ECLAT-2

Directorate General XII

A Concerted Action Towards the
Improved Understanding and Application of Results
from Climate Model Experiments in
European Climate Change Impacts Research

Climate Scenarios for Water-Related and Coastal Impacts

ECLAT-2 KNMI Workshop Report No. 3

KNMI, the Netherlands, 10-12 May 2000

Edited by:
Jules Beersma, Maureen Agnew,
David Viner and Mike Hulme

Published by the Climatic Research Unit, UEA, Norwich UK.
October 2000
(Further copies of this report can be obtained from d.viner@uea.ac.uk)

Contents

page numbers

Introduction to ECLAT-2

Mike Hulme and David Viner

Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, Norfolk NR4 7TJ. (m.hulme@uea.ac.uk)

ECLAT-2 is a Concerted Action Initiative funded through the Climate and Environment Programme of DGXII of the European Commission. The Initiative started in July 1998 and will run until June 2001. ECLAT-2 is co-ordinated by the Climatic Research Unit at the University of East Anglia, Norwich, UK, and has a Steering Committee comprising representatives from 12 other organisations in Europe.

ECLAT-2 Objectives

Some of the world's leading climate modelling centres are based in Europe and with a large number of high quality interdisciplinary research teams examining the effects of climate change on a wide range of natural, managed and social systems, Europe can also claim to be at the forefront of research into the impacts of climate change. The European Union continues to fund both of these areas of research through the Climate and Environment Programme of DGXII. Further enhancement and exploitation of these research successes requires improved co-ordination and efficiency of flows of information between the climate modelling, observed climate data and impacts research communities. More importantly, users of climate model results need to be kept abreast of developments in climate modelling and, through working together with scientists engaged in climate modelling, need to improve the ways in which climate model results are applied and interpreted in impacts research.

ECLAT-2 therefore has two specific objectives:

Primary Objective: to improve the understanding and application of results from climate model experiments in EU climate change impacts research projects.

Secondary Objective: to keep EU researchers into the impacts of climate change abreast of developments in climate modelling and informed about the availability of results from new climate change experiments performed in Europe and worldwide.

These two objectives are being achieved primarily through a series of four workshops initiated, designed and run by the ECLAT-2 Steering Committee, in association with climate impacts researchers throughout Europe. Each of these workshops involves between 20 and 40 participants drawn from the main European climate modelling centres and from the European climate change impacts research community. A larger ECLAT-2 Forum meeting will be organised towards the end of the Concerted Action to review the advancement of knowledge and methodology represented through the four ECLAT-2 workshops. An ECLAT-2 web site has been established (http://www.cru.uea.ac.uk/eclat) and the four workshop reports will be published and widely distributed within Europe and beyond.

ECLAT-2 therefore provides a focal activity for improving the understanding and application of climatological data within on-going and proposed future climate change impacts projects of the EU Climate and Environment Programme. The ECLAT-2 workshops are also complementary to, and supportive of, other major international climate scenario activities, such as those occurring under the Intergovernmental Panel on Climate Change (IPCC), the International Geosphere Biosphere Programme (IGBP) and the Human Dimensions of Global Environmental Change Programme (HDP).

The Management of ECLAT-2

The ECLAT-2 Partners and Steering Committee consist of representatives from each of the four major climate modelling centres in Europe (the Hadley Centre, MPI/DKRZ, Meteo-France, LMD/IPSL) and representatives from the climate scenario construction and climate change impacts communities. All of the ECLAT-2 Partners (see list below) are automatically members of the Steering Committee, but additional people may be co-opted onto the Steering Committee during the lifetime of ECLAT-2. We also list four organisations who have a special consultative role in ECLAT-2, but which for various reasons are not full Partners to the Initiative. The Steering Committee liaises primarily through electronic means and through occasional meetings that coincide with other Workshops or Conferences. One full meeting of the Steering Committee is organised each year. The Steering Committee formulate and guide the ECLAT-2 Workshop series and the Forum meeting, although these Workshops are hosted locally by members of the ECLAT-2 Network.

The ECLAT-2 Project is co-ordinated by the Climatic Research Unit (CRU) from where the ECLAT-2 email list and website will be run and from where the Workshop Reports will be published. Readers of this Report can be added to the ECLAT-2 email list by contacting Dr David Viner at d.viner@uea.ac.uk.

The ECLAT-2 Contracted Partners

- CRU, Climatic Research Unit, Dr Mike Hulme and Dr David Viner
- Department of Geography University of Southampton, Dr Nigel Arnell
- KNMI, Royal Netherlands Meteorological Institute, Dr Jules Beersma
- MTT, Agricultural Research Centre of Finland, Dr Timothy Carter
- ICAT, University of Lisbon, Professor Joao Corte-Real
- PIK, Potsdam Institüt für Klimafolgenforschung, Professor Wolfgang Cramer
- DMI, Danish Meteorological Institute, Dr Eigal Kaas
- LMD, Laboratoire de Meteorologie Dynamique, Professor Katia Laval
- Meteo-France, Dr Serge Planton

ECLAT-2 Non-Contracted Partners

- Hadley Centre, Dr Geoff Jenkins
- MEDIAS-France, Michel Hoepffner
- EUMETET/ECSN, José Diaz
- DKRZ, Deutsches Klimarechenzentrum, Dr Ulrich Cubasch

The ECLAT-2 Workshops

These meetings form the main activity of the ECLAT-2 Concerted Action. A series of four Technical Workshops are planned and these will be held at approximately six monthly intervals. A larger ECLAT-2 Forum meeting will be held towards the end of the three year Concerted Action. Each ECLAT-2 Workshop will possess the following characteristics and will last between two and three days:

- Workshop themes and broad design agreed by the ECLAT-2 Steering Committee.
- Discussion papers (either single or multi-authored) on the relevant Workshop theme(s) commissioned by the organisers.
- Workshop organisation and hosting shall be delegated to members/institutes in the ECLAT-2 Network. These hosts need not be Partners to the proposal.
- Representatives of climate modelling centres and climate change impacts research projects to be present at each Workshop.

- Participation to be limited to between 20 and 40 people, some places being reserved for invitation only.
- Expenses of participants to be met by ECLAT-2 up to an agreed maximum limit. Workshop hosts will be responsible for distributing travel and subsistence costs, with a set budget for each Workshop.
- A consolidated Workshop report to be prepared and published after each Workshop.

The four Workshop themes, venues and approximate dates are as follows:

EW-1 (RED): Helsinki (FMI), Finland, April 14th-16th 1999
"Representing Uncertainty in Climate Change Scenarios and Impact Studies"
This workshop will (1) review the various sources of uncertainty in climate change and related scenarios, their relative importance and their representation in climate change impact studies, and (2) work towards a series of recommendations for a more systematic treatment of uncertainty when designing and applying climatic scenarios for impact studies. Specific topics considered will include: uncertainties in social and economic projections, uncertainties in representing observed climate, climate modelling uncertainties, uncertainties in climate impact modelling, and an assessment of techniques for estimating uncertainty in climate change studies. The two-day workshop will comprise a series of short invited papers and commentaries, with a substantial amount of time dedicated to group discussion and the preparation of the workshop report.

EW-2 (GREEN): Potsdam (PIK), Germany, October 13th-15th 1999
"Climate Scenarios for Agricultural, Ecosystem and Biological Impacts"
This workshop will review the construction and application of climate change scenarios in areas related to agriculture, ecosystems and other biological indicators. Specific topics to be covered will include the incorporation of different time-scales of climate variability in climate change scenarios, enhancing consistency between climate and impact models, and representing the direct effects of CO2 and other atmospheric constituents alongside the impacts of climate change.

EW-3 (BLUE): de Bilt (KNMI), Netherlands, May 10th-12th 2000
"Climate Scenarios for Water-related and Coastal Impacts"
This workshop will review the construction and application of climate change scenarios in areas related to water and coastal indicators. Specific topics to be covered will include the specification and incorporation of daily and sub-daily weather extremes in climate change scenarios, the use of weather generators and statistical downscaling techniques, and the interaction between sea-level change, storms and storm surges.

EW-4 (BROWN): Toulouse, France, October 25th-27th 2000
"Applying Climate Scenarios for Regional Studies: with particular reference to the Mediterranean"
This workshop will review the construction and application of climate change scenarios in regional-scale impacts assessments. Particular reference will be made to the Mediterranean region, but examples will be drawn from other regional studies in Europe. Specific topics to be covered will include the use of Regional Climate Models in regional scenario construction, the achievement of consistency between point, local and regional-scale scenarios, and the integration of climate impacts results across regions.

Towards the end of ECLAT-2, a larger Forum meeting will be held. This meeting will be designed to draw together the conclusions from the Workshop series and to present these to a wider audience, including representation from DGXII and maybe other relevant EU Directorates, and representatives from all of the climate impacts projects funded by the EU, especially new projects funded under the 5th Framework Programme. It will also be an opportunity to identify priorities for future research in this area, again drawing upon the conclusions of the four ECLAT-2 Workshops. This Forum meeting would be held over two days with participation of around 50 people.

The Benefits of ECLAT-2

The primary objective of the ECLAT-2 Concerted Action is to facilitate the better understanding and application of climate model results within on-going and future EU Climate and Environment Programme's climate change impacts research projects. The secondary objective is to enable improved communication between climate modellers and users of climate model results and to allow climate change impacts researchers to be kept abreast of developments in climate modelling in Europe and about the availability of results from climate model experiments.

Improved construction, and more consistent application, of climate change scenarios within EU climate impacts research projects allows for more effective integration and continent-wide interpretation of the results from these research projects. It also enables the strength of European climate change modelling activities to be better exploited by EU climate impacts researchers. ECLAT-2 strengthens the European contribution to international climate change activities such as the IPCC and the policy development under the UN Framework Convention on Climate Change. Within the IPCC, for example, a requirement for comparability in regional impacts assessments for the Third Assessment Report (TAR) due in the year 2001 has already been recognised and one or more chapters dealing with issues of climate scenario construction and application are planned for the TAR. ECLAT-2 activities coalesce European expertise in these areas and enable European scientists to make a more effective contribution to IPCC. The ECLAT-2 Network allows for better communication within the impacts projects of the EU Environment and Climate Programme and between scientists involved in climate modelling, climate scenario construction and climate scenario application.

Climate Scenarios for Water-Related and Coastal Impacts Workshop Introduction

Jules Beersma

Royal Netherlands Meteorological Institute (KNMI), P.O. Box 201, 3730 AE De Bilt, the Netherlands (Jules.Beersma@knmi.nl)

Climate change research brings together scientists from a wide range of scientific disciplines. Traditionally, different communities having their own scientific journals, meetings and networks. In order to practise sound science, especially in the complicated area of climate change and to make sensible climate change impact assessments it is necessary that the different communities involved meet, exchange knowledge and keep each other informed about new developments. However, in the application of climate scenarios, a technical and very important issue, the communication between on the one hand the climate modelling and scenario developing communities and on the other hand the impacts community and policy advisers was initially rather limited. The European Union ECLAT-2 Concerted Action is an initiative that is addressing and serving the need for enhanced communication between the traditionally different scientific communities involved in climate change.

This is the report of the workshop '*Climate Scenarios for Water-Related and Coastal Impacts*' which was organised by the Royal Netherlands Meteorological Institute (KNMI) and held at the conference centre 'Ernst Sillem Hoeve', Lage Vuursche, the Netherlands from 10-12 May 2000. It was the third, or 'Blue', workshop in a series of four workshops in the framework of the European Union ECLAT-2 Concerted Action. The workshop brought together 39 specialists from 13 countries including: climate modellers, climatologists, scenario developers, downscalers, hydrologists, coastal impact analysts, statisticians and policy advisers.

The two main objectives of the workshop were:

- To review the construction and application of climate scenarios in areas related to water and coastal indicators, including the specification and incorporation of (sub) daily weather extremes in climate scenarios, and the use of weather generators and downscaling techniques.

