are known as the variable sign restrictions. Combining equations (1)–(3), the analytical formulation of our problem is as follows:

$$\max f(X_1, X_2) = 200X_1 + 400X_2 \tag{4}$$

$$\frac{1}{40}X_1 + \frac{1}{60}X_2 \le 1$$

$$\frac{1}{50}X_1 + \frac{1}{50}X_2 \le 1$$

$$X_i \ge 0 (i = 1,2)$$

3.3. THE GENERAL LINEAR PROGRAMMING FORMULATION

Generalizing formulation (3), the general form for a Linear Programming problem is as follows (Thie, 1988):

Linear Objective Function (LOF) maximization:

$$\max\{f(X_1, X_2, ..., X_n)\} = \max\{\sum_{i=1}^{n} c_i X_i\} \tag{5}$$

under Linear Constraints (LC):

$$\sum_{j=1}^{n} a_{ij} X_j \begin{pmatrix} \le \\ or \\ = \\ or \\ \ge \end{pmatrix} b_i, (\mathrm{i} = 1, ..., m) \tag{6}$$

The LC (6) might be used in important particular cases, when variables signs are prescribed:

$$(X_j \geq 0) or (X_j \leq 0), (j = 1,...,n) \tag{7}$$

We conclude our discussion on the general LP formulation, by formally defining the solution search space and optimality. Specifically, we shall define as the feasible region of the LP of equations (4)–(6), the entire set of vectors $\mathbf{X} = (X_1,...,X_n)^T$ that satisfy the LC of (4) and the sign restrictions of (7). An optimal solution to the problem is any feasible vector that further satisfies the optimality requirements expressed by (5)–(7). Introducing integrality requirements for some of the variables in an LP formulation turns the problem to one belonging in the class of (Mixed) Integer Programming (MIP) or Integer Programming (IP) (Gomory, 1963; Korbut and Finkelstein, 1969).

3.4. GRAPHICAL LP'S INTERPRETATION

In this section, we consider a solution approach for LP problems, which is based on a geometrical representation of the feasible region and the objective function (Thie, 1988). In particular, the space to be considered is the n-dimens ional space with each dimension defined by one of the LP variables (X_1, X_2). Thus we present an illustration for the two-variable case.

We start our investigation regarding the geometrical representation of 2-var linear constraints by considering first constraints of the *equality type*, i.e.,

$$a_1X_1 + a_2X_2 = b \tag{8}$$

It is a well-known result that, assuming $a_2 \neq 0$, this equation corresponds to a straight line with slope $s = -\dfrac{a_1}{a_2}$ and intercept $d = \dfrac{b}{a_2}$. In the special case where $a_2 = 0$, the solution space (locus) of equation (8) is still a straight line perpendicular to the X_1 -axis, intersecting it at the point $(\frac{b}{a_1}, 0)$. Notice that the presence of an equality constraint restricts the dimensionality of the feasible solution space by one degree of freedom, i.e., it turns it from a planar area to a line segment.

Consider the *inequality constraint*:

$$a_1 X_1 + a_2 X_2 \begin{pmatrix} \le \\ or \\ \ge \end{pmatrix} b \tag{9}$$

The solution space of this constraint is one of the closed *half-planes* defined by the equation (9). To show this, let us consider a point (X_1, X_2), which satisfies equation (9) as equality, and another point (X_1', X_2') for which equation (9) is also valid. For any such pair of points, it holds that:

$$a_1 (X_1' - X_1) + a_2 (X_2' - X_2) \begin{pmatrix} \le \\ or \\ \ge \end{pmatrix} 0 \tag{10}$$

Interpreting the left side of (10) as the inner (dot) product of the two vectors $\mathbf{a} = (a_1, a_2)^T$ and $\Delta\mathbf{X} = ((X_1' - X_1), (X_2' - X_2))^T$, and recognizing that $\mathbf{a}^T \cdot \Delta\mathbf{X} = |\mathbf{a}| \cdot |\Delta\mathbf{X}| \cos(\mathbf{a}, \Delta\mathbf{X})$, it follows that line $a_1 X_1 + a_2 X_2 = b$, itself, can be defined by point (X_1, X_2) and the set of points (X'_1, X'_2) such that vector **a** is at right angles with vector $\Delta\mathbf{X}$. Furthermore, the set of points (X'_1, X'_2) that satisfy the > (<) part of equation (10) have the vector $\Delta\mathbf{X}$ forming an acute (obtuse) angle with vector **a**, and therefore, they are "above" ("below") the line. Hence, the set of points satisfying each of the two inequalities implied by equation (9) is given by one of the two half-planes the boundary of which is defined by the corresponding equality constraint. Figure 4 summarizes the above discussion.

An easy way to determine the half-plane depicting the solution space of a linear inequality, is to draw the line depicting the solution space of the corresponding equality constraint, and then test whether the point (0,0) satisfies the inequality. In case of a positive answer, the solution space is the half-space containing the origin, otherwise, it is the other one.

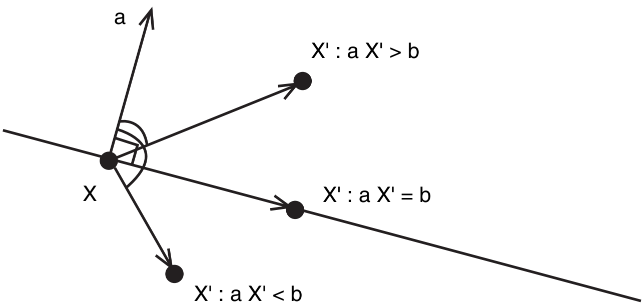

Figure 4. Half-planes: the feasible region of a linear inequality.

From the above discussion, it follows that the feasible region for the prototype LP of equation (4) is the shaded area in Figure 5:

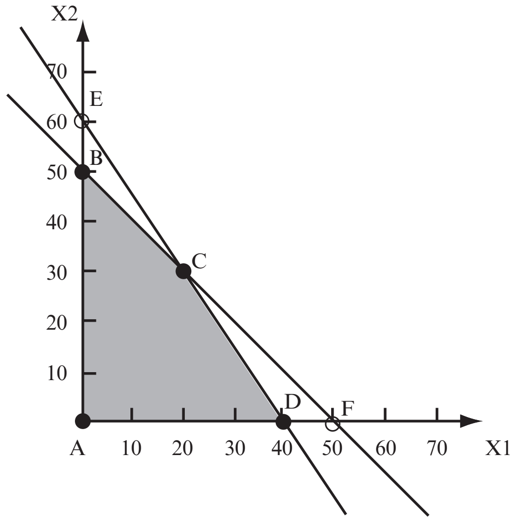

Figure 5. The feasible region of the example LP considered in 3.4.

Next step is a maximization (minimization) of objective function. The most typical way to represent a two-variable function $(a_1X_1 + a_2X_2)$ is to perceive it as a surface in an (orthogonal) three-dimensional space, where two of the dimensions correspond to the independent variables X_1 and X_2, while the third dimension provides the function value for any pair (X_1, X_2). However, in the context of our discussion, we are interested in expressing the information contained in the two-variable LP objective function $(a_1X_1 + a_2X_2)$ in the Cartesian plane defined by the two independent variables X_1 and X_2. For this purpose, we shall use the concept of contour plots. Contour plots depict a function by identifying the set of points (X_1, X_2) that correspond to a constant value of the function $(a_1X_1 + a_2X_2) = a$, for any given range of a ‘s. The plot obtained for any fixed value of a is a contour of the function. Studying the structure of a contour is expected to identify some patterns that essentially depict some useful properties of the function. In the case of LP’s, the linearity of the objective function implies that any contour of it will be of the type:

$$(a_1X_1 + a_2X_2) = a \tag{11}$$

i.e., a straight line. For a maximization (minimization) problem, this line will be called an isoprofit (isocost) line. Assuming that $c_2 \neq 0$, equation (11) can be rewritten as:

$$X_2 = -\frac{c_1}{c_2} X_1 + \frac{a}{c_2},$$

which implies that by changing the value of a, the resulting isoprofit/ isocost lines have constant slope and varying intercept, i.e., they are parallel to each other (which makes sense, since by the definition of this concept, isoprofit/isocost lines cannot intersect). Hence, if we continuously increase a from some initial value a_o, the corresponding isoprofit lines can be obtained by "sliding" the isprofit line corresponding to $(a_1X_1 + a_2X_2) = a_o$ parallel to itself, in the direction of increasing or decreasing intercepts, depending on whether c_2 is positive or negative.

The "sliding motion" suggests a way for identifying the optimal values for, let's say, a max LP problem. The underlying idea is to keep "sliding" the isoprofit line $(a_1X_1 + a_2X_2) = a_o$ in the direction of increasing a 's, until we cross the boundary of the LP feasible region. The implementation of this idea on the LP of equation (4) (see also Figure 5) is depicted in Figure 6. From Figure 6, it follows that the optimal daily production levels for the prototype LP are given by the coordinates of the point corresponding to the intersection of line $\frac{1}{50}X_1 + \frac{1}{50}X_2 = 0$ with the X_2-axis, i.e., $X_1^{opt} = 0; X_2^{opt} = 50$. The maximal daily profit is $200 \cdot 0 + 400 \cdot 50 = 20.000$ \$.

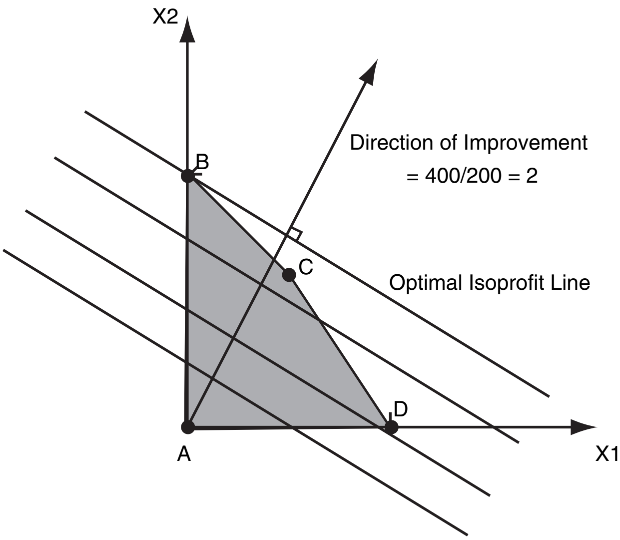

Figure 6. Graphical solution of the example LP (6).

Notice that the optimal point is one of the “corner” points of the feasible region depicted in Figure 3. Can you argue that for the geometry of the feasible region for 2-var LP’s described above, if there is a bounded optimal solution, then there will be one which corresponds to one of the corner points? (This argument is developed for the broader context of n-var LP’s in the next section.).

There are two fail options related to LP problem solution. First is absence of any solution, when feasible region is empty. Consider again the original example (6), modified by the additional requirements (imposed by the company’s marketing department) that the daily production of product P_1 must be at least 30 units, and that of product P_2 should exceed 20 units. These requirements introduce two new constraints into the problem formulation, i.e., $X_1 \geq 30$; $X_2 \geq 20$. Attempting to plot the feasible region for this new problem, we get Figure 4, which indicates that there are no points on the (X_1, X_2)-plane that satisfy all constraints, and therefore our problem is infeasible (over-constrained).

Second particular option is an unbounded solution. In the LP’s considered above, the feasible region (if not empty) was a bounded area of the (X_1, X_2)-plane. For this kind of problems it is obvious that all values of the LP objective function (and therefore the optimal) are bounded.

Summarizing the above discussion, we have shown that a 2-var LP can either

- Have a unique optimal solution which corresponds to a “corner” point of the feasible region, or
- Have many optimal solutions that correspond to an entire “edge” of the feasible region, or
- Be unbounded, or
- Be infeasible

4. Application to the Weather Ensemble Forecasting

4.1. MULTI-USER CONSORTIUM

Requirements for weather forecast products can vary significantly and are typically oriented to the needs of specific user groups. Nonetheless, in many respects the requirements are rather similar, such as a common need for information on basic variables such as temperature, humidity, and precipitation (mean, maximum, minimum). On other hand, it is hardly to imagine that every user could provide their own forecast product because of substantial costs of both inputs observing data and model development/maintenance.

In the case of specified forecast some additional observations might be required to increase prescribed reliability or probability. Therefore, it is more rational to select a set of few forecast models and observing systems, which respond to the right extent to optimal set of requirements generated by multi-user economical and mathematical model. Consortium of multi-user will get benefits of mathematically optimal decisions under minimal costs. User investments in a weather forecast system should be proportional to their expected benefits derived from the early warning of short-term weather fluctuations or extreme events. Under circumstances a consortium of multi-users approach would be more likely to derive benefits from the mathematically optimal decisions for minimum investment. Meteorological community is interested in such approach in order to reduce a number of observing programs and forecasting models. Latter might become a background to increase its efficiency (Pokrovsky, 2005, 2006, 2009).

4.2. ELEMENTARY STATEMENT OF THE PROBLEM

Let us assume that there are *n users* of climate forecasting data with their *n* benefits of early warning: c_i (i = 1,.., *n*). These users are interested to forecast *m* specific *meteorological events* numerated as j = 1,…*m*. But usefulness of them are various and described by matrix of coefficients A=$\{a_{ij}\}$. Each magnitude a_{ij} can be considered as expenses of *i*-th user with account for *j*-th meteorological event delivered by some forecast model. *Minimum efficiency* for *i*-th user is bounded by value $b_i^{\min}$. Let us introduce *decision maker variable*:

$$x_i = \begin{Bmatrix} 1, if\_i-th\_user\_adopts\_forecast\_data \\ 0, otherwise \end{Bmatrix}$$

Now we come to formulation of optimization problem for $\{ x_i \}$:

$$\max \sum_{i=1}^{n} c_i x_i \qquad (12)$$

under constraints:

$$\sum_{j=1}^{n} a_{ij} x_j \geq b_i^{\min} \qquad (13)$$

Another interpretation of coefficients and more complex method to derive them is possible. A generalization to the forecast multi-model case is evident.

4.3. ILLUSTRATIVE EXAMPLE

Let us consider a multi-user decision making to many meteorological events taken into account simultaneously. We used the ECMWF EPS prediction system for T850 anomaly, Europe, Jan–Feb, 1998 (see Figure 7) (details in Richardson, 2000) with n = 3 (number of users), m = 4 (number of meteorological events). Selected users respond to different values of the cost to loss ratio: C/L. The higher C/L – the less expected losses L under fixed protective expenses C, or highest protective costs under constant losses. Thus, the requirements of the user 3 are weaker than those of the user 1. On other hand, the EPS economical efficiencies presented in the raw of Table 1 are quite different for various meteorological events to be forecasted. Matrix of the EPS forecast relative economic values are presented in Table 1, minimal efficiencies for each user – in Table 2. We stated more minimal efficiency for the user 3 in order to compensate its maximal C/L value assumed lowest losses or highest protective costs. In the case of equal priorities of all users we come to the optimal solution x_{opt} for (12) constrained by (13) (Table 3). This solution showed that the EPS forecasting system has prior importance for the user 2. Least contribution is related to the user 3. That might be explained by its highest C/L magnitudes. Let us now enhance a priory importance of the user 3 by changing values of target function (1) from c = (1, 1, 1) to c = (0.5, 0.5, 1). Even in this case the user 3 remains at second place after user 1. It is interesting to note that the output for the user 1 is an insensitive one with account to a priory weights.

TABLE 1. Matrix of constraints - $A = \{a_{ij}\}$.

Users	Meteorological events:			
	(T<–8K)	(T<–4K)	(T>+4K)	(T>+8K)
1	0.40	0.36	0	0
2	0.32	0.29	0.32	0.19
3	0.22	0.19	0.41	0.46

TABLE 2. Constraint vector of minimal efficiencies – $b_{min.}$

Users	b_i^{min}
1	0.1
2	0.2
3	0.3

TABLE 3. Optimal decision "x" in the case of equitable users (c = (1, 1, 1), central column) and in the case of priority for the user n 3 (c = (0.5, 0.5, 1), right-hand column).

Users	x_{opt}	x_{opt}
1	2.31	2.26
2	5.21	0.36
3	0.85	1.99

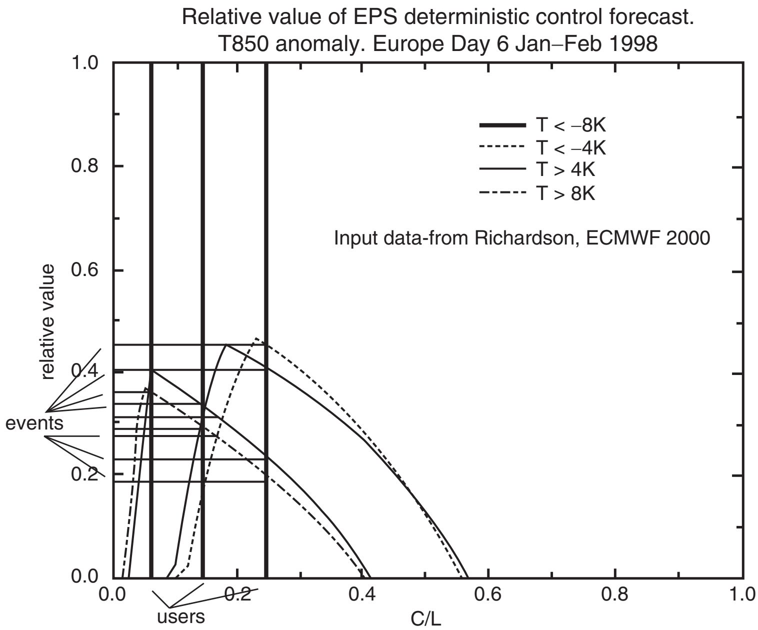

Figure 7. EPS forecast relative values responded to multi-user and multi-event case (Richardson, 2000).

5. Decision Making in Energy Sectors due to Climate Change Projections

5.1. IPCC GLOBAL SCENARIOS

The IPCC developed several scenarios of the GHG emissions scenarios to 2100, together with potential global temperature rise and associated climate impacts (IPCC, 2007). The IPCC scenarios are used here because of absence of similar detailed IEA and WBCSD scenarios concerned CO_2 reduction in an emission. A reduction of 6–7 Gt of carbon (22 Gt CO_2) emissions per year by 2050 compared to the A1B and B2 scenarios (Figure 8) would place us on a 550 ppm trajectory rather than 1,000 ppm CO_2, but a step-change evolution in our energy infrastructure would be required, utilizing resources and technologies such as: (1) a further shift to natural gas nuclear energy; (2) renewables; (3) bio-products; (4) carbon capture and storage; (5) advanced vehicle technologies; and others.

A lower carbon world will require a marked shift in the energy/development relationship, such that similar development levels are achieved but with an average 30% less energy use. Both energy conservation through behaviour changes and energy efficiency through technologies play a role.