- To provide guidelines both for the application of climate scenarios in current and future water-related impact assessments and for further development of regional and local climate scenarios.

Four keynote papers, that broadly covered the theme of the workshop were pre-circulated to the workshop participants, and formed the basis for the workshop. To set the scene, Timothy Carter began with a summary of the first ('Red') ECLAT-2 workshop, '*Representing Uncertainty in Climate Change Scenarios and Impact Studies*' held in Helsinki, Finland. The four keynote papers were presented next. The first, 'Stochastic downscaling methods to assess the hydrological impacts of Climate Change on River Basin Hydrology' (András Bárdossy) gave an overview of downscaling methodologies for use in hydrology with an application of a conditional weather generator to the upper Neckar catchment in Germany. The next keynote paper, 'Climatological changes in storm surges and river discharges: the impact on flood protection and salt intrusion in the Rhine-Meuse delta' (Pieter Jacobs) discussed the type of impacts that is typical for exposure units at the interface of the hydrological and coastal sectors, using the Rhine-Meuse delta as an example. Eigil Kaas presented the third keynote paper, 'Scenarios for extra-tropical storm and wave activity: methodologies and results' on recent climate model estimates of future changes in severe extra-tropical storms and the resulting changes in wave statistics. The final keynote paper, 'Climate change effects on storm surges:

methodologies and results’ (Roger Flather) discussed the components that contribute to changes in sea levels and methodologies to estimate the changes in these components, with an emphasis on storm surges. In an additional paper, entitled ‘Development of daily precipitation scenarios at KNMI’, Adri Buishand presented a statistical downscaling model in which atmospheric moisture is included as a predictor variable to obtain improved daily precipitation scenarios. All papers are to be found in the section ‘Keynote Papers’ of the report (pp.18).

The papers served to introduce the workshop topics and to provide material for discussion in two breakout sessions, which were another key activity of the workshop. Each breakout session consisted of three working groups. The first breakout session was sector oriented, working groups were appointed to compare the climatic needs with the availability of climate scenarios in one of the three main sectors: (1A) hydrological impacts, (1B) coastal impacts or (1C) impacts at the interface between these two. While making use of the results of the first breakout session, the working groups of the second breakout session were assigned to approach the application and construction of climate scenarios from a methodological viewpoint. Working group (2A) discussed the usefulness of 'artificial scenarios', (2B) assessed the strengths and weaknesses of different downscaling techniques and (2C) addressed the incorporation of changes in (natural) variability and extremes in climate scenarios. The six working groups reports are included in this book (pp.93).

A final presentation was given by the EU officer for European water resources (Panagiotis Balabanis): ‘Sustainable management and quality of water. An overview of related EU RTD activities with emphasis on the implications of climate change on hydrological regimes and water resources’. The workshop concluded with a final plenary session; a summary of the workshop and the recommendations discussed are included in this book (pp.128).

Key Findings from the First ECLAT-2 workshop "Representing Uncertainties in Climate Change Scenarios and Impact studies"

Timothy R. Carter[1] and Mike Hulme[2]

1. Impacts Research Division, Finnish Enviroment Institute, Box140, Fin-00251, Helsinki, Finland. (tim.carter@vyh.fi)

2. Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK (m.hulme@uea.ac.uk)

"If you don't know what you want, all roads will lead you there"

General observations on uncertainty

A number of general conclusions emerged from discussions at the first ECLAT-2 Workshop concerning the nature and magnitude of uncertainties surrounding estimates of future climate change and its impacts. These can be categorised according to different links in the causal chain of effects from socio-economic driving factors, through consequent climate changes and sea-level rise, to the impacts of, and adaptations to, climate change.

- *Driving factors*. Future developments of socio-economic driving factors are largely unknowable, and cannot be assigned objective probabilities. For this reason, it is suggested that a range of scenarios (e.g., the SRES emissions scenarios) be applied in impact assessments rather than a single best guess or average case.

- *Climate change*. Uncertainties in estimates of future climate change due to large-scale climate processes are probably more important for assessing the likely range of most impacts than uncertainties in resolving sub-grid scale details about future climate change. While regional climate models may provide more credible information on changes in climate than GCMs in regions of heterogeneous terrain (e.g., land-sea boundaries, mountain areas), these models nevertheless exhibit uncertainties in estimates of large-scale climate change that are comparable to those found in GCMs.

- *Sea-level rise*. Uncertainties in estimated regional sea-level rise due to thermal expansion for a given global-mean rise are comparable to uncertainties in estimates of mean global sea-level rise.

- I*mpacts*. Uncertainties in estimates of future impacts are highly dependent on the sector, exposure unit and region of interest. For instance, climate change and direct CO_2 effects on crop productivity are often stronger (and the uncertainty lower) in climatically marginal regions than in core producing regions. However, these uncertainties can be dwarfed by uncertainties in future productivity associated with future agricultural policy, management and technology. Furthermore, the relationship between key scenario/impact uncertainties may change and switch priority depending on the time horizon considered (for example, global-mean temperature changes estimated for the four SRES "marker" emissions scenarios describe only a narrow range up to 2050, but a much wider range by 2100). Nevertheless, it is not necessarily the case that uncertainties always increase at subsequent stages in the scenarios/impacts analytical cascade; they might narrow due to differing levels of adaptive capacity.

How effectively do scientists treat uncertainty?

A consensus view from the first ECLAT-2 Workshop was that scientists have failed to address uncertainties adequately in the great majority of climate impact assessments conducted to date. A general point concerns the identification of different types of uncertainty. Various typologies were proposed at this first Workshop, including:

1. A threefold classification of primary sources of uncertainty: (i) measurement error, (ii) variability (including inherent randomness and variability over temporal and spatial scales), and (iii) model structure (i.e, model simplifications, omissions and mis-specifications).
2. A fourfold classification, according to the general sources of uncertainty: (i) theory, (ii) data, (iii) assumptions, and (iv) scenarios.
3. A twofold classification distinguishing (i) 'probable error', which is uncertainty attributable to factors that are inherently unpredictable (also referred to as unknowable knowledge), and (ii) 'probable bias', which is uncertainty due to imperfect knowledge and which is liable to change over time with improved understanding.

These alternatives are not exhaustive, but it is evident that many previous impact studies have either ignored these types of distinctions or have confused them. More specific points concerning the treatment of uncertainty can be illustrated for the same categories as outlined in the previous section:

- *Driving factors.* There has been a temptation to adopt 'best guess' scenarios of future driving factors of global change, based either on averaging of alternative scenarios or on selection of the middle or other preferred case. The former approach can lead to inconsistencies between scenario components that are not present in the individual scenarios being averaged. The latter approach can lend the appearance of higher likelihood to the central case, as is well illustrated by the widespread adoption of the IS92a scenario of greenhouse gas emissions as a reference, although it was only one of six alternative emissions scenarios produced by the IPCC in 1992. It is now acknowledged that uncertainties can only be explored adequately if a set of alternative scenarios are adopted, each offering a self-consistent view or storyline of the future.

- *Climate change*. Errors and homogeneities of observed climatological data are fairly well recognised and many of them have been quantified. These data are commonly applied as a reference in impact assessments, but their uncertainties are rarely accounted for even though it would be a fairly straight-forward exercise to evaluate them. Scenarios of future climate from models are commonly applied in impact assessments, and there are emerging techniques to account for the range of uncertainty in emissions, climate sensitivity, regional climate change and natural climatic variability. However, these are seldom applied systematically in impact assessments. The application of expert judgement-based methods to obtain probabilistic assessments of future climate is a controversial approach that is gaining in acceptance in some quarters. However, it exhibits many pitfalls, and in the opinion of some participants at the Workshop these methods rely on 'belief' as much as on scientific understanding. Assumptions about prior probabilities in such exercises need to be made explicit.

- *Sea-level*. Risk assessment methods, employing the use of simple models and expert judgement, have been applied to global sea-level rise to obtain quasi-probability distributions of future outcomes. However, this approach is not yet feasible for regional sea-level rise, due to the requirement to apply more complex global models, and the limited number and differing assumptions of model simulations conducted to date.

- *Impacts*. Some impact assessments include systematic uncertainty analyses and sensitivity analyses of impact models. These exercises can be very helpful in defining the level of confidence in model estimates, but are not commonly undertaken, either because of excessive model complexity (for example, in some integrated assessment models), or because of time and resource constraints. Many of the largest uncertainties in model-based estimates of impacts relate to factors not included in models, but which may assume increasing importance over the time scales of relevance for a changing climate (e.g., effects of pests, diseases and weeds on crop production; effects of nitrogen deposition on forests).

What information on uncertainty is required by stakeholders?

One of the questions posed at the first Workshop concerned the value of information on uncertainties for stakeholders. It was recognised in the different Breakout Groups that there are many different categories of stakeholder, each having different requirements for information on climate change and its impacts (see Section 4). However, although generalisations are difficult, a few themes surfaced in discussion:

- *Robustness of results*. It was thought important to stress the robust aspects of assessments (including levels of confidence) as well as the uncertainties. An excessive emphasis on uncertainties might detract from important messages about likely consequences of climate change.

- *Operational application*. Several participants argued that uncertainty information is likely to be most useful to stakeholders if posed in an operational or decision-making context. If one goal of a stakeholder is to minimise risks, then useful information might be obtained, for example, by distinguishing between the relative sizes of the ‘probable error’ and ‘probable bias’ (see the twofold classification of uncertainty described above).

- *Focus for scientists*. The question was posed, but not resolved, as to whether scientists should channel their investigations of uncertainty towards narrowing the range of uncertainty, or rather towards providing information on uncertainties in a more effective way. Given that uncertainty will remain inherent in all descriptions of future climate, efforts in the latter area will always be important.

What research is required to improve the treatment of uncertainty?

Uncertainties in assessing vulnerability

Research into climate change impacts and adaptation is undergoing a shift away from scenario-driven, “dose-response” type impact assessments towards more integrated studies that address system vulnerability and adaptability to climatic perturbations. This shift, which is likely to accelerate, has been largely policy driven, recognising the need to evaluate levels of climate change that threaten key social, economic and ecological systems. It requires a better understanding of the uncertainties involved in assessing vulnerability (i.e., the performance of impact models and the quality of input and validation data) to lay alongside the uncertainties in projecting alternative storylines of the driving factors of global change and uncertainties in future atmospheric composition, climate and sea-level. Some specific research recommendations from the Workshop included:

- The testing and intercomparison of impact models should be improved and their suitability for application under conditions of changed climate evaluated more critically than hitherto. If necessary, models should be excluded from consideration in impact assessments if their performance against past observations is inadequate or their range of operation is limited to present-day conditions. Model ‘invalidation’ may thus be a more relevant goal of model testing than model ‘validation’, and could serve to narrow the uncertainty range of estimates by excluding inappropriate models.

- The development of simple empirical relationships or models that demonstrate similar behaviour to more complex process-based models, may provide an opportunity for undertaking detailed uncertainty analysis that is prohibited in complex models by insufficient computer power and resources.

- More studies are required to examine how the statistical properties of observed and modelled responses change as values are scaled up or down.

- Continued improvements to GCMs should be encouraged. As well as providing more confidence in estimates of future climate, improvements to land parametrisation schemes and to ocean dynamics offer the promise for obtaining new information from GCMs that has hitherto been derived in impact models. Examples include GCM estimates of the surface water balance, including evapotranspiration, and regional estimates of sea-level rise due to thermal expansion.

Uncertainties in assessing scenarios of future change

In some sectors for which the possible impacts of future climate change have been evaluated (e.g., water resources), the uncertainties in estimates of systemic response to climate change may be narrower than the uncertainties attributable to alternative views of the future (e.g., estimates of future streamflow under different climatic scenarios). In these cases, the choice of scenarios has a critical bearing on the predicted outcomes. A number of key research tasks were identified for enhancing the quality and usefulness of scenarios:

- The driving factors underlying new impact assessments conducted during the first few years of the 21st century should be based on the SRES emissions scenarios or related exercises. These should be used to force climate model runs to obtain scenarios of future regional climate, and downscaled to regions, as appropriate, for characterising future climates consistent with these non-climatic assumptions of the future.