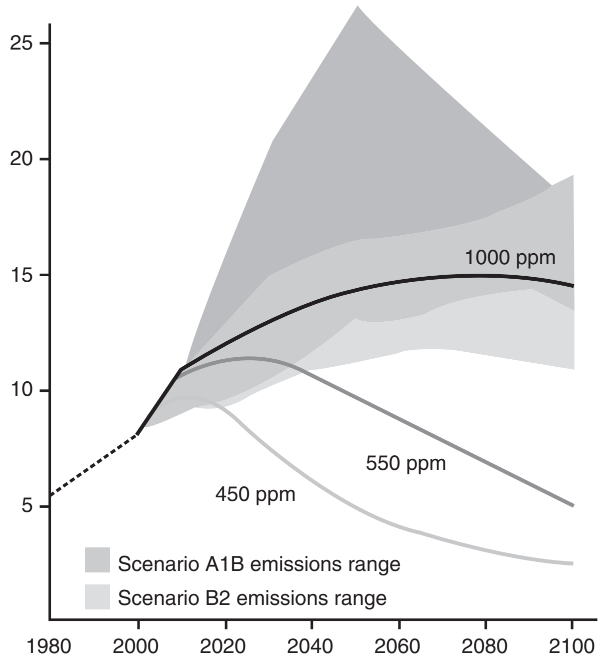

Figure 8. The GHG emissions scenarios to 2100 associated with potential global temperature rise and related climate impacts (IPCC, 2007).

Such a trend is a feature of the IPCC B1 storyline, which sees a future with a globally coherent approach to sustainable development. It describes a fast-changing and convergent world toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies.

5.2. STATEMENT OF REGIONAL OPTIMISATION STRATEGY

Above IPCC approach is relevant for global scale politics. Meanwhile, there is a question how to achieve prescribed emission limits in scale of each state, region and its economy. There are two statements aimed to restriction of GHG emission by means of optimal strategy implementation.

First one is related to minimization of total GHG emission. It might be formulated as following optimisation problem. We need to find a minimum of objective (cost) function:

$$\min\{\varepsilon\} = \min\{\sum_t \sum_i x_{t,i}\varepsilon(t, source(i))\} \tag{14}$$

under constraints:

$$0 < \sum_i x_{t,i}\varepsilon(t, source(i)) \leq \delta(t) \tag{15}$$

Here $\varepsilon(t, source(i))$ is an emission of *i-th* regional source at time *t*. Admissible total regional emission at a given time *t* is $\delta(t)$. Objective function depends on decision making variables $x_{t,i}$, which indicate an individual weight of each emission source at given time *t*. Solution of (14)–(15) LP problem permits to suggest an optimal decision based on desirable relative (proportional) contribution of different sources in a given time slot in order to achieve minimum total emission under individual admissions responded to specific development conditions of *i-th* economic unit.

In many cases it is desirable to follow some prescribed emission scenarios developed for a given state, region or economy sector by international agreement(s). More specific statement of optimisation problem might be suggested in this case. Its main idea is a minimization of the deviation of the GHG emission from projected scenario. Object (cost) function in this case has a following expression:

$$\min\{|\varepsilon - \hat{\varepsilon}|\} = \min\{|\sum_t \sum_i x_{t,i}\varepsilon(t, source(i)) - \hat{\varepsilon}(t)|\} \tag{16}$$

under constraints:

$$0 < |\sum_i x_{t,i}\varepsilon(t, source(i)) - \hat{\varepsilon}(t)| \leq \delta(t) \tag{17}$$

$\hat{\varepsilon}(t)$ is a prescribed emission trajectory for *i-th* source emission in (16) and (17). Admissible deviation from prescribed emission trajectory is described by $\delta(t)$ which is a function of *t*. Solution of (16)–(17) LP problem $\{x_{t,i}\}$ permits to suggest an optimal decision based on desirable relative (proportional) contribution of different sources in a given time slot in order to achieve minimum deviation of emission as function of time under individual admissions responded to specific development conditions of *i-th* economic unit. Next section suggest illustrative example for above approach.

5.3. ROAD TRANSPORT

Road transport GHG emissions contributed 1.5 Gt (gigaton) in 2000. This could rise to over 3.0 Gt by 2050 (WBCSD, 2004a) as the number of vehicles exceeds two billion. If all these vehicles increase efficiency level (e.g. using hybrid or advanced diesel technology) emission could be lower 1.0 Gt by 2050. If 800 million vehicles utilized new hydrogen technology (including novel cell technology) emission could also be lower 1.0 Gt by 2050.

Let us assume that a “step by step” increasing in efficiency of transport technologies is a most realistic scenario. That can lead to a smooth lowering in an emission rate by one car per year. This lowering might de different in various groups of cars. The vehicles provided by hybrid systems give most rapid decreasing in emission rates. Most promising is a hydrogen technology reducing GHG emission rate to zero. The hybrid technology is a more wide used now. It can lead to substantial contribution in total emission rate reduction in a group of vehicles (see Figure 9). Slower progress in emission rate decreasing is expected in a group of tracks with diesel engines.

Having in disposal a specific scenario for GHG emission rate evolving for next several decades in different group of transport one can use the DM algorithms developed in Section 4 to a problem of optimisation in development of various transport group to minimize total emission effect. In fact, let us introduce following notation:

$$a_{ij} = \varepsilon(t_j, source(i)) \tag{18}$$

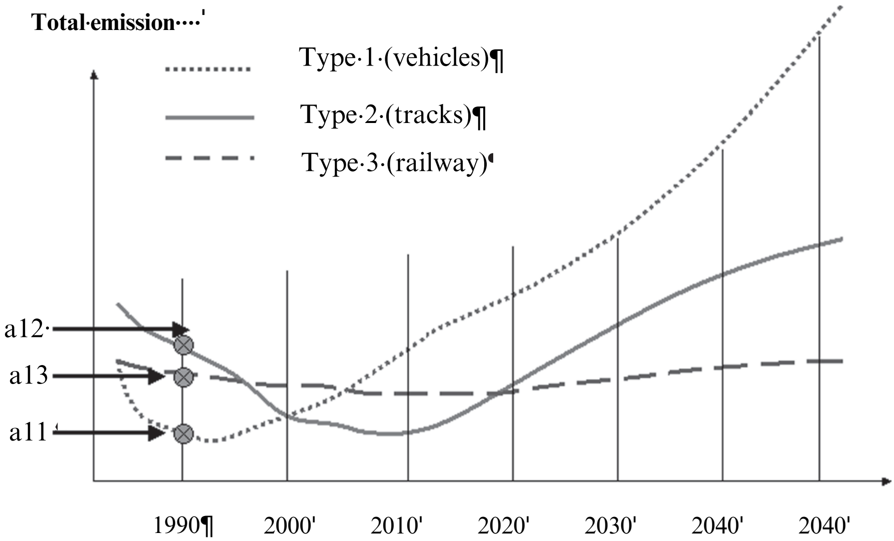

Figure 9. Emission rates in different group of transport: a scenario up to 2050.

for emissions considered in formulas (14)–(17) discussed in Section 5.2. Coefficients a_{ij} entered in formula (6) (see Section 3) might be deduced from emission scenario presented in Figure 9. Further, decision maker can define the upper and lower admissible total emission rates per year and introduce these values as coefficients $b_i$in (6). Function (5) might be determined on a base of regional conditions by decision maker.

Our nearest aim is to apply above technique to some climate change and energy supply scenarios discussed in this paper.

6. Conclusion

Approach based on MP and LP found a wide application area in many branches of economical sciences. It assisted in decision making related to multidimensional target function constrained by many linear cost restrictions. Major advantages of this approach with account to alternative Bayes techniques are related to: (1) a more simple interpretation of a prior uncertainty in search parameters by means of the confidential bands instead of the probability distributions function; (2) a more simple computations and more CPU time saving in a multidimensional case. This paper shows that similar problems arisen in many important practical areas might be efficiently solved by described approach.

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HOW SYNOPTIC DATA CAN BE USED TO INVESTIGATE THE EFFECT OF CLIMATE CHANGE ON BLACK-OUT RISK? A STUDY ON TRENDS IN SNOW DEPOSITION ON POWER LINES

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Abstract. The paper concerns the study of long time trend of snowfall events causing accretion of ice sleeves on Italian overhead electric lines. This effort is needed to assess the impact of climate change on the continuity and safety of electrical service. In recent years, wide areas of Italy have experienced icing events dangerous for the electric lines, mainly for snow precipitations. The accretion of sleeves on wires involves several meteorological variables (temperature, precipitation, wind intensity and direction). However how these physical variables interact to give rise to critical icing events is an open research issue. Fifty-year long meteorological data series are available only from standard WMO measurements. The work presented in this paper investigates the long term trend of snowfall conditions, based on standard observations, which yield ice accretion on wires. The results show some evident local climatic trend further analysis and more accurate observations are needed to corroborate these findings.

Keywords: Wet-snow icing; ice load; synoptic weather data; long term trends

1. Introduction

The impact of future climate change on infrastructures of the electric system of a country is manifold. In order to assess this impact, it is necessary the use of long time series of meteorological data. Standard WMO measurements are often the only source of information for this kind of study. One of the extreme meteorological events affecting electric line is the ice accretions on wires.

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Figure 1 shows how icing can heavily influence the reliability of electric lines. In many northern countries, as Canada, Norway, the most important atmospheric phenomenon involved in icing is the so called “in-cloud icing”. On the other hand, in more temperate countries like Italy, France and Japan, icing caused by wet-snow deposition is also important (Admirat et al., 1990; Eliasson et al., 2000). In these countries heavy snowfall events are more frequent than low clouds with high content of water, as in colder countries. Unfortunately, in Italy, no specific research about wet-snow accretion has been carried out except for the study conducted by (Paoli and Tavano 1983), which is about ice accretion on conductors linked to the in-cloud icing conditions in a mountain region (the Ligurian Apennines).

In recent years, wide areas of Italy, principally at low altitudes, have experienced wet-snow icing events, and some of them have caused serious damages along electric lines with black-out occurrences (Bassini et al., 2006). These areas have the highest electric lines density and the structures are built with less restrictive hardiness criteria.

A recent work on correlation between winter electric failures and meteorological local conditions (Bonelli et al., 2008) shows that the most of failures occurs during snowfall events characterized by air temperature ranging between −1°C and +2°C, duration of more than 12 h and wind intensity ranging in a wide interval. The last one is an undefined condition since electric lines can sometimes collapse due to the action of wind alone.