- There should be continued intensive research into abrupt and/or non-linear events (e.g., a re-orientation of the thermohaline circulation of the ocean or rapid deglaciation of the West Antarctic) which need to be accounted for in any uncertainty analysis.

- The downscaling of climate information from GCMs is a key requirement for some impact applications, especially those requiring information on weather-related events at high temporal resolution (e.g., high intensity, short duration rainfall events; high winds, storm surges). It should not be assumed, however, that downscaling large-scale climate change information is always a necessary or cost-effective strategy for scenario construction. In addition to intensified research to refine downscaling methods, more impact studies are needed that assess the relative value of different downscaling approaches.

- More research is needed into new methods, including expert judgement and statistically-based approaches, for obtaining probability density functions of future outcomes where these are unknown. Improved information on the probability distribution of future climate will require model simulations for a wider range of emissions scenarios and for a greater number of ensembles. One option for obtaining the latter at relatively low cost, is to use time-slice experiments with global climate models.

- Decadal-scale natural climatic variability needs to be better-quantified, using palaeoclimatic reconstructions, observations and models, so that it can be accounted for in climate scenarios and impacts assessments.

What guidance is required for scientists in addressing uncertainty?

One of the clear messages to emerge from this first ECLAT-2 Workshop was that a proper treatment of uncertainty is merited at all stages of a climate change impact assessment. This applies to the development of climate change and non-climatic scenarios, the evaluation of impact models or alternative experimental methods, the quality control and application of measured data, the analysis of model-based or experimental results, and the presentation and communication of results to diverse audiences. On the other hand, however, there was also substantial agreement that the current practice of impacts assessment falls disappointingly short of this desirable goal.

Numerous examples were presented throughout the first Workshop to illustrate important uncertainties needing to be accounted for at different stages of an impacts assessment. A number of standard techniques were also described for addressing these uncertainties. The fact that climate change impact studies seldom apply such procedures suggests that proper guidelines are urgently required by the research community. It also draws a shroud over much of the published research on climate change impacts which may, at best, be understating the uncertainties, and at worst, providing blatantly misleading information. This is an uncomfortable situation for informing the decision process.

Some of the features of assessments that were identified as requiring guidance included:

- *Goals of an assessment*. In defining the aims of an assessment, stakeholder involvement was regarded as critical. Dialogue is important to ensure that any evaluation of uncertainties undertaken by scientists is both relevant and expressed in appropriate terms for the stakeholder.

- *Selection of scenarios*. It would be useful to have improved guidance (e.g., a ‘performance index’) on the trustworthiness of different climate model estimates of future climate for use in impacts assessment. There should be better descriptive and interpretive information on scenarios and related inputs to impact studies.

- *Selection of impact models*. Guidance is required on how to enhance the documentation and transparency of impact models. There is also a need for improved access to such documentation, and to results of model intercomparison activities and information on key model parameters. A clearing house for different model types would be useful to assist researchers in selecting appropriate models for their impacts work.

- *Evaluation of uncertainties*. One of the major gaps in the methodology of climate impact assessment, is a comprehensive guide to tools and procedures for estimating uncertainties at each stage of an impact assessment. The Discussion Paper by Katz in the first ECLAT-2 “Red” report offers a taxonomy of approaches to uncertainty estimation. A next step would be to identify appropriate tools for different types of climate impact assessment.

- *Presentation of uncertainties*. There are many alternative methods of representing uncertainty, but no agreed guidelines on “best practice”. There was a general feeling in the Workshop that reports of impacts assessments should make clear which uncertainties are considered and which are suppressed. Studies should also pay more careful attention to presentation - both for stakeholders and for other scientists. Moreover, impact analysts and policy makers should be prepared to work with scenarios that comprise probability distributions. This is an emerging research area, and guidance will be required in both the application of risk assessment techniques and the interpretation of such information.

Key Findings from the Second ECLAT-2 Workshop 'Climate Scenarios for Agricultural, Forest and Ecosystem Impacts'

Wolfgang Cramer

Department of Global Change and Natural Systems, Potsdam Institute for Climate Impact Research, PO BOX 60 12 03, D-14412 Potsdam, Germany (Wolfgang.Cramer@pik-potsdam.de)

The topic of this workshop: climate scenarios for agricultural, forest and ecosystem impacts, may have given the impression to many people of a rather technical issue, which requires specialists exchanging knowledge about the practical application of models and techniques. Not surprisingly, the discussion took a quite different approach and encompassed the following issues: What is climate impact assessment? Why are we doing it? Who are we doing it for? At what scale? What is the uncertainty of our results? In addressing these rather more fundamental issues, participants clearly assisted each other in finding out each individual's position in a rapidly growing field of fundamental and applied science – and this was indeed the main underlying goal of the meeting. Clearly, none of these broad questions has a simple answer. It is precisely the continuous revisiting of the logical foundations and objectives of climate change impacts assessments that eventually may lead to insights which are both, scientifically sound *and* politically relevant.

As far as the more narrow problem - the definition and application of suitable climate scenarios - was concerned, participants were specifically looking for methodologically stable solutions that could be applied, if possible, *across sectors* and *across scales*. Trying to identify a 'good practice' posed difficult, due to a variety of constraints – these are covered in the Working Group reports and shall not be repeated here. Some additional problems, which arose repeatedly in formal discussions, as well as during coffee breaks, are given here:

- Access to climate data is still a significant problem for many groups working on climate impact studies. This limitation may concern both observations of historical and present-day conditions, and output from scenario generation activities elsewhere. It is surprising that this remains an issue, given the amount of resources that have been used for networking and database creation in recent years. One effort that has been successful in this regard is the IPCC Data Distribution Centre for scenario information, which provides observed climate data, socio-economic scenario information and results from GCM experiments; see http://ipcc-ddc.cru.uea.ac.uk. The workshop had the impression that many such limitations were in fact more due to either the commercialisation of weather services in some countries, or else the reluctance of some model development teams to see 'their results' being used in an inappropriate way.

- Climate scenario data are often generated from model simulations that had other primary goals than climate change impacts assessment studies. This is no surprise since climate modellers have the primary and well-justified needs to better understand dynamical processes in the atmosphere and its associated systems. Climate change scenarios for impact assessments are usually an offspring rather than an intended result from such studies. It is important that climate impact modellers understand this situation: Global Climate Model (GCM) experiments are necessary to investigate the kinds of changes that could occur in the future. Being explorative rather than predictive they can therefore only serve as indications of 'kinds of futures'.

- The intimate coupling between greenhouse gas emissions, atmospheric processes and modifications of the land surface, either through land use or through impacts of climate change, in fact prohibits the possibility of 'accurate' predictions to ever exist. Increased rainfall, for example, ultimately leads to increased water availability which will modify ecosystem processes. These feedback to the atmosphere by altered evapotranspiration and other fluxes. Off-line scenarios, as they are usually encountered in impact assessments, will always suffer from this inconsistency which should be recognised.

- Few recent climate impacts assessments have included a consistent consideration of climate variability. This is unfortunate, since variability is likely to confound attribution of climate change related impacts for quite some time (even in the presence of global change, see Hulme *et al*. 1999). This is a severe limitation, since many impact sectors are sensitive to changes in variability, and the potential of climate models to simulate the various dimensions of climate variability is still limited.

In conclusion, there is no single 'best practice' in the development and use of climate scenarios, but there are a number of pitfalls that need to be avoided in the future. Most prominent among these are the wrongful presentations of some impact scenario calculations as 'predictions' of change. All we can really do is exploit the scenario technique to explore a range of different conditions, within which we are likely to find an estimate of the sensitivity of the sector being studied.

Determining this sensitivity however yields, if it is done following scientific standards, a powerful message. Policy concerning abatement of future emissions of greenhouse gases will have to consider whether the climate system *potentially* could develop conditions that are detrimental for services provided to human society by its environment. 'Good practice' would then be equivalent with policy that minimises and/or avoids this risk being taken.

Reference

Hulme M, Barrow, E. M., Arnell, N.W., Harrison, P. A., Johns, T.C. and Downing, T.E. (1999) Relative impacts of human-induced climate change and natural climate variability, Nature 397, 688-691.

Keynote Papers

page numbers

Keynote Paper 1

Stochastic Downscaling Methods to Assess the Hydrological Impacts of Climate Change on River Basin Hydrology

András Bárdossy

Institut für Wasserbau, Universität Stuttgart, Pfaffenwaldring 61, D-70550 Stuttgart, Germany
(bardossy@iws.uni-stuttgart.de)

ABSTRACT

Climate change may influence the hydrological cycle at different temporal and spatial scales. The temporal scales may vary from a resolution of 5 minutes (urban hydrology) to months (water balancing). The spatial resolution may vary from a few km^2 to several thousands of km^2. The driving meteorological variables have to be estimated at the GCM scale. Unfortunately, present deterministic models (nested models) are not particularly good at reproducing the mean and variability of important climatic variables. Furthermore, the extremes, which are an important basis for hydrological design, cannot be accurately determined from short simulations.

In this paper an overview of stochastic downscaling models is given. Methods based on classification approaches are compared to regression type approaches. A classification method is presented which uses an objective function related to surface variables. The corresponding downscaling model, with a daily temporal resolution, is applied to different climatic regions including Germany and Greece. The problem of different time scales is discussed. Possible improvements of using additional variables such as sea-surface temperature anomalies and local vorticity are discussed. Finally, the model is applied to assess the impact of climate change on the hydrologic regime of the Upper Neckar catchment, a medium-scale river in southern Germany. The main aim is to quantify possible impacts on the water budget and occurrence of extreme events (floods and droughts) at a medium time scale (referring to several decades). A rainfall-runoff-model is therefore applied to represent the hydrological conditions of the catchment. A modified version of the HBV-Model is used for rainfall-runoff-modelling and for calculating the water balance. Downscaling is performed for both observed and GCM modelled large-scale atmospheric variables. A doubled CO_2- scenario is then created and predictions about the impact of climate change on the local weather parameters and changes in hydrological regimes are evaluated. Results based on observed large-scale features are compared to doubled CO_2- scenarios based on GCM control runs. The main objective is to assess the magnitude and direction of change in the water balance.

INTRODUCTION

Climate change will have an important impact on the hydrological cycle at a variety of temporal and spatial scales. The temporal scales may vary from very short intervals to annual balances. Spatially the effect may be local, regional or global. Human activities may be influenced at all temporal and spatial scales. Water-related projects often have life spans of 50 to 100 years. The design of these projects therefore needs to consider the possible effects of climate change. The purpose of this paper is to describe downscaling methods that may be able to provide some indication of future hydrological changes.

It is widely accepted that general climate models (GCMs) are the best physically based means of describing the effects of increasing concentrations of atmospheric CO_2. Unfortunately, these models have a very coarse spatial resolution (typically grid-boxes of several hundred kilometres). They reproduce the general meteorological features, but are very inaccurate for single grid-boxes. Thus, the useful (or credible) grid-box size is even coarser than the computational grid. Table 1 compares the temporal and spatial scales in GCMs and hydrological modelling.

	GCM Calculation	Hydrological requirement	Available data
Time	~0.5 h	5 min - year	daily, monthly
Space	300 x 300 km	local - 500 km^2	GCM grid

Table 1. Temporal and spatial scales in GCMs and hydrological modelling.

Although precipitation is the most important hydrological input, it is not well modelled by GCMs. Systematic errors in mean values and annual cycles means that hydrological models cannot directly use the GCM output. Therefore, downscaling methods are used to provide more reasonable, small-scale information. Downscaling is attempting to provide subscale realisations from a higher temporal and/or spatial scale. This means that a relationship between the large-scale and small-scale information has to be established:

$$Z(u,t) = F\left(L(\tau,U)\right) \tag{1}$$

Where Z(u,t) is the local variable (for example precipitation) at location u and time t, and *L(t,U)* is the global information over the domain *U* at time (or time interval) . Unfortunately, the relationship F in equation 1 is not unique, since a large number of realisations of *Z(u,t)* might correspond to the same large-scale information. Thus, the task is to assess the possible distribution of *Z(u,t)* which should be as specific as possible. For this purpose, physical and empirical relationships can be used. In addition, F has to be accurate and represent a specific relationship; a successful downscaling also requires reliable large-scale information. Therefore, only *L(τ,U)* which are accurately modelled by the large-scale models can be considered. Downscaling should be performed for all hydrologically relevant parameters.

In this paper, a short overview of downscaling methods is presented. This is followed by a description of a circulation pattern based technique, which is applied to data for Germany and Greece. Finally, the downscaled series are used in a rainfall-runoff model for the Upper Neckar catchment to assess possible future hydrological consequences of climate change.

DOWNSCALING APPROACHES

There are two different methodological approaches to downscaling:

1 dynamic downscaling; and

2 empirical or statistical downscaling.

In the case of dynamic downscaling, nested regional climate models (Giorgi and Mearns, 1991) are used to simulate subgrid-scale features. They operate at a higher spatial resolution (15 - 50 km) using the time varying atmospheric conditions obtained from the GCMs. The advantage of this method is that it delivers meteorologically consistent downscaled variables. However, the uncertainty in this method and the non-uniqueness of the solution is generally not taken into account.

Empirical downscaling methods are based on local observations that are used to estimate appropriate downscaling functions F. The assumption of these methods is that the statistical relationship between the large-scale and the local-scale features remains the same even under a changing climate. Empirical methods can generate a large number of realisations – it is therefore possible to assess the uncertainty of the prediction. Further local details, which cannot be examined by the dynamical models, can be considered in these models. In principle, there are three different methods for empirical downscaling:

1 regression;

2 conditional probability; and

3 resampling.

With regression techniques, the relationship between the large-scale and the local information is described using an explicit function (Wilks, 1989, Wilby *et al.*, 1999). The form of the function is usually selected so that the parameters can be estimated without major numerical difficulties. The explanatory variables are often selected using a kind of trial and error procedure. Once the parameters are assessed, suitable techniques are required to ensure that there is appropriate variability in the series (for example, inflated regression). The choice of explanatory variables is very important. With a large number of large-scale variables available, one can always find high correlations of which some will be purely due to chance. Split sampling can highlight these problems, and is strongly recommended.

Other empirical techniques use an intermediate step. The large-scale information is first classified using empirical, statistical or other methods. Downscaling is then performed using stochastic models, with parameters dependent on the conditional probability (CP) types.

Resampling methods identify similar situations in the past, and depending on the degree of similarity, assign probabilities to these situations. This approach generates physically feasible spatial patterns of the surface variables. However, the application is restricted to the observed values. Even though no new extremes might occur on the observation time scale.

CIRCULATION PATTERNS

It is obvious that there is a close relationship between atmospheric circulation and climate variables. Lamb (1977) stated that even the highly varying precipitation is strongly linked to the atmospheric circulation. McCabe *et al.* (1989) classified nine weather types for Philadelphia, using seven climatological parameters for a period of 34 years (1954-1988) as a basis for stochastic precipitation modelling. Hay *et al.* (1991) developed a daily precipitation model based on atmospheric circulation for spatially distributed stations. In their model, the different stations were connected to each other through the same circulation pattern. Wilson *et al.* (1990) developed a daily precipitation model using a weather classification scheme for the Pacific Northwest US. Bogárdi *et al.* (1993) used k-means clustering to generate the classification patterns.

The pressure data used here, were the NMC grid data for different windows over Europe at a 5° x 5° resolution. Several geopotential heights (700 hPa, 500 hPa and sea level pressure (SLP)) were used. The classification method selected was the fuzzy-rule based classification (Bárdossy, 1994; Bárdossy *et al.*, 1995) combined with the simulated annealing algorithm. It consists of three steps:

1 data transformation (calculation of anomalies);

2 definition of the fuzzy rules; and

3 classification of the observed data.

Classification using fuzzy sets may be considered as a mathematical representation of imprecise statements such as ‘high pressure’ or ‘above normal’. Each circulation pattern is described by a rule containing a set of locations with prescribed anomalies. Four types of anomalies are considered:

- points with very high atmospheric pressure;
- points with high atmospheric pressure;
- points with low atmospheric pressure; and
- points with very low atmospheric pressure.

Additionally, for each pattern a large number of locations are considered to be unclassified. Thus, each rule can be described by a discrete vector = (v(1) ,..., v(L)), where v(gl) is the fuzzy class assigned to the pressure gridpoint gl. Each day is classified by selecting the pattern for which the fulfilment grade of the corresponding rules is highest. For more details, refer to Bárdossy *et al.* (1992).

Optimised classification means that the rules are assessed for a specific goal: the best description of the local surface variables. Thus, performance measures for the classification of surface variables needs to be defined. For this purpose, additional objective functions are included. The first objective is to obtain high/low probabilities of exceeding a threshold for days where it really was exceeded, and low values where this was not the case:

$$O_1(\theta) = \frac{1}{S}\sum_{s=1}^{S} \sqrt{\sum_{i=1}^{I} \left(p(u_s, CP(i)) - \overline{p}(u_s)\right)^2} \quad (2)$$

Here S is the number of stations with precipitation observations at locations u_s, I is the number of days with precipitation, $p(u_s, CP(i))$ is the probability of a day with precipitation exceeding at location u_s with the given $CP(i)$, $\overline{p}(u_s)$ is the probability of a day with precipitation exceeding without considering any classification. The higher the value of this function, the better the *CPs* can distinguish between wet and dry days, and the more successful is the classification.

The task of the optimisation is to achieve *CPs* that explain as much as the variability in precipitation behaviour as possible, obtaining some very wet and some very dry *CPs*. For precipitation amounts, the following objective function is used:

$$O_2 = \frac{1}{S}\sum_{s=1}^{S}\frac{1}{I}\sum_{i=1}^{I}\log\left|\frac{z(u_s, CP(i))}{\overline{z}(u_s)}\right| \quad (3)$$

Here $z(u_s, CP(i))$ is the mean precipitation amount on a day with the given *CP* for station s, and $\overline{z}(u_s)$ is the mean daily precipitation at the same station without classification. The higher the value of O_2 the better the classification.

It is possible to simultaneously consider more objective functions, by defining an overall objective:

$$O = \sum_{l} \alpha_l O_1(\theta_l) + O_2 \tag{4}$$

This method can also be used to measure the quality of a classification for daily temperature. In this case, the aim of the classification is to obtain CPs that explain as many anomalies (deviations from the annual temperature cycle) as possible. The objective function which measures this, is defined as:

$$O_3 = \frac{1}{S}\sum_{s=1}^{S}\frac{1}{I}\sum_{i=1}^{I}\left|T(u_s, CP(i), i) - \overline{T}(u_s, i)\right| \tag{5}$$

$T(u_s,CP(i),i)$ is the daily temperature at location *s* on day *i* with *CP(i)*, and *T(us,i)* is the mean daily temperature at location *us* according to the annual cycle.

Optimisation algorithm

A simulated annealing algorithm is used because the problem is a combinatorial optimisation, and the objective function has a complicated implicit form. The algorithm can be described briefly as follows:

1. Set the initial annealing temperature to qo

2. Select a rule k randomly

3. Select a location i randomly

4. Select class v* randomly

5. Set v(i) = v* and perform the classification

6. Calculate the performance O* for the altered rules

7. If O* < O then accept the change and let v(i) = v*

8. If O* O then with a probability exp $\left(\frac{O - O^*}{q_s}\right)$ accept the change

9. If the change is accepted, replace O by O*

10. Repeat steps 2 - M times

11. Decrease the annealing temperature by setting q_s+1< q_s

12. Repeat steps 2 - S times, or until no more changes are performed.

The quality of the classification is measured by various features of the objective function. However, for the purpose of objectiveness, a split sampling approach is selected to assess the performance.

APPLICATION

The classification methodology described above was applied to several regions of Europe. For example, the 12 CPs obtained by optimising precipitation data from 9 German stations, are presented. The daily 500 hPa elevations were used for defining the CPs. Figure 1 and 2 show the anomalies for these 12CPs.

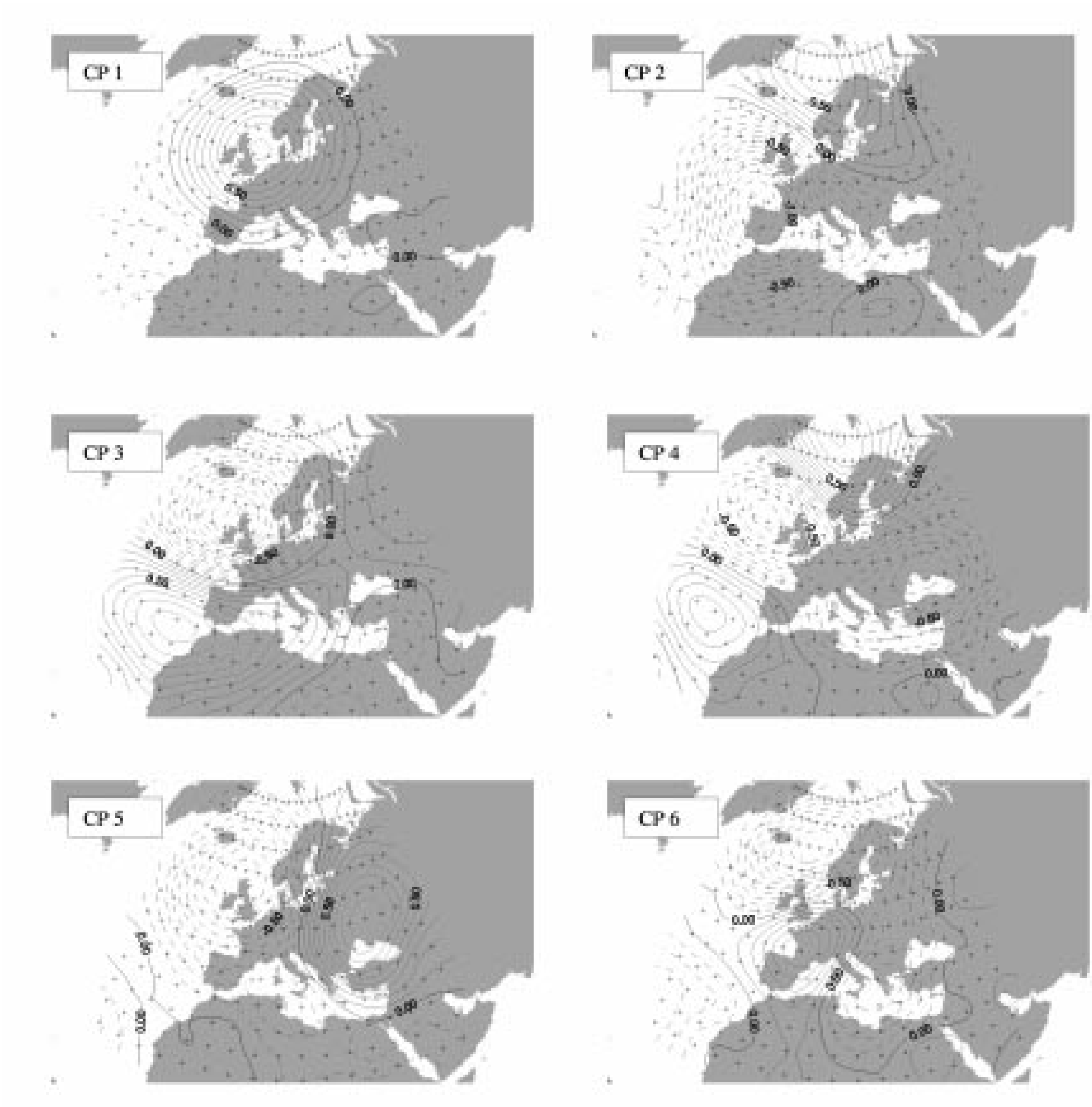

Figure 1. Pressure anomaly maps for the validation period (1970-1979) obtained by optimised fuzzy rules, CPs 1-6.