Figure 1. Damages on electric line due to wet-snow accretion on wires.

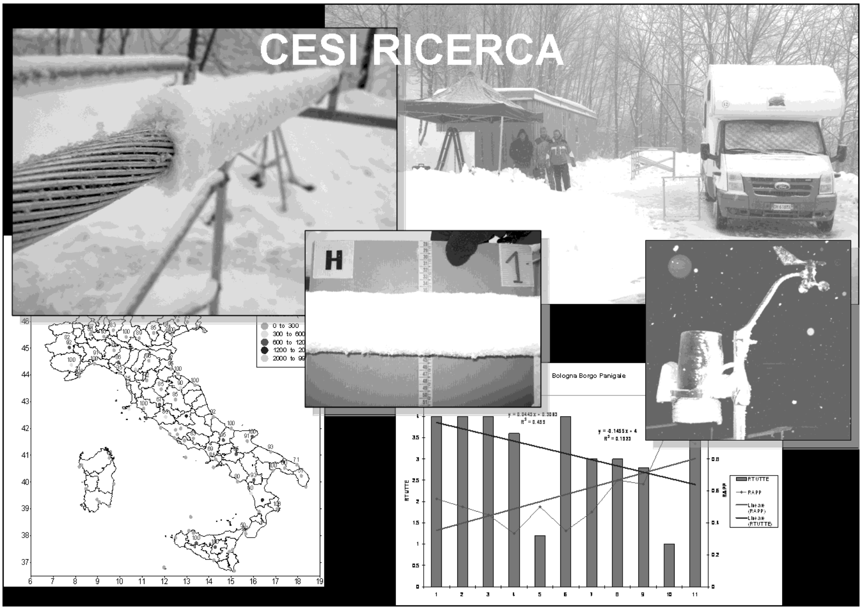

Figure 2. ERSE activity research on wet snow deposition.

ERSE, in the frame of its mission concerning the investigation of the relation between electric system and environment, is involved in a research program devoted to improve the knowledge of the wet-snow accretion on the electric lines in Italy. The activity, as shown in Figure 2, includes experimental campaign, evaluation of ice accretion models, extracting information about long time trends of the wet snowfall events from standard meteorological data-set.

The present work studies in depth how long term trends of meteorological conditions, favourable for ice accretions, can be deduced analyzing standard WMO reports.

2. Long Term Trends in Snow Deposition

Probably, the longest homogeneous time series of ice measurements in the world is that from Studnice in the Czech Republic (Fikke et al., 2007). Studnice series represents the annual maxima ice loads on a wire from 1940 to 1998, mainly concerning the in-cloud ice accretions. The paper underlines the dramatic increase of ice accretion in the last 20 years. It is not clear if and how this increase is related to global warming but the scientific and electric communities should be aware of a possible increase in risk of the ice accretion. Regarding Italy, no series like those of Studnice are available, neither for ice load, nor for wet-snow accretion; therefore only standard WMO, as SYNOP and METAR reports, can be used to investigate long time behaviour of weather conditions responsible of wet-snow accretion. These reports contain measurements of the main meteorological parameters (temperature, wind, pressure), the observations of hydrometeors (for example: rain, snow and hail) and others atmospheric conditions. WMO regulation code (WMO-No.8; 1983) provides rules in order to individuate and report those phenomena.

First of all, it is important to understand how the wet-snow accretion works. Wet-snow contains flakes made up of ice crystals suspended in a liquid water matrix at temperature just above the freezing point, usually ranging between 0.5°C and 2°C. When the snow flakes reach the wire, the ice crystals bon together and the wind contributes to the accretion of an ice-sleeve on the wire, that can have a wide range of density (Leblond et al., 2006). Sometimes a following decrease in air temperature may contribute to better bind the sleeve around the wire. Alternatively the rotation of the wire helps ice to fall down. Wet-snow accretion can produce an extra linear load on the wire up to 10 kg/m, that may cause the breaking of the line supports which is often followed by an electrical failure. A simple sketch of ice accretion by wet-snow is represented in Figure 3. The complexity of this phenomenon is approached by Sakamoto and Admirat (Sakamoto, 2000; Admirat et al., 1990) developing some ice accretion models that use standard meteorological data as input. From these models is evident that accretion is triggered by a narrow range of values for temperature and wind, during the snowfall event: air temperature must be around 0°C and wind intensity less than 10 m/s.

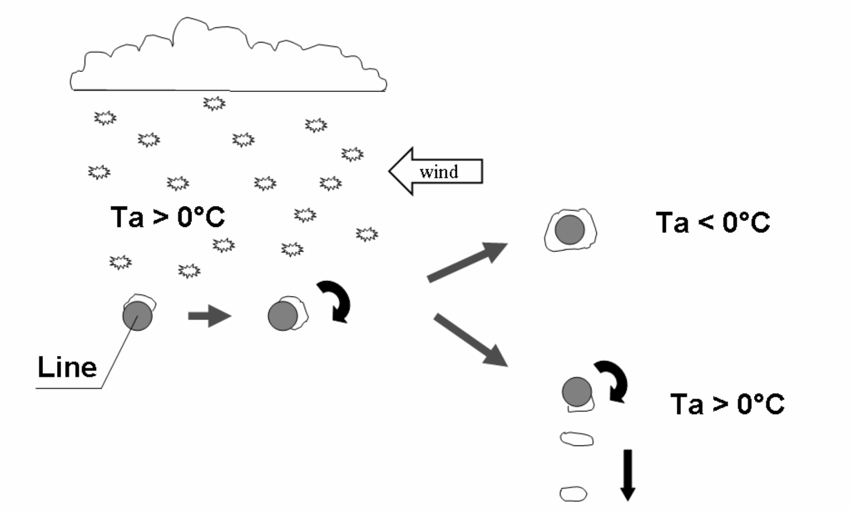

Figure 3. Ice accretion scheme on an overhead line due to wet-snow precipitations: the rotation of the wire enhances the accretion of the snow sleeve, wind and temperature contribute to stick snow on the wire.

Because of wet-snow icing is not normally measured by standard weather stations, this work tries to define some possible meteorological conditions for wet-snow precipitation, by means of standard WMO parameters, regularly detected by manual stations. The "*present weather*" observation on SYNOP and METAR reports, has been used as the main indicator of snowfall. In particular, only the observations labelled as "70" to "79", in the SYNOP and "SN" in the METAR codes, related to snowfall events, are extracted.

The average temperature during every snowfall has been computed in order to classify "warm" or "cold" event respectively the one above or below 0°C. Only long snowfall events are selected in order to reject some erroneous and isolated observations. For this reason, an event is defined only when its duration is more than 6 h and the time interval between two snow observations is less than 12 h. The definition of the two kind of snowfall events is shown in Figure 4.

The definition of warm snowfall event, used in this work, is practical to limit the whole meteorological conditions to only those potentially starting the ice accretion process. In this way the number of warm snowfall is only an upper limit of the number of accretion events.

Series of snowfall events have been extracted from a 50-year data set of synoptic reports, provided by Italian National Air Force Meteorological Service. The map in Figure 5 reveals that, due to the lack of data for many synoptic stations, only six series, mainly located in the northern part of Italy, have been used to investigate long term trends. They come from the

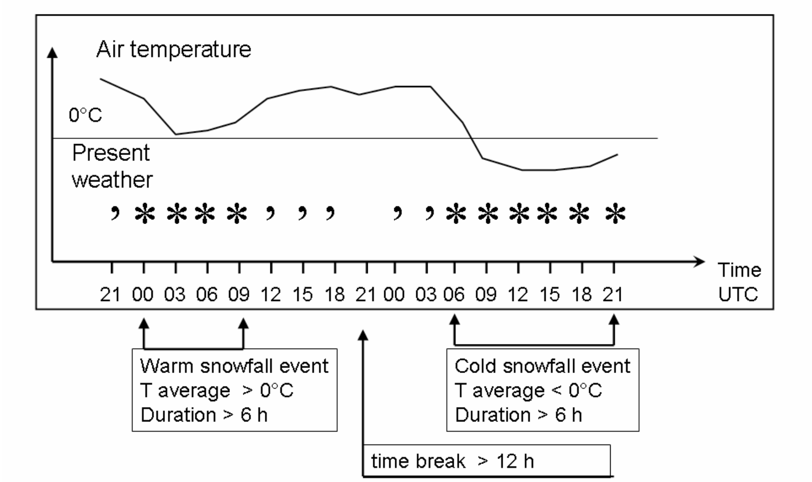

Figure 4. Snowfall event definition (stars means snow, commas drizzle) and the air temperature, more or less than 0°C, determines the discrimination between warm and cold events.

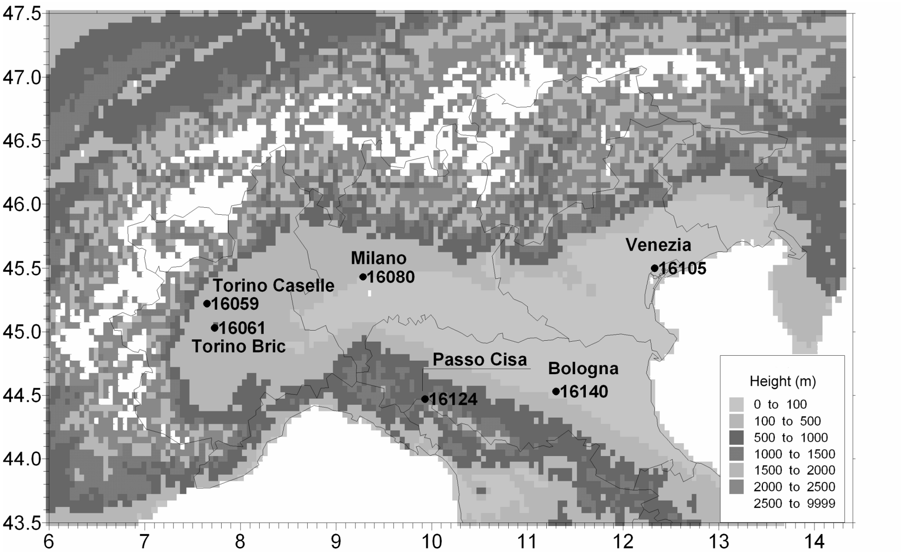

Figure 5. The study area: six stations cover a wide area of northern Italy.

stations of Torino Caselle, Torino Bric, Milano Linate, Bologna Borgo Panigale, Venezia Tessera and Cisa Mountain Pass. These time series are available from 1951 to 2005, except for Venezia station where the data are available since 1961.

For each station series, the annual number of cold and warm snowfall events has been computed and the long term trend analyzed. Only three series are shown in Figures 6–8.The number of snowfall events are grouped in 5 years interval from 1951 to 2005. The grey bars are related to all snow events (AE), the dark grey bars only to warm events (WE). With the same grey tone, the two dashed lines were computed by the least square method, and their equation parameters are shown on the graph. For each series the Mann Kendall test has been computed for assessing the trend statistical significance (Bihrat, 2002).

Torino Caselle, a station located in the west part of the Po Plain at about 280 m above sea level, has very variable numbers of AE and WE across the series, but WE doesn’t reveal a significant trend, instead of AE that significantly decreases at 79% level of confidence (l.c.).

The graph in Figure 6, for the station of Torino Bric, a hill near the city of Torino, 700 m high, shows a slight decrease for both series, but they don’t seem significant at any level of confidence. The histogram for Milano, displays no significant decrease in AE and WE that remain quite constant as in Torino.

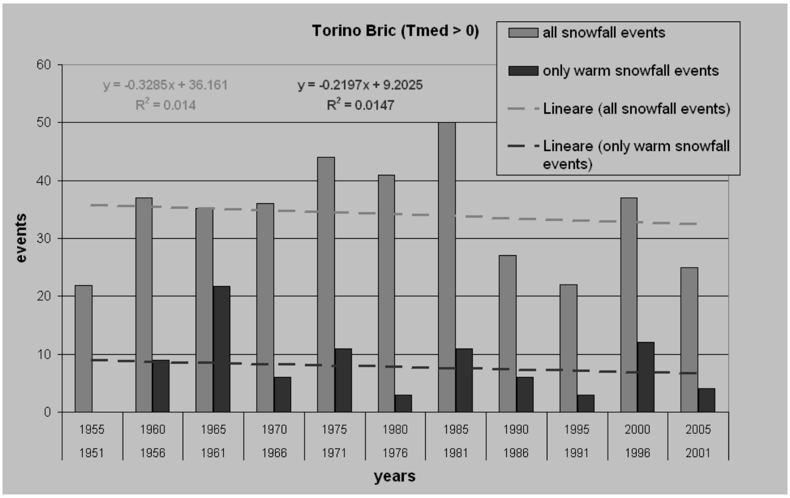

Figure 6. Torino Bric time series: there are no significant trends for both series.

Bologna station presents a decrease of AE (97% l.c.) and a slight but not significant increase of WE. The Venezia time series, Figure 7, that is shorter than the others stations, shows a significant increase of WE (91% l.c.) and a quite constant of AE. The last series, belongs to the only mountain station, Cisa Mountain Pass (1,039 m) on the Liguria Apennines. It is evident in Figure 8 the decrease of AE (96% l.c.), instead of the series of WE that is negligible and it doesn't show any trend.

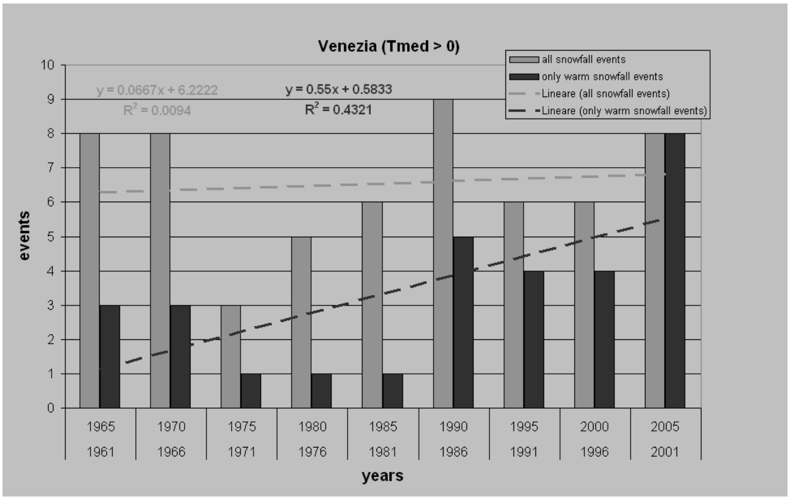

Figure 7. Venezia Tessera time series shows a significant increase in warm snowfall (91% level of confidence); the increase of total snowfalls is not relevant.

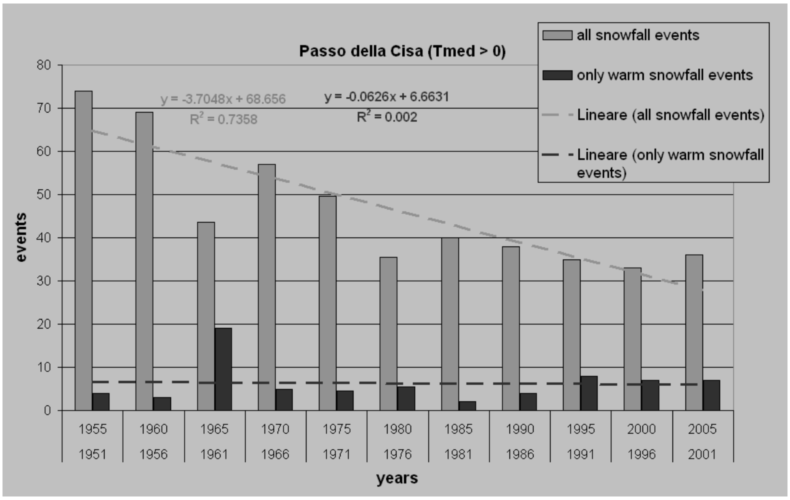

Figure 8. Passo della Cisa time series: it is relevant the strong decrease of total snow events. The warm events are almost constant.

Table 1 summarises the results obtained from the computation of the time series trends for the six stations. The arrows mean an increasing or decreasing trend and "slope" indicates the variation of number of events in a 5 years interval. "MK" refers to Mann Kendall test for the H_0 hypothesis, rejected (yes/no) with different levels of significance (%).

TABLE 1. Verification scores for each time series. The arrows indicate an increase or decrease in the trend and "slope" indicates the variation of number of events in a 5 years interval. "MK" refers to the Mann Kendall test for the H0 hypothesis, rejected (yes/no) with different levels of significance (%).

Station	Period	Tot snowfall	Slope	MK H0 rejected	Warm snowfall	Slope	MK H0 rejected
Torino (285 m)	1951–2005	↓	–0.78	Yes 79%	=	–0.15	No
Bric (709 m)	1951–2005	↓	–0.33	No	↓	–0.22	No
Milano (102 m)	1951–2005	↓	–0.71	No	=	0	No
Venezia (2 m)	1961–2005	=	0.07	No	↑	0.55	Yes 91%
Cisa (1,039 m)	1951–2005	↓	–3.7	Yes 96%	=	0	No
Bologna (51 m)	1951–2005	↓	–0.73	Yes 97%	↑	0.2	No

3. Conclusion

The goal of this study is to assess the actual climatic trend of snow accretion risk on overhead electric lines in Italy. We know that this risk is related to wet-snow condition that causes the snowflakes to stick on the wire. The snowfall event has been defined, by means of the standard WMO variables, with the purpose to separate observed weather condition needed to the snow accretion process from the others. Six meteorological stations, located in Northern Italy, have been selected. The trends for the number of the wet-snow only and total snowfall events have been analyzed with the least mean square technique. The Mann Kendall test has been used to state the level of confidence of non zero slope. Although the total number of snowfall events is generally decreasing, the number of warm snowfall events, necessary for the sleeve accretion, remain constant, except for the northeastern region, where they are increasing. The strongest decrease of total number of snowfall is found on a mountain station, the Cisa Mountain Pass. We are confident that this generalized behaviour could be the effect of a significant slow variation of climate over the area at south of the Alps. It is straight to ask ourselves whether this change is due to the global increase of atmospheric temperature but probably these hypothesis may be supported by other analysis.

4. Appendix: The Mann Kendall Test

The existence of a trend in a series of number of snowfall events is detected by a statistical test. Since these events are not normally distributed and homoscedatisc (homogeneous variance), a non-parametric test has been used, the Mann-Kendall test. The Mann-Kendal test is based on the statistic S as each pair of observed values yi, yj (i>j) of the random variable is inspected to find out whether $y_i > y_j$ or $y_i < y_j$. Let the number of the former type of pairs be P, and the number of the latter type of pairs be M. Then S is defined by the relationship $S = P - M$ and Z follows the standard normal distribution where:

$$
\begin{aligned}
Z &= (S-1)/\sigma_s \qquad && \text{if} \quad S > 0 \\
Z &= 0 && \text{if} \quad S = 0 \\
Z &= (S+1)/\sigma_s && \text{if} \quad S < 0
\end{aligned}
$$

and:

$$\sigma_s = \sqrt{n(n-1)(2n+5)\frac{1}{18}}$$

The null hypothesis that there is no trend, is rejected when the computed Z value is greater then $Z_{\alpha/2}$ in absolute value. The Mann Kendall test has been computed for each series to assess the significance of the non zero trend. H_0 is rejected at different levels of significance α. The authors have used the R software to compute the MK test.