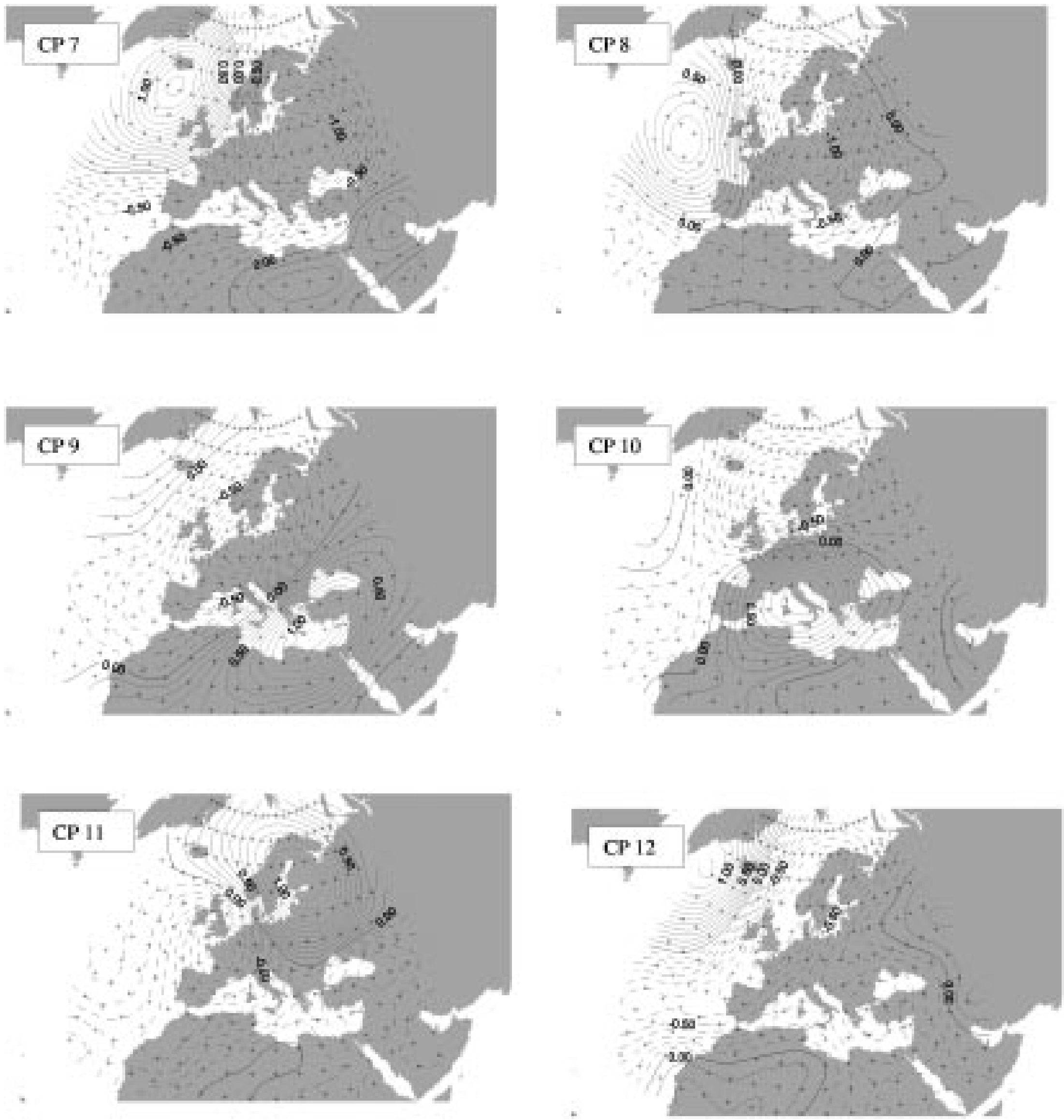

Figure 2. Pressure anomaly maps for the validation period (1970-1979) obtained by optimised fuzzy rules, CPs 7-12.

The classification for temperature led to a different classification. However, statistical tests shows that these patterns are not independent.

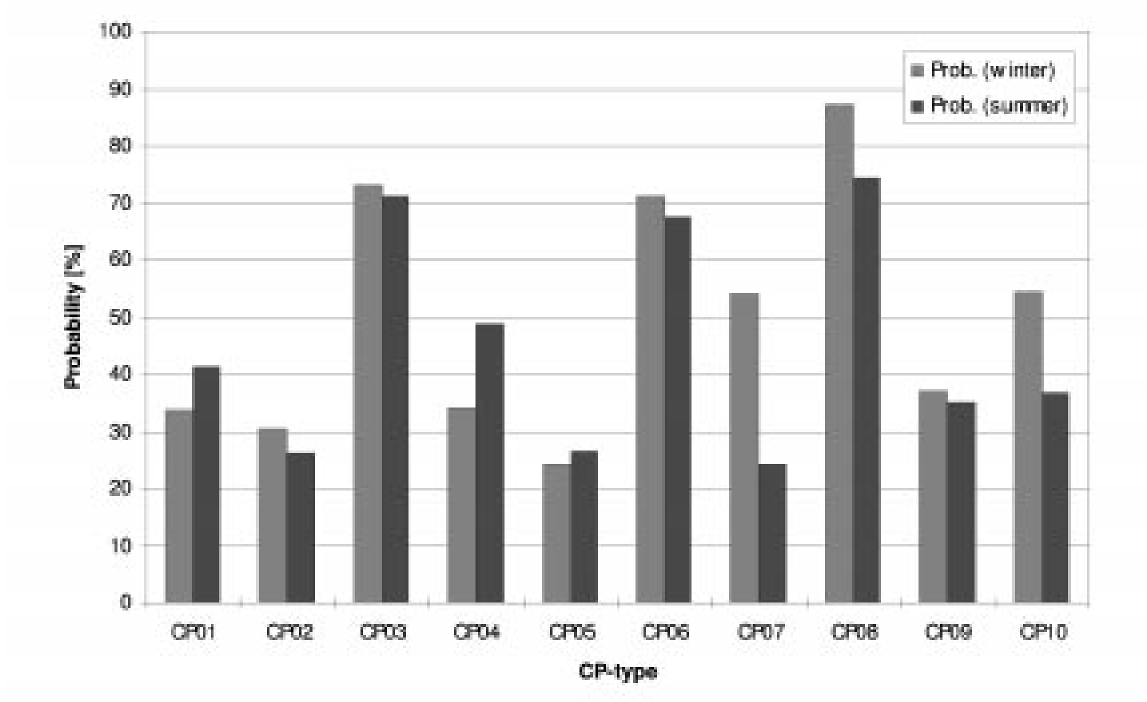

Figure 3. Conditional probabilities of precipitation for different circulation patterns of the Upper Neckar catchment.

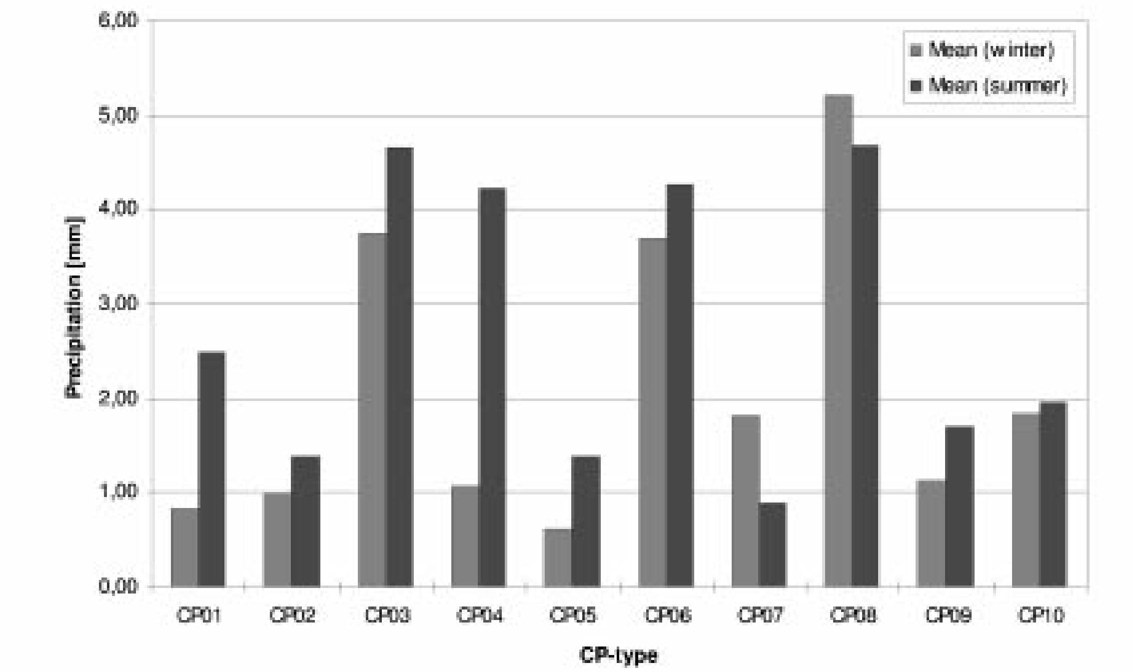

Figure 4: Conditional mean daily precipitation amounts for different circulation patterns of the Upper Neckar catchment.

Figure 3 shows the conditional precipitation probabilities for the Upper Neckar catchment. The conditional precipitation amounts are shown in Figure 4, and one can see that the precipitation behaviour of the patterns is very different. Figure 5 shows the different annual cycles of temperature for two different *CPs.*

CONDITIONAL DOWNSCALING

Classifications can provide conditional mean precipitation amounts and probabilities of precipitation occurrence or temperature anomalies for specific locations. However, downscaling aims to produce realistic series that reproduce the temporal and spatial variability. For this purpose, specific models have to be developed.

Precipitation model

Let = {1 ,..., n} be the set of possible atmospheric circulation patterns. Let $\tilde{A}_t$ be the random variable describing the actual atmospheric circulation, taking its values from A. Let the daily precipitation amount at time *t* and point *u* in the region *U* be modelled as the random function *Z(t, u), u U*. The distribution of rainfall amounts at a selected location is skewed. In order to relate it to a simple normally distributed random function *W(t, u)* (for any locations u_1 ,..., u_n the vector $(W(t, u_1) ,..., W(t, u_n))$ is a multivariate normal random vector) the following power transformation relationship is introduced:

$$Z(t,u) = \begin{cases} 0 & \text{if } W(t,u) \le 0 \\ W^{\beta}(t,u) & \text{if } W(t,u) > 0 \end{cases} \qquad (6)$$

Here is an appropriate positive exponent. This allows the mixed (discrete - continuous) distribution of *Z(t, u)* to be related to a normal distribution. As the process *Z(t, u)* depends on the atmospheric circulation pattern, the same applies to $W(t, u_n)$. The reason for this transformation is that multivariate processes can be more easily modelled if the process is normally distributed. The problem of intermittence can also be handled in this way, as the negative values of W are declared as dry days and dry locations. The exponent is needed because the distribution of precipitation amounts is generally considerably more skewed than the truncated normal distribution.

The relationship between *W(t, u)*. and the circulation pattern $\tilde{A}_t$ is obtained through the rainfall process *Z(t, u)* using equation (6). The probability of rainfall occurring at time *t* and location *u* depends on $\tilde{A}_t$:

$$P\left[W(t,u) > 0 \mid \tilde{A}_t = \alpha_i\right] = P\left[Z(t,u) > 0 \mid \tilde{A}_t = \alpha_i\right] = p_i(u,t) \qquad (7)$$

The distribution of daily rainfall amounts at location u *Fi(z| u)* also depends on $\tilde{A}_t$ and the time (day of the year) *t*:

$$P\left[Z(t,u) < z \mid \tilde{A}_t = \alpha_i, Z(t,u) > 0\right] = F_i(z \mid u,t) \qquad (8)$$

Equation (6) establishes the link between *W(t,u)* and rainfall *Z(t,u)*, and thus the multidimensional rainfall process is fully described. The parameters of W(t) depend on the CP and the day of the year *t*. The dependence on *t* is described using a Fourier series.

Temperature model

Unlike precipitation, daily mean temperature is much less variable in space, and much of the variability can be explained by the topography. The established annual cycle has to be taken into account. For this purpose, the average elevation of a pressure level (such as 700 or 500 hPa) H_p is used. Furthermore, temperature depends on the previous day's temperature and the CP, and is associated with the precipitation of the same day.

$$T(u,t) = F(u, H_p(t), \widetilde{A}_t, T(u,t-1), Z(u,t)) \quad (9)$$

The link between precipitation and temperature is established using an indicator:

$$I_z(t) = \begin{cases} 1 & \text{if } \frac{1}{|G|}\int_G Z(t,u)\,du \geq z_0 \\ 0 & \text{else} \end{cases} \quad (10)$$

The indicator depends on the areal precipitation, which is estimated from the observation points by ordinary kriging (Matheron, 1973) using the spatial correlation function of precipitation. Thus, the kriging weights ëi do not depend on the time t.

$$\frac{1}{|G|}\int_G Z(t,u) = \sum \lambda \;\; Z(u_i, t) \quad (11)$$

Using the notation:

T*(t) = (T(u1, t),..., T(um, t))*

c(I) = (c1(I),..., cm(I))

d(I) = (d1(I),..., dm(I))

One method is to assume a general relationship between the pressure surface and elevation, with residuals depending on the circulation pattern and annual cycle.

$$E[T(t)] = c(I_z(t))H_p(t)+d(I_z(t))+R_i(t) \quad (12)$$

$R_i(t)$ is the residual depending on the CP_i and the time of the year *t*. The components $R_i(u, t)$ of this function are expressed with Fourier series:

$$R_i(u,t) = \sum_{k=0}^{K} (a_k(R_i,u)\sin(k\omega t) + b_k(R_i,u)\cos(k\omega t)) \quad (13)$$

To obtain a model which replicates the natural variability, a first order auto-regressive (AR(1)) process is used:

$$T(t) = c(I_z(t))H_p(t) + d(I_z(t)) + R_i(t) + P_i(T(t-1) - (c(I_z(t-1))H_p(t-1) + d(I_z(t-1)) + R_i(t-1))) + S_i Ø(t) \quad (14)$$

Note that the expectation of the previous day is calculated using the present day's *CP*.

Figure 5 shows the average annual cycle of observed temperature dependent on *CPs* in the Aller catchment, for the period 1963-1993. Temperature clearly depends on the geopotential pressure height, i.e., the *CPs*. In winter, the average temperature during *CP01* days is warmer than during *CP09* days. In summer, the opposite is found - the average temperature is warmer during *CP09* days than during *CP01* days.

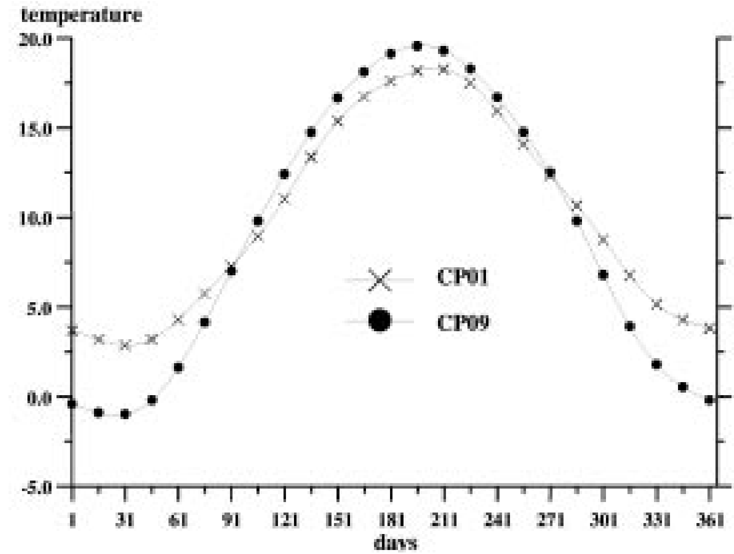

Figure 5. Observed annual cycle of temperature for different CPs.

Temperatures clearly depend on precipitation and *CP*, as shown in Figure 6. In winter, wet days (P > 1 mm/day) are warmer than dry days, whereas in summer they are colder. In addition, the average daily altitude of the geopotential pressure heights (for example, the 700 hPa surface) is coupled with daily temperature.

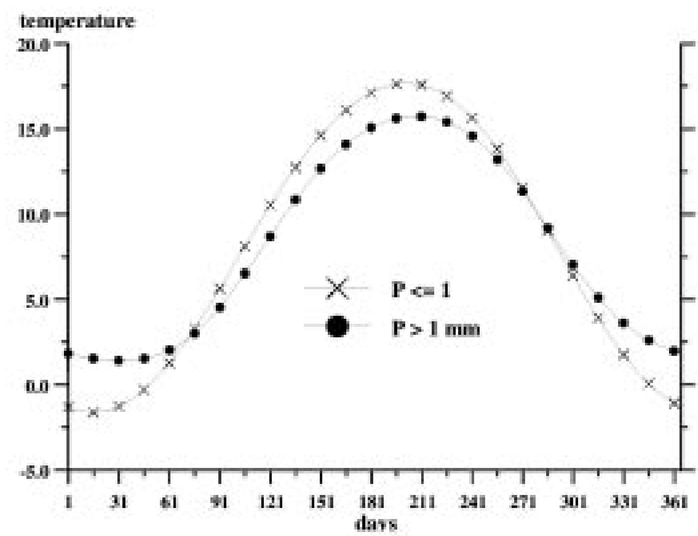

Figure 6. Observed annual cycle of temperature for different precipitation conditions.

Application

The methodology described above was applied to several different locations, of which two are presented here. In Figures 7 and 8 the observed annual cycle of precipitation is compared to the simulated cycle. Figure 9 shows the observed and simulated annual precipitation amounts for a period of 20 years for Lüdenscheid, Germany.

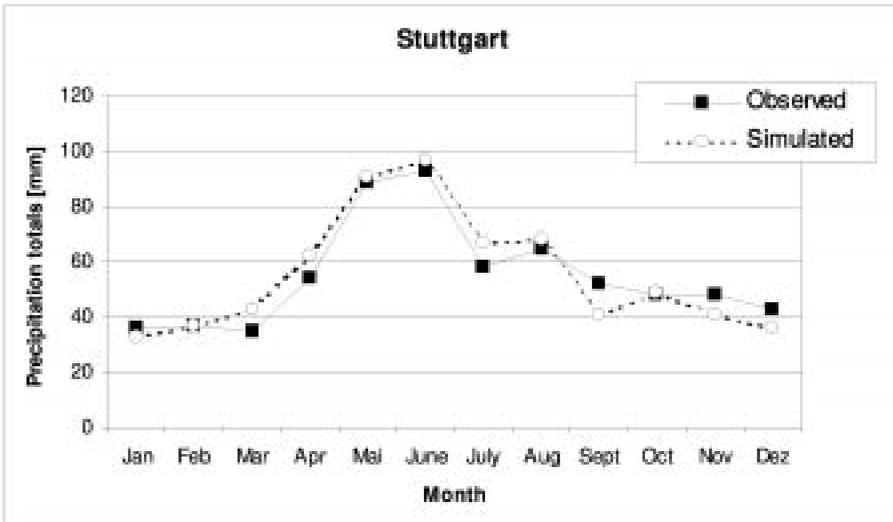

Figure 7. Observed and simulated annual cycle for precipitation at Stuttgart.

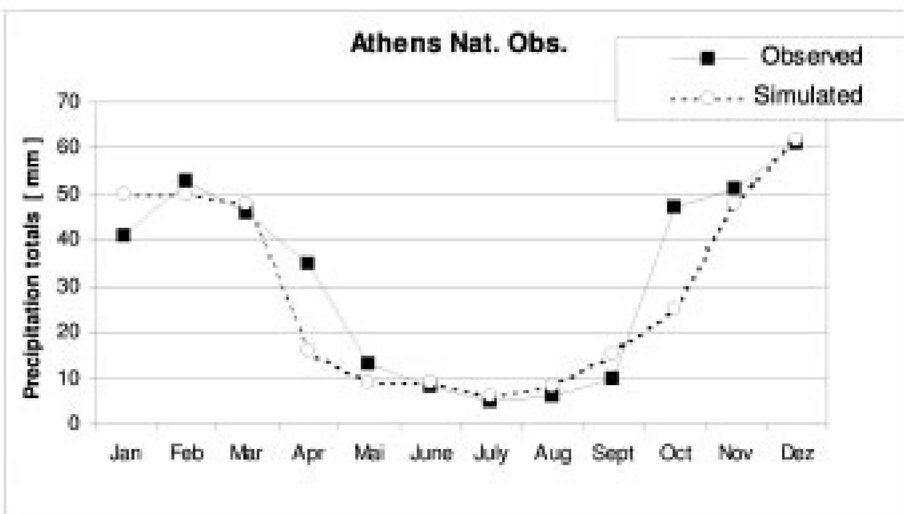

Figure 8. Observed and simulated annual cycle for precipitation at Athens.

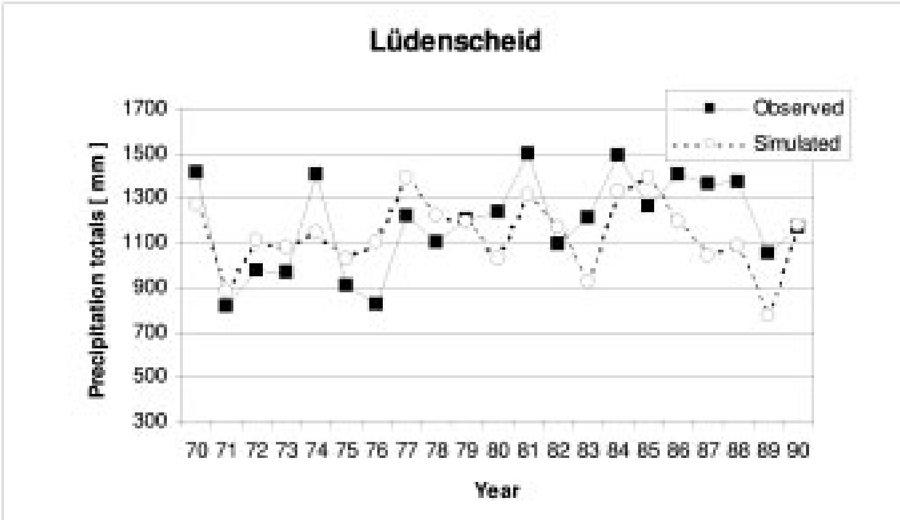

Figure 9. Observed and simulated annual precipitation amounts for Lüdenscheid.

Disaggregation

Hydrological modelling requires precipitation data at a high temporal resolution. Observations and downscaling results are usually at a daily (or monthly) resolution and therefore have to be disaggregated.

$$Z(u,t) = \sum_{d=1}^{D} Z_D(u,t_d) \qquad (15)$$

Z(u, t) represents the precipitation amounts, $Z_D(u, t_d)$ is the precipitation amount for sub-period d of day *t* and *D* is the number of sub-periods within one day.

The statistical relationship between daily and subscale (hourly, 15 minutes) precipitation statistics is conditioned on the *CPs*. Figure 10 shows the relationship between daily precipitation amounts and the probability of a wet hour for different circulation patterns in winter. Figure 11 shows the same relationship for summer. One can see that the relationship varies according to the different circulation patterns. In summer, the probabilities are lower than in winter. Probabilities are low for *CP04* in summer - this circulation pattern corresponds to high pressure centred over central Europe and in summer, convective precipitation sometimes occurs on days with this pattern.