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NATURAL RISKS MANAGEMENT IN THE GAS TRANSMISSION SYSTEM (GTS) OF RUSSIA AND THE CONTRIBUTION OF CLIMATE SERVICES UNDER GLOBAL CLIMATE CHANGE

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Abstract. The paper reviews statistical information about impacts of extreme natural phenomena and factors on accident rate of Russia's gas transmission system (GTS) and their consequences to secure sustainable gas supply. Special attention is given to anthropogenic factors that worsen emergency situation. Data on rare natural phenomena occurring in the territory of Russia is compared with parameters of emergency situations that affects the GTS elements/components. The authors also highlight the role of climate information and services intended to enhance gas supply sustainability under the global climate change. Natural risks to the GTS are analyzed and evaluated and decision making based on available climate information is considered.

Keywords: Gas transmission system; accident; natural risk; natural hazard; climate change climate information; flood; landslip; karst; geocryological processes

1. Introduction

The Unified Gas Supply System (UGSS) of Russia is an industrial-engineering complex incorporating objects of gas production, processing, storage and distribution that are grouped into a single integrated engineering system through gas transmission system (GTS). For their energy security both our country and Commonwealth of Independent States (CIS), and European countries depend on the reliability of Russian gas supply and attache particular

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significance to sustainable undisturbed operation of technological facilities of Russia's GTS.

The length of the Russian GTS amounts to over 1,52,000 km, which are operated under different natural conditions. The GTS operation process, as a large energy system, is heavily impacted by a great number of factors. Some of these factors, including natural ones, refer to accidents with difficult-to-predict consequences. The existing GTS facilities, as well as the regions to be prospected/identified for GTS construction are under the influence of practically all the known types of hazards (of geological and hydrometeorogical origin), such as earthquakes, landslips, rockfalls, karst and suffusion phenomena, subsidence of loess-type rock, mud flows, floods, extreme meteorological events, etc.

The global warming in the territory of Russia increases the probability, recurrence and distribution of natural disasters (heavy precipitation, high temperatures, strong winds and floods) which contribute to initiating unfavourable geodynamic processes. The existing building norms and codes for long-distance pipelines substantially secure normal operations under natural disasters. At the same time there are objective reasons for the occurrence of emergency situations initiated by natural factors, which may have great effect upon the GTS operations:

- Increased variability of the climatic conditions for the past decade, which results in a growth of recurrence of hazardous hydrometeorological phenomena and activity of exogenous geological (generally landslips and mud flows) and geocryological processes.
- Activation of some dangerous natural processes in natural-anthropological systems, which under undisturbed natural conditions (at a stage of the feasibility study) were not fixed and did not appear to be a serious hazard.
- Extension of the GTS without appropriate infrastructure support in underdeveloped areas, where regular monitoring of natural process was not possible and thus appropriate calculation of construction parameters could not be afforded.

Climate information is of considerable importance, as it allows taking into consideration the ever changing hydrometeorological situation forced by global warming.

Norms and methods, in which initial data are climatic characteristics, are widely used in the gas industry. One can separate out the following major tendencies in using climatic information:

1. When forecasting peak loads and planning gas consumption and distribution. To solve these problems one needs to consider predictive estimates of the climate change while developing long-term energy budget
2. When designing gas production and transportation facilities and during their modernization and rehabilitation. For enhancing functional reliability of designed projects it is necessary to consider possible consequences of the climate change for their whole service life
3. Hydrometeorological support of offshore operations

In this paper the second tendency in applying climatic information will be highlighted in more detail. In this case it is important to identify risk factors and to define safety principles in GTS operation, the solution of which depends on climatic information.

2. Identification of the Most Serious Risk Factors

Identification of the most serious risk factors is an important step in evaluating natural risk to the GTS facilities (Vlasova, 2006; Vlasova and Rakitina, 2007).

The analysis of engineering inspection reports on causes of accidents for the period between 1990 and 2007 has shown that the share of natural hazards in the accident rate on linear pipeline portions amounts to 7.8%. On the other GTS facilities (mainly at gas distribution stations [GDS]) this share accounts for 7%.

The causes of “natural” accidents for linear pipeline portions are as follows:

- Activation of landslip processes (5% of the total accidents)
- Rainfall floods (1.7%)
- Mud flow processes (0.6%)
- Loss of permafrost load-carrying capacity (0.4%)
- Soil subsidence (0.2%)

The causes of “natural” accidents for GDS are as follows:

- Lighting (5.6%, excluding linear pipeline portions)
- Underflooding with underground waters (1.4%)

Under the realization of natural risk sources the occurrence of accidents on linear elements is eight-fold of that for other facilities of the GTS. Besides, linear elements are subjected to a larger number of risk sources. A considerable part of these natural hazards processes are amplified by the global climatic change.

By target components "natural" accidents occurring on linear sections can be divided into: linear pipeline portions (54%), aerial crossings (20%) and river bed and flood-plain sections of underwater crossings (11%).

3. The Influence of Natural Factors on the GTS Stability

To evaluate the influence of natural hazards on the GTS stability let us consider consequences of some accidents caused by extreme natural processes of different strength and occurrence, including floods, landslips, mud flows and cryogenic processes. At the same time we investigate the potential contribution of climate information and services in the risk management of emergency situation.

3.1. HIGH WATER AND RAINFALL FLOOD

The analysis of accident rate carried out for the period since 1971 shows that there have not been any accidents at compressor stations and gas distribution station initiated by floods. Stringent requirements for designing compressor stations do not allow, in general, their construction within flooding areas. At the same time, over 30 GDSs, more than 100 wells and many other facilities are located within zones of flood risk.

Linear pipeline portions are the components which are subjected to flooding to the largest extent. Hazardous zones are also areas of underwater pipeline crossings. In the GTS there are over 2,500 pipe runs that cross water obstacles (over 1,600 crossings), with a total length (only in river bed areas) being over 1,400 km.

Let us compare data on floods of infrequent occurrence in the territory of Russia and parameters of emergency situations at the GTS facilities.

Large floods (with the occurrence of one time in 55–100 years) and catastrophic floods (with the occurrence of one time in 100–200 years and less) are a result of combination of maximum factors that form these floods. These factors exceed the norm by 1.5–3 times and, as a rule, are distributed over vast territory. For example, in 1966 and 1969 the floods were observed in Western and Eastern Siberia, in the Ob, Yenisei and Lena basins. In 2002, the flood was observed in the Northern Caucasia. During the periods of high water of infrequent occurrence one may note floods related to emergency discharge of water from reservoir storages. In some years, when water inflow into reservoir storages exceeds their maximum volume, there appears the necessity in discharging maximum volume of water. Flooding of riverside areas due to large-volume discharges in tail waters of reservoir storages during spring flood of infrequent occurrence was observed on the Volga-Kama cascade in 1979, 1985, 1991 and 1992.

It should be noted that, from the above mentioned catastrophic floods, only the flood situation that took place in 2002 in the territory of the Southern Federal Okrug caused accidents on gas pipelines, though these accidents occurred on pipeline branches supplying gas to small settlements. At that occasion, the following objects were subjected to failure: three above-surface crossings and one underwater crossing. The pipeline branches failed/crashed in view of the damage to the supports and direct action of water to the pipelines. The failures were repaired in 5–10 days.

Accidents on gas pipelines caused by small floods (mainly by rainfall floods) were observed in the mountains and foothills of the Northern Caucasia. Usually these were pipeline branches crossing rivers and streams. Rainfall floods initiated accidents in this region in 1971, 1984, 1987, 1990, 1991, 1997, 1999 and 2005. Anthropogenic factors also played its role in these accidents, namely: intensive economic activity in floodplains and design errors resulted from underestimation of design data of extreme levels of rivers due to insufficient periods of observations.

During spring flood there were accidents on long-distance gas pipelines. However, in this case emergency situations were a result of multiyear influence of flood waters. However, this influence was a background factor (the accident in 1999 on pipeline underwater crossing through the Volga River and the accident in 2001 on pipeline underwater crossing through the Ob River). It should be noted that these accidents did not interrupt gas supply. During the failure elimination, the gas was supplied by backup lines. Thus crossing of small rivers and streams by gas pipeline branches is a most critical to flood effect. In case of major floods, the occurrence of which are 1–2 times a 100-year period, several emergency situations are possible.

A critical consequence of climate change within the territory of the Russian Federation relates to the problems of flood and high water. The rise in loads on underwater lines is likely due to predictable increase of annual and seasonal flow of numerous Russian rivers, a change in their ice regime, a growth in recurrence and scales of ice-clogging floods and activation of channel and erosion processes on water collection areas.

While working out measures for the prevention of the accidents, a special role should be played by climate information that takes into consideration climatic variability and changes for the past decades. An important component of the climate information is the improvement of hydrological characteristics, especially their past and expected extreme values, which are used as the basis for engineering solutions in gas pipeline and the protection of facility project components.

3.2. MUD FLOWS

At present time mud flows represent a threat, generally, to GTS facilities of the Northern Caucasia. At the same time practically all the territories identified/planned for the GTS development are characterized by mud flow threat. Therefore, let us consider the most hazardous emergency situation that took place on the "700-mm cross section (dia)" Maikop-Samurskaya-Sochi gas pipeline (near the settlement of Lazarevskoye) in August 1991. The reason for this accident was heavy mud flows caused by waterspouts of the Black Sea that reached the mountain slopes and rain showers which continued for 12 h. The resultant mud flows damaged the gas pipeline on three sections.

Complicated conditions for routing gas pipelines in the mountains, an increase in the frequency of meteorological hazards which trigger mud flows and the highly developed (densely populated) territory are the objective external factors which will explain the high risk for similar accidents. To improve gas supply to Sochi the Dzhubga-Lazarevskoye-Sochi gas pipeline is currently under construction. The length of offshore section will amount to 160 km. Strengthened measures for eliminating mud flows and landslips will be provided.