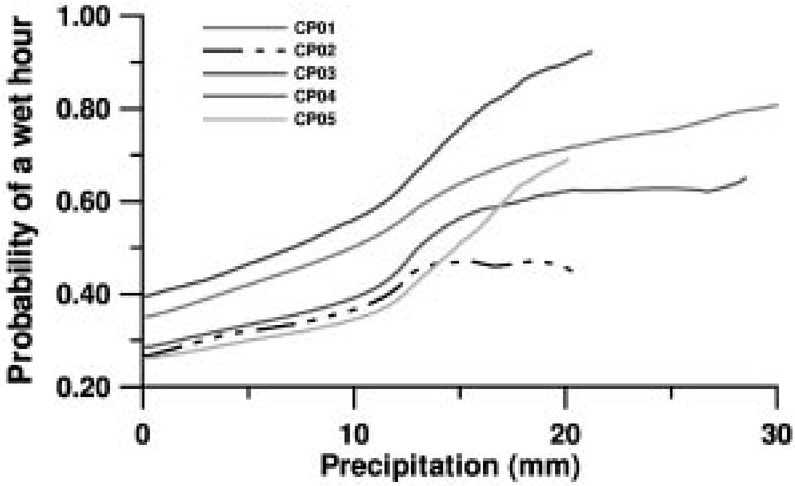

Figure 10. Relationship between daily precipitation amount and probability of a wet hour for different CPs in winter.

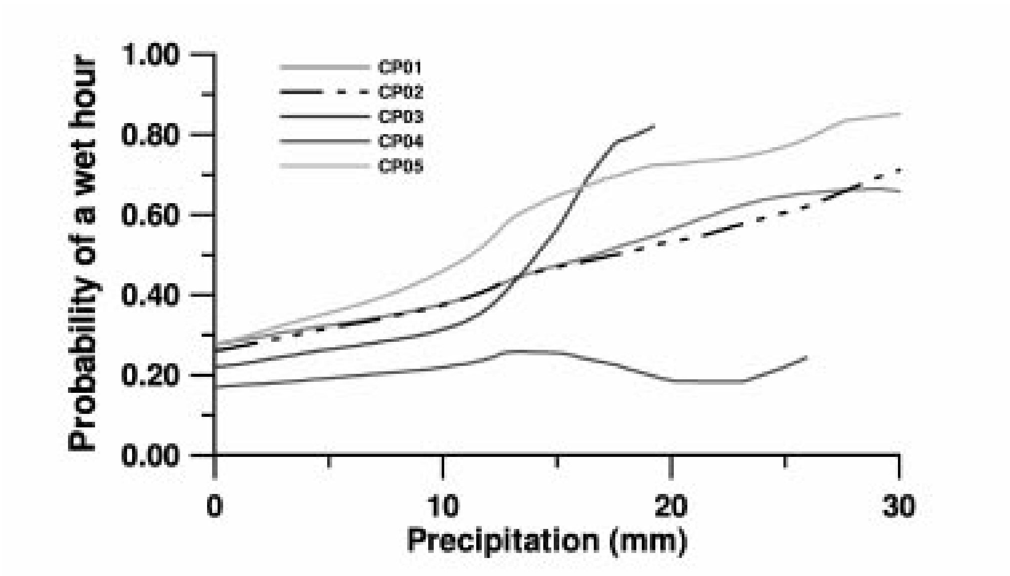

Figure 11. Relationship between daily precipitation amount and probability of a wet hour for different CPs in summer.

HYDROLOGICAL APPLICATION

The downscaling method described above was applied to the Upper Neckar catchment in southwest Germany. The runoff characteristics of this catchment are not affected by large hydropower plants or other water management constructions. The catchment combines regions with low anthropogenic influence (especially in the higher altitude zones) with those of intense agriculture. In addition, the Upper Neckar catchment, with a size of approximately 4000 km^2, can be considered a typical example of a mid-German medium-size river catchment. Data were available from 1961 to 1990.

The results for the hydrometeorological impacts of climate change can be summarized as:

- A significant decrease in precipitation for the 2xCO_2 scenario; this is a clear signal, beyond the limits of natural variation (see Figure 12).

- A general warming of about 1°C is observed but is only significant in the annual mean due to the modelling problems mentioned above.

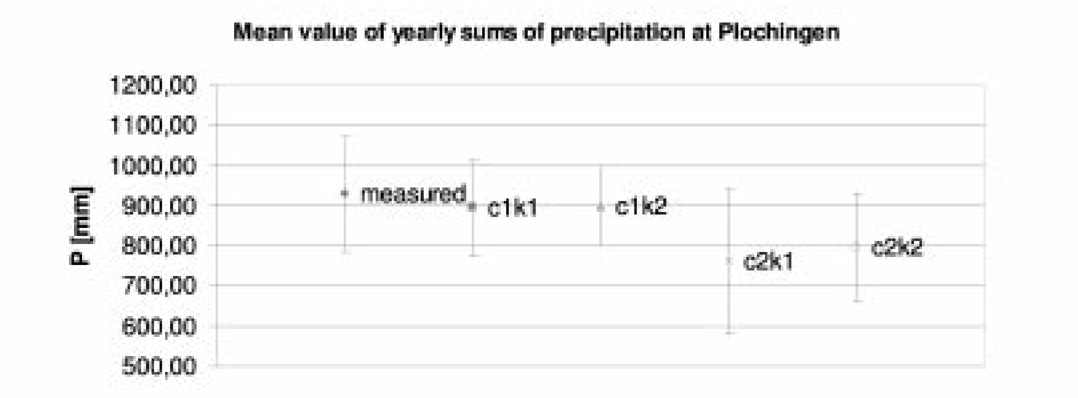

Figure 12. Mean annual areal precipitations for the observed and the 1xCO_2 (c1) and 2xCO_2 (c2) scenarios for the Upper Neckar catchment.

The hydrological model was calibrated for the period, 1981-1990. The calibration was done manually. In order to avoid the effects of a random optimal parameter set, three independent calibrations were carried out. The calibration parameters used were the storage constants, the threshold values for the surface runoff and the percolation into the deeper storage. The calibrated parameter sets were validated for the two periods 1961-1970 and 1971-1980. All parameter sets perform well for the calibration period. The performance is slightly worse for the validation periods, but the fits are still reasonable. Although high peaks are not generally well matched, this is typical for continuous models and explains the lower variance of the simulated series.

The hydrological modelling results indicate a change for all the components of the water balance in all sub-catchments of the Upper Neckar basin, within each month of the year as well as for the total annual amounts. Precipitation decreases, especially of at least 20% in spring and of 30-40% in late summer, may affect agriculture because there would be less rainfall during the growing periods of the plants. The results indicate that precipitation decreases could be greater at lower elevation. This would increase potential agricultural losses, because agriculture is more likely to be located in the lowlands than in the hilly regions. In addition, the higher spring temperatures would encourage earlier vegetative growth, which would require even more water.

For all scenarios, regardless of the modelling technique selected, discharge decreases in each month of the year (see Figure 13). The largest decreases occur in the late summer months. As water resources are reduced in these already sensitive months, further problems of water availability may result. Losses will be more substantial at lower altitudes than in the hilly regions.

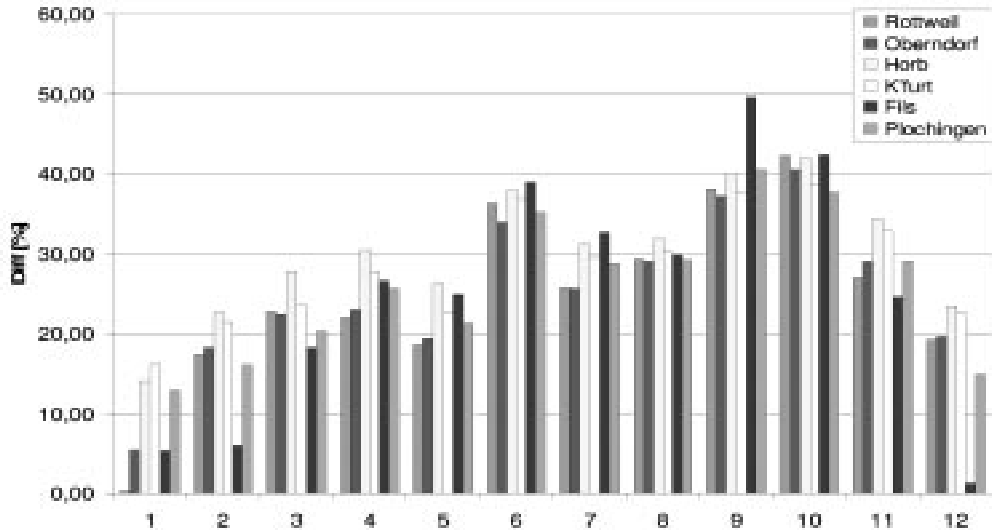

Figure 13. Changes in discharge between 1xCO2 and 2xCO2 scenarios for the sub-catchments of the Upper Neckar catchment.

In terms of evapotranspiration (ETP), there will be an increase during the winter months and a decrease during the summer months. Whereas the increase of ETP during the winter period is approximately the same for all subcatchments, the decrease in ETP in the summer varies depending on the altitude of the region. In hilly regions, the decrease in ETP will not be greater than 10% whereas in the lowlands, the decrease could be greater than 15%. Since at high altitudes, the decrease of both precipitation and ETP is less than in the lowlands, temperature seems to be the limiting factor. In the lowlands, the greater decrease in precipitation reduces the availability of water for evaporation, and ETP decreases. Therefore, the limiting factor for ETP in the lowlands is the availability of rainfall.

CONCLUSIONS

An estimation of the regional consequences of climate change requires data at a different temporal and spatial scale to that provided by the GCMs, and downscaling methods are therefore required. The methods available for downscaling include dynamic and empirical approaches. The non-uniqueness of the downscaling technique must be reflected in the results in order to show the related uncertainties.

In this paper a circulation pattern classification method and a corresponding precipitation/temperature model was presented. A case study shows that the largest uncertainties are in the GCM modelling itself. Therefore, the projection of climate change has to be treated carefully and is considered to be of only limited quality due to inaccuracies in the GCM output. For a reliable projection of local climate change, a significantly improved GCM output is required.

ACKNOWLEDGEMENT

Research leading to this paper was partly funded by the European Union sponsored research projects ACCORD and CC-HYDRO.

REFERENCES

Bárdossy, A., Duckstein, L., and Bogárdi, I. (1995) Fuzzy rule based classification of atmospheric circulation patterns, **International Journal of Climatology** 15, 1087-1097.

Bárdossy, A., Plate, E.J. (1992) Space-time model for daily rainfall using atmospheric circulation patterns, **Water Resources Research** 28, 1247-1259.

Bogardi, I., Duckstein, L., Matyasovszky, I. and Bárdossy, A. (1993) Application of a space-time stochastic model for daily precipitation using atmospheric circulation patterns, **Journal of Geophysical Research** 98(D-9), 16653-16667.

Gerstengarbe, F.W. and Werner, P.C. (1993) Katalog der Großwetterlagen Europas nach P. Hess und H. Brezowsky 1881-1992. 4., vollst. neu bearb. Aufl.; Berichte des Deutschen Wetterdienstes 113; Selbstverlag des DWD, Offenbach a.M.

Giorgi, F. and Mearns, L.O. (1991) Approaches to the simulation of regional climate change. A review, **Reviews of Geophysics** 29, 191-216.

Hay, L.E., McCabe, G.J., Wolock, D.M. and Ayers, M.A. (1991) Simulation of precipitation by weather type analysis, **Water Resources Research** 27, 493-501.

Hess, P. and Brezowsky, H. (1969) Katalog der Großwetterlagen Europas. 2. neu bearb. u. erg. Aufl.; Berichte des Deutschen Wetterdienstes 113; Selbstverlag des DWD, Offenbach a.M.

Lamb, H.H. (1977) **Climate, Present, Past and Future. Vol. 2: Climatic History and the Future**. Methuen & Co Ltd, London, 835 pp.