3.3. LANDSLIP PROCESSES

These processes are widely distributed in the territory of the GTS operation and bring the threat to linear pipeline portions. The occurrence of mass activation of landslips practically in all the regions, which are dangerous from the viewpoint of landslips, accounts for one over a period of 8–12 years. Some researchers note a considerable growth of activation frequency for the last decade due to the global climate changes (Zerkal and Korolev, 2007). Analysis of accident rate dynamics for linear pipeline portions in Northern Caucasia region shows that maximums of accident rates caused by land slips coincide to a great extent with maximums of landslip process activity in the region.

In the Northern Caucasia landslips often caused accidents on small-diameter (108–530 mm) gas pipeline branches and in some cases on long-distance gas pipelines (Maikop-Samurskaya-Sochi and Stavropol-Grozny) running in complicated mountain conditions. In 57% cases, the accidents led to the interruption of gas supply to small settlements for the period from 0.5 to 1 day. As for the long-distance gas pipelines, gas supplies were interrupted in 25% cases. More serious situations with landslips occur when large-diameter (1,420 mm) gas pipelines cross large rivers (Volga, Kama, Malaya Sosva, etc.).

Gas pipeline crossing through the Kama River can be cited as an example. Due to the activation of landslip processes, which have not been observed before, several accidents took place on different gas lines for the period between 1990 and 1999. However, it should be noted that gas supply due to accidents on gas pipeline crossings through the Kama and Volga Rivers was not interrupted. At the same time and in order to prevent further emergency situations considerable protective measures were required.

Under “Program of works on protecting long-distance gas pipelines of the Uzhgorod corridor against landslip processes on underwater crossing through the Kama River”, complex measures on preventing the similar accidents (relaying of pipelines, stabilization of river slopes, monitoring of deflected mode and river bed control) have been accomplished.

3.4. CRYOGENIC PROCESSES

Cryogenic processes bring the greatest threat to zones of non-continuous and continuous permafrost. Accidents on pipelines laid in permafrost result from thawing permafrost with high content of ice. This process leads to uneven soil settling, displacement of piles, “floating” condition of pipes and pipeline deformation.

The problem of loss in buried gas pipeline longitudinal stability is slight. In permafrost distribution zones this problem is related to CS downstream gas with a temperature exceeding that of natural soil. This, in turn, results in permafrost thawing and subsidence formation or floating-up of a gas pipeline. Besides, a gas pipeline can cross areas with local negative processes and soils of different ice content and temperature. At present gas artificial cooling units allow reaching gas pipeline temperature conditions to those of surrounding soil. However, in different seasons and at the diversity of properties of soil, in which a pipeline is buried, one cannot exclude completely a loss in longitudinal stability.

To our opinion one must avoid incorrect explanations of these accidents as a result of the global warming. We think that such accidents are caused by design errors and violation of operating rules. At the same time, it should be noted that the present warming aggravates and complicates the above negative anthropogenic and natural processes.

In permafrost developing zones the global warming results in the reformation of soil thermic regime. Some Russian researchers point out that a depth of seasonal thawing is not a sufficiently accurate indicator of global climate changes, as the seasonal thawing process takes place exclusively in warm period, while the warming itself is governed generally by winter period. The analysis of experimental data obtained in the process of long monitoring of cryolithic zone at permafrost study stations has proved that the present climatic change is not always accompanied, contrary to the opinions of many researchers, by a sufficient increase in depth of soil seasonal thawing. For different landscape conditions probably significant trends of multiyear changes in seasonal thawing depth under the conditions of changing climate can be characterized both as positive and negative values (Pavlov, 2008).

It is worth to note that the problem of longitudinal stability loss is also typical for swamp land and flooded lands beyond a continuous permafrost zone. However, in spite of different engineering solutions, this problem is still under consideration. One of the consequences of the global warming for the Russian plains, which are characterized by overwatering, shallow groundwater and poor drainage capacity, may lead to underflooding of vast regions. For gas pipelines, the consequences of land underflooding and swamping growth under the conditions of climate change may result in increasing cases of pipeline design position change due to longitudinal stability loss. In turn, this situation may result in pipeline floating-up, a change in soil corrosivity and activation of soil heaving. All the above mentioned will require additional activity in restoring a pipeline design position and improving the requirements to corrosion protection of the existing and designed pipelines.

Some researchers note that the global warming in different regions of Russia is different. For example, in the Arctic the process of the global warming is less pronounced. The present climatic models, especially at regional level, do not give sufficiently correct predictive quantitative estimates due to complex structure of the factors having impacts on global climate change and its consequences. That is the reason why regional climate information on the observed and expected climate changes is of especial importance for the regions with such an extended system as Russia's GTS. At that we should take into account the prospects for its further development.

The climate information used for working out preventive measures on eliminating accidents in permafrost zones is the basis for predictive estimates that can be used in the process of a change in geocryological conditions during the global warming. Thus expenses on design options to adapt the GTS technological objects to natural environmental (conditions) changes depend eventually on completeness and correctness of the information on past, present and future climates.

3.5. METEOROLOGICAL PROCESSES

Meteorological processes with extreme parameters (snowfalls, winds, snowstorms, coating of ice and sticking of wet snow on wires) can be classified as hypothetical risk sources for interrupting operation of the gas transmission system. Extreme meteorological processes have little effect on buried gas pipelines and thus on the GTS as a whole. However, these natural hydro meteorological hazards may, indirectly, influence the GTS functioning by interrupting external power supply to compressor stations. Nevertheless, it should be noted that power facility damage due to off-design natural phenomena (storms, wire frosting-up, catastrophic floods, etc.) is the second by importance precondition of power accidents. Major accidents on the UGSS bring the threat to the GTS interrupted operation. This fact is determined by functional interconnection of two systems of the fuel-energy complex.

In the context of climate warming one may expect the increase in wind loads and extreme meteorological phenomena in some Russian regions that can lead to enhancing the probability of electric power supply systems damages. To work out measures on enhancing the GTS sustainability under major power failures, the climate information must reflect an actual situation of the last decades about the occurrence of meteorological hazards in different regions.

3.6. MARINE HYDROMETEOROLOGICAL HAZARDS

Climate warming aggravates the intensity of negative phenomena, including the formation of ice-bound conditions; wind-wave activity (particularly, storms in cold periods in the waters with very scattered ice); spray freezing; and wearing away of sea coasts formed by loose permafrost rocks. Retaining the tendency that became evident at the end of twentieth century – at the beginning of twentyfirst century in increasing the probability of icebergs appearance within the regions of northern offshore fields is to be expected. The risk of arctic pack ice invasion into more southern parts of the sea remains.

Considering the prospects for the development of production and transportation facilities and their protection in freezing seas and on the arctic shelf, as well as the exploration of the entire shelf of the Arctic Ocean (from the Barents Sea to the Chukchi Sea) it is advisable, besides new design options on HC resources development, to plan the development of systems of hydrometeorological support of offshore operations and the creation of special iceberg and ice situation management service.

4. Conclusion

The prospects for gas sector development are related to the extension of Russia's gas transmission system (GTS) in the developed areas and the construction of new transmission systems in the territories under development, including Yamal Peninsula, the Arctic shelf, the Siberian platform, Sakhalin Island and other regions being in harsh climatic conditions. The selection of measures on providing Russia's GTS sustainable functioning and development under the conditions of climate change requires consideration of regional climate change features, which are evident at the time being and which are expected in the nearest future.

Production and transportation facilities and the construction of new fields are being designed according to the changes of hydrometeorological factors that have occurred for the part 10-year periods. Nevertheless, it is necessary to improve the methods of accounting of their trends for the nearest 5–10 years. At the same time, revision of previous estimates of extreme values of hydrometeorological parameters (flow characteristics during high water, wave height, etc.), the values of which have been already built into project design, may be required as well. To develop dedicated and more effective measures on monitoring technical state of active facilities (e.g. river crossings) it is advisable to assess adverse effects differentiating them by regions and types of the most probable hazards.

At the same time, due to the inaccuracy of predictive quantitative characteristics of climate change, especially their extreme parameters, one needs to avoid excess margin of safety and rise in cost of facilities based on data of global forecast. Therefore, regional estimates of trends in hydro-meteorological factors and consequences of global warming in the regions of the highest risk will allow enhancing the quality of design work and safety operation of facilities under construction and natural and engineering complexes.

From the above, climatic data is an integral part of information base in evaluating natural risks. This evaluation is needed for designing new gas supply systems in the existing and future areas and for making economically sound decisions on prevention of emergency situation. Inadequate evaluation of a degree of danger and risk that can be caused by natural hazards (including those triggered by climate change) may result in inefficient usage of operating, maintenance and financial potential.

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WEATHER/CLIMATE RISK MANAGEMENT FOR THE ENERGY SECTOR: WORKSHOP RECOMMENDATIONS

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Abstract. Three working groups (WGs) were formed to address the five objectives of the Workshop. These objectives were: (A) To identify vulnerabilities of energy sector to extreme weather events in the context of climate change adaptation; (B) To identify impediments to the use of weather/climate information for the energy sector in the context of climate change adaptation; (C) To suggest ways to improve and/or facilitate the transfer of knowledge between weather/climate scientists and the energy experts to allow an optimal use of climate risk management; (D) To outline proposals to improve the way in which weather/climate information is used for modelling demand and to provide warnings for potential disruptions on energy operations and infrastructure; (E) To discuss possible contributions of the weather/climate scientists and the energy experts to climate change adaptation policies for energy security. All three WGs addressed the first two objectives in their early phases of discussion and then each of them went into greater detail in discussing C (WG1), D (WG2), E (WG3). Thus objectives C, D and E are the distinguishing attributes of the three WGs. The main recommendations of each WG are presented in this chapter. See also Troccoli et al. (2009).

Keywords: Weather; climate; energy; risk management; adaptation; policy

1. Recommendations from Working Group 1

WG1 concluded that it is important that the information needs of the Energy Sector be identified and communicated by the energy sector itself. Meteorology and climate offices can provide critical and valuable information, but it needs to be recognized as such by industry before industry will take

[1] All Workshop Participants

advantage of it. There is therefore a need to develop a relationship of service provider and client. To achieve this, the development of energy advocacy groups that can communicate, on behalf of the industry, the weather and climate data and information needs to the met/climate research community is recommended.

Once the appropriate group is identified and formed, it is suggested that a conference or other forum to engage the energy industry are organized in order to elicit from them their interests and needs for climate and weather data. It is also recommended that a session on weather and climate information at a regularly scheduled energy sector meeting, such as "Sparks and Flames" be held.

Wider capacity building for the group or its members could be assisted by other activities such as awareness raising through concise summaries of this workshop to industry newsletters and popular science press. Target newsletters include: newsletters of World Bank, regional development banks, donor agencies, and industry newsletters (US Energy Association, World Energy Forum (http://www.worldenergyforum.com). Popular press includes: Wired Magazine, Popular Science, Discover Magazine. In addition to these news articles, the development and dissemination of a "Climate and weather best practices" survey is recommended. The aim of the survey would be to identify examples of cases where the industry has used climate and weather information to improve the bottom line. Once best practices are identified through the survey, they should be analyzed for opportunities to propagate such practices in other places. It was noted that this process will require some seed funding for the website maintenance, organization of the survey, and preparation of sessions for the meeting.

2. Recommendations from Working Group 2

The group recognized that there are different requirements for modeling and meeting demand for energy by the energy sector. Modelling demand requires information about temperature, precipitation and other variables that are already represented in weather and seasonal prediction, although greater efficiencies will be obtained as the medium and longer term predictions improve. There are more demanding and different requirements of weather data by the energy sector to allow it to meet the demands for energy efficiently. These are only partly met by the current delivery of weather information to the energy sector. The requirements of the renewable energy sector are particularly different; this sector is very likely to become more important in the future with demands for national energy independence and for reduced carbon emissions. Different data are required for routine efficient operation and for emergencies. Emergencies can be weather-induced, for which accurate predictions are required. Emergencies can also be caused by other operational exigencies, and can require fast access to environmental information to predict and manage the spread of possible pollution, and to predict even the behaviour of possible pollution. In light of this discussion, specific recommendations address:

2.1. NEED FOR OBSERVATIONS

The needs of the energy sector for observations are varied. There is a need to continue the observations to assimilate into weather forecast models, to supplement them for high-resolution models and to verify them for the energy sector. Observing System Simulation Experiments (OSSEs) need to be performed to verify that the observing system is fit-for-purpose for the requirements of the energy sector and to allow the error estimates and biases to be made on the predictions. This requirement is particularly important in areas where the energy sector is operating where there are few observations, such as in some developing countries or in circum-polar regions.

2.2. CONSISTENCY OF DATA

For use in modelling energy demand and energy production models it is crucial that predicted data and historical data (analyses, re-analyses) are consistent. Small errors (bias, changes in statistical characteristics, etc.) might be amplified by the transfer models to unacceptable levels. It would be desirable to make available post-processed forecasts that are consistent with “observations”. For longer time scales the consistency of data sets should be ensured and re-analyses should be continued up to the present in (near) real time.

2.3. ACCESS TO DATA

Ready and reliable access to data and forecasts of some weather services should be facilitated using live access servers and similar Grid computing technology. The lack of such access is a real hindrance, especially for smaller companies in the energy sector. Met Services must attribute resources (financial and manpower) to inform potential users about data and to ensure the availability of these data. Annual workshops or conferences, tailored to the energy sector in which the Met Services present their data and how to access them are recommended. A good example of such a practice is the annual Eumetsat User’s meeting.

2.4. ACCESS TO OBSERVATIONAL DATA FOR DOWNSCALING AND VERIFICATION PURPOSES

A quality-checked set of reference observations should be provided in a user friendly way that can be used for downscaling and verification purposes. This data set should be updated in (near) real time. For the assessing and modelling of energy parameters (production, demand) the access to climate and energy data with high temporal and spatial resolution is essential but the related datasets are still not easily accessible in most parts of the world. The problem is threefold. Firstly, although datasets exist, they are not publicly available. Especially across administrative borders, the collection and use of relevant data can be tedious, amongst others due to different standards. Secondly, owing to lack of meteorological/climatological observations even basic data is not available in many developing countries and scarcely populated areas. Thirdly, distributed energy generation systems such as are now being introduced, especially with renewables, often do not record data in a way that can be used for national or supranational strategic energy management and planning purposes. It is recommend therefore that the monitoring of climate and energy system should be extended particularly when distributed energy generation systems are installed; that the energy and climatological data from observations and models should be readily available; that the exchange of energy data (even aggregated) between the energy companies and the regulatory and scientific communities should be enhanced to improve the introduction of new ways of using the observations and model products; and consequently that the aggregation of energy data should take into account the needs of climate/energy research, although the raw data are often sensitive (relevant for business).

3. Recommendations from Working Group 3

After having agreed on definitions of key terms such as “Energy Security”, “Extreme Weather Event” and “Climate Change Adaptation”, WG3 made observations and recommendations on each of the three objectives in its Terms of Reference. Of these, a select list is provided here.

With regard to objective A, it was observed that (a) Proposed that the optimal initial way forward is to examine and deal with current vulnerability; (b) Vulnerabilities should be examined through the life cycle of energy generation/use, namely: exploration, extraction/production, transportation, refining, generation, transmission/delivery, disposal; further, the life cycle as listed should be interpreted, as appropriate, for all types of energy source, both mined and renewable. The WG concluded tentatively that the most vulnerable part of the energy life cycle to climate variability and change is likely to be either transportation or transmission. Noting that current funding for adaptation, at least under the GEF and UNFCCC schemes, is roughly US$500 million as compared to requirements estimated for Africa alone as between US$7 and 10 billion, the WG expressed a view on the need for further research to be conducted into methods for increasing funding, suggesting the funding should be counted outside of Official Development Assistance and might possibly be a mix of grand and concessional loans; additionally the WG agreed that funding should not be restricted to structures such as GEF and UNFCCC and that ways should be explored to link climate change adaptation in the energy sector to existing financial instruments such as the global carbon market, especially where adaptation strategies overlap with mitigation actions (e.g. energy efficiency; demand side management).

In terms of objective B, the WG recommended research on: the creation and storage of data; the extent to which data are used in practice (any issues identified may be provide significant implications regarding training and research); regional and site-specific models; weather/climate maps, including risk maps, appropriate to all aspects of the life cycle for individual energy sources (e.g. wind maps, water resource maps), that would act additionally as educational tools. Regarding adaptation the WG recommended developing sociological and institutional tools to involve populations in defining local needs, and research into the financing of adaptation projects; noting that adaptation is so wide in context that engaging sufficient financing is a major international issue, the WG expressed the opinion that fund diversion, perhaps from, say, military or other government spending, would likely be required. A further recommendation was the production of guidelines for the use of weather and climate information in energy projects through their life cycles covering project structure and design, data requirements, science issues, funding issues, management requirements and case studies. Following the above, the WG proposed the concept of "energy teams" (a particular need was identified for biomass projects in developing and dry countries, but the concept is readily extendable) that would have mixed representation to facilitate open debate. Additionally the WG noted the need for facilitating policy level discussions, particularly in regard to: (a) tariffs/taxes (the WG agreed the perception that these, currently, were often created only to fill holes in exchequers rather than to address environment/climate/energy issues and that governments needed to take steps, including research, to address this); (b) development of the energy sector in consideration of weather/climate issues, focusing on mitigation, adaptation and energy security – the model of the 'Bali Breakfast' was offered within this context as a way of generating opportunities for discourse with policy makers and for engaging jointly the "weaker" environmental ministries with the "stronger" energy and financial ministries; (c) development and implementation of national energy strategies, legal and regulatory frameworks, and public/private partnerships.

Finally, with reference to objective E, the WG recommended the development of benchmarks for energy security specific to individual countries as models to be considered by other countries; these would be based on a wide spectrum of considerations and would assist in distributing information on vulnerabilities and options. The WG recommended that all projects be examined by experts for weather/climate sensitivities and that such sensitivities be accommodated within project designs, management and outcomes and in terms of both mitigation and adaptation; the 'Climate Disclosure Project' (http://www.cdproject.net/) was mentioned as a possible model. Returning to the issue of financing research the WG identified the following priorities: research in applied climatology, including in transfer to action; research into metrics and indicators re weather/climate and energy (e.g. see Michaelowa et al., 2009, Chapter 5, this volume); undertaking of a gap analysis, covering, but not limited to, science for climate resilience re energy and options for action; given that GEF funding is sometimes over complex, research into funding availability outside official lines (noting a call in a UNFCCC paper that 85% of funding for adaptation should originate from the private sector); research into training and capacity building requirements, into policy definition and into policy processes; research into improved building codes and monitoring. Lastly, national and international institutional frameworks were a frequent issue of debate, with consensus that these frequently are not fit for purpose within at least the energy context (lack of time restricted detailed examination of reasons perceived, but these included inadequately drawn terms of reference, duplication and competition, and limited constructive interaction between organisations); improved frameworks should incorporate on-the-ground needs of populations (rather than of governments) and inclusion of all interest groups (business and social).

References

Troccoli A, Boulahya MS, Dutton JA, Furlow J, Gurney RJ and Harrison M (2009) Weather and Climate Risk Management in the Energy Sector, to appear in Bull. Am. Meteorol. Soc.

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