Maheras, P. (1988) The synoptic weather types and objective delimitation of the winter period in Greece, **Weather** 43(2), 40-45.

McCabe, G.J., Hay, L.E., Kalkstein, L.S., Ayers, M.A., Wolock, D.M. (1989) Simulation of precipitation by weather-type analysis. **International Symposium on Sediment Transport Modeling**, Aug. 14-18, 1989, New Orleans.

Wilby, R.L., Wigley, M.L., Conway, D., Jones, P.D., Hewitson, B.C., Main, J. and Wilks, D.S. (1998) Statistical downscaling of general circulation model output: A comparison of methods, **Water Resources Research** 34(11), 2995-3008.

Wilks, D.S. (1989) Statistical specification of local surface weather elements from large-scale information, **Theoretical and Applied Climatology** 40, 119-134.

Wilson, L.L., Lettenmaier, D.P., and Wood, E.F. (1990) Simulation of precipitation in the Pacific Northwest using a weather classification scheme, **Surveys in Geophysics** 12, 127-142.

Yarnal, B. (1984) A procedure for the classification of synoptic weather maps from gridded atmospheric pressure surface data, **Computers and Geosciences** 10, 397-410.

Yarnal, B. (1993) **Synoptic Climatology in Environmental Analysis; Studies in Climatology Series**, Belhaven Press, London and Florida.

Yarnal, B. and White, D. (1987) Subjectivity in a computer-assisted synoptic climatology I: classification results, **Journal of Climatology** 7, 119-128.

Yarnal, B., White, D. and Leathers, D.J. (1988) Subjectivity in a computer-assisted synoptic climatology II: relationships to surface climate, **Journal of Climatology** 8, 227-239.

Keynote Paper 2

Climatological Changes in Storm Surges and River Discharges: the Impact on Flood Protection and Salt Intrusion in the Rhine-Meuse Delta.

Pieter Jacobs, Gerard Blom and Theo van der Linden

RIZA - Institute for Inland Water Management and Waste Water Treatment,
Dept. WST, Van Leeuwenhoekweg 20, 3316 AV Dordrecht, the Netherlands
(p.jacobs@riza.rws.minvenw.nl)

ABSTRACT

Management of the Rhine-Meuse delta in the Netherlands involves, among a great number of issues, three major fields of interest: protection against flooding, fresh water supply and shipping. The water system in this area is mainly driven by the combined effects of tide and river discharge. To be able to anticipate changes in these driving mechanisms, so that the functions of the aforementioned fields of interest are guaranteed, detailed projections of climate scenarios are needed. In particular, quantitative estimates of future changes in sea-level rise, average storm duration and intensity, and the occurrence and duration of extremely low and high river discharge are required.

At RIZA, a tool has been developed to calculate the combined effects of changes in boundary conditions and management interventions (mainly of morphological conditions) on the hydrodynamical characteristics of the delta area. This DSS (Decision Support System), which is based on a one-dimensional numerical model, has been used to investigate the effects of climate change on areas of management: risk of flooding due to a combination of peak river discharge and storm surge, and salt intrusion caused by a combination of low river discharge and storm surge. The third aspect, the effects of climate change on shipping, has not been examined since the mean water level in a large part of the area is expected to increase.

For the first aspect, estimates of mean sea-level rise and increases of peak river discharge are used to assess the increased risk of flooding. The accuracy of the model results is largely impeded by uncertainty in the estimates of temperature change, sea-level rise and increases in peak discharge of the rivers Rhine and Meuse, and of the characteristics of the storm surges: the intensity, duration and frequency of occurrence of storm wind fields. Furthermore, there is a need for greater insight into the dependency between the occurrence of storm surge and peak discharge, since the method used in the DSS is based on the assumption that all stochastic variables are independent.

To estimate the level of salt intrusion in the delta area, periods of low river discharge are simulated. It is expected that these periods will occur more often in the future, and that the average duration will increase. However, detailed estimates of these changes are not yet available. The effects of an increase in average water level at the sea boundary of the delta are investigated as well as the combined effects of a change in low river discharge and sea-level rise. Finally, the sensitivity of the results with respect to the estimate of sea-level rise is discussed and the implications for climatologists addressed.

INTRODUCTION

The influence of climate on the hydrology of river deltas such as found in the Netherlands, reveals itself in various ways. First, there is the direct influence of precipitation on the delta area as well as on the entire catchment area (which determines the river discharge). The wind field alters the net inflow or outflow of seawater and river water, respectively. These aspects of climate are expected to change significantly over the next century or so, mainly due to the greenhouse effect (whether human-induced or not). Furthermore, climate changes at a global scale are expected to increase the mean sea level, which indirectly affects the hydrodynamics of the delta hydrology.

Some of the climate parameters that are expected to change over the next century are investigated here to estimate their impact on the hydrology of the Rhine-Meuse delta in the Netherlands. This approach was adopted in a study in the 80's and early 90's (WL|Delft Hydraulics, 1990), in which a physical model of the Rhine-Meuse estuary was used to determine the effects of changing sea level and river discharge on water levels and salt intrusion. However, with this physical model it was not possible to apply some statistical methods used to determine the design levels of primary dikes and dams (DBW/RIZA, 1987a). In this paper, a statistical method is used for estimating both the effects of climate change on flood protection and salt intrusion in the Rhine-Meuse delta.

The paper is structured as follows: first, the study area will be introduced. Second, after defining a reference situation that is valid for the present-day situation, changes in storm duration and intensity are considered, and the results of model calculations for present and future situations are presented. Third, the effects on salt intrusion of changes in summer river discharge and sea level are simulated. Finally, key conclusions are drawn and some remaining questions addressed.

STUDY AREA

Almost 50% of the land surface in the Netherlands lies below mean sea level, therefore the sea represents a constant threat. This is particularly the case for the Rhine-Meuse estuary, which forms the transition zone between fluvial and marine water systems. The area is bounded on the eastern side by the rivers Lek and Waal (both downstream branches of the Rhine) and the Meuse (in Dutch: Maas) and on the western side by the North Sea (see Figure 1). Like many delta areas, the Rhine-Meuse estuary region serves a large number of functions and activities, such as living and working in the urban area of Rotterdam-Dordrecht, the harbour of Rotterdam (one of the largest in the world), agriculture, fishing and recreation. A number of these activities are directly dependent on the estuarine hydrology: recreation, shipping and fresh-water supply for industrial, agricultural and drinking water purposes.

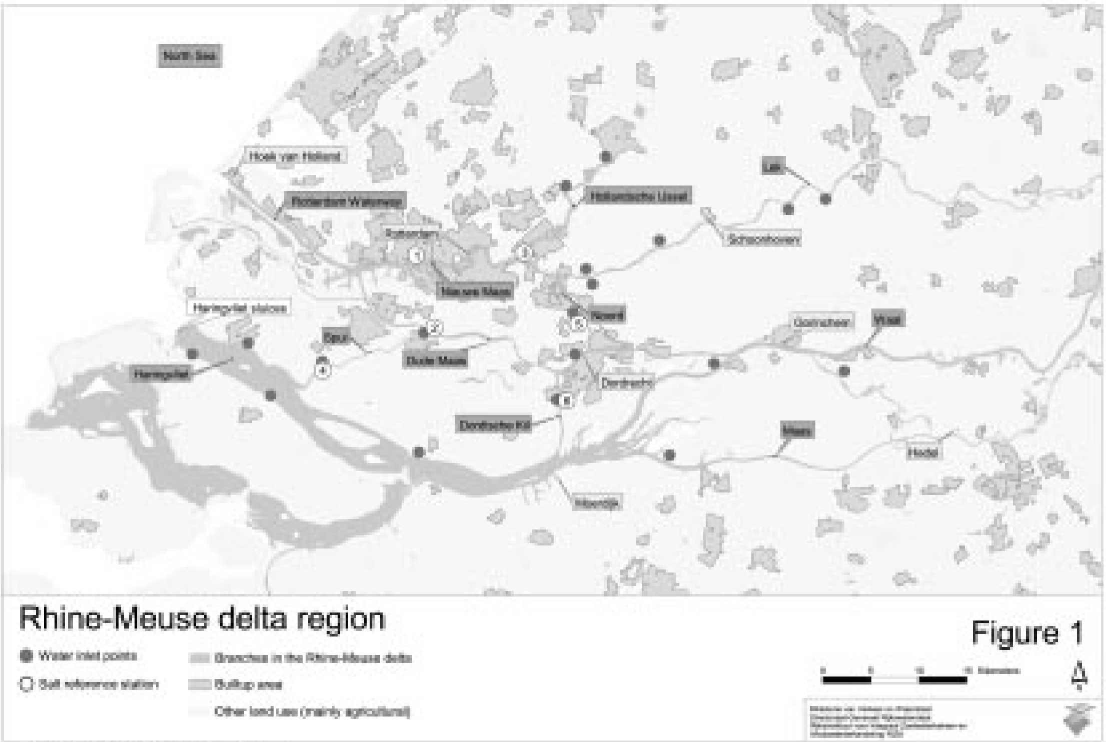

Figure 1. Rhine-Meuse delta region.

The hydrodynamic characteristics of the area are mainly governed by discharge of the rivers Rhine and Meuse and by the water level at the sea boundary. The wind field also plays an important role: it influences water levels, both at the sea boundary and in the estuary. These three boundary conditions vary in space and time, so that the hydrodynamics of the system are very dynamic.

Apart from the more natural influences on the Rhine-Meuse estuary mentioned above, human influences are substantial. The rivers Rhine and Meuse are regulated by sluices far upstream, while in the lower part of the estuary, three contributing rivers have split into a rather complicated network of branches with interconnecting channels (see Figure 1). The Haringvliet sluice gates are used as a way of regulating water flow. At present they are opened only during low tide and attempt to maintain river discharge along the Northern branch at a sufficiently high level to minimise salt intrusion through the Rotterdam Waterway. Furthermore, there are three storm surge barriers in the area: the so-called Maeslant barrier in the Rotterdam Waterway, the Hartel barrier in the Hartel Canal and the barrier at the mouth of the Hollandsche IJssel.

The effects of the aforementioned climate change on the hydrodynamical characteristics of the Dutch delta area are particularly important for two key (fresh) water management activities: protection against flooding and limiting the increase of salt intrusion into the delta to guarantee the availability of sufficient fresh-water supply. Flood protection is currently guaranteed by sufficiently high dams, river dikes, storm-surge barriers and the Haringvliet sluices.

In addition to increased protection from storm surges, current control of the Haringvliet sluices has also created a large fresh-water reservoir, which supplies water for drinking water companies and for agricultural irrigation. In fact, there are numerous abstraction points for drinking and agricultural water in the Rhine-

Meuse delta region. Some of these lie in a part of the delta, which is occasionally influenced by sea water (see also Figure 1). It is clear that timely anticipation of the climatic changes influencing the Rhine-Meuse delta is vital to several areas of water management.

HIGH RIVER DISCHARGE REGIME: IMPACTS OF STORM DURATION AND INTENSITY ON FLOOD PROTECTION

Introduction

For most of the study area, land is protected against flooding by a combination of dunes, dikes and storm surge barriers. For the dimensioning of dike heights, an acceptable inundation frequency is defined. The design water level, which is the level associated with this frequency, is calculated by simulating 54 different combinations of river discharge and wind set-up (an increase in the water level of the sea boundary above the value of the astronomical tide – see Figure 2) with a one-dimensional hydrodynamical model (RIZA, 1991).

Failures of the storm-surge barriers are also accounted for by this method. Under the assumption that river discharge, wind set-up and the failure of storm-surge barriers are independent phenomena, the probability of each combination can be calculated and the water level frequency distribution constructed (see Table 1; DBW/RIZA, 1987a and RIZA, 1995). In Table 2 the acceptable inundation frequencies and corresponding water levels are given for 6 locations in the study area (see also Figure 1). Note that the mean water level in most of the study area is approximately equal to the mean sea level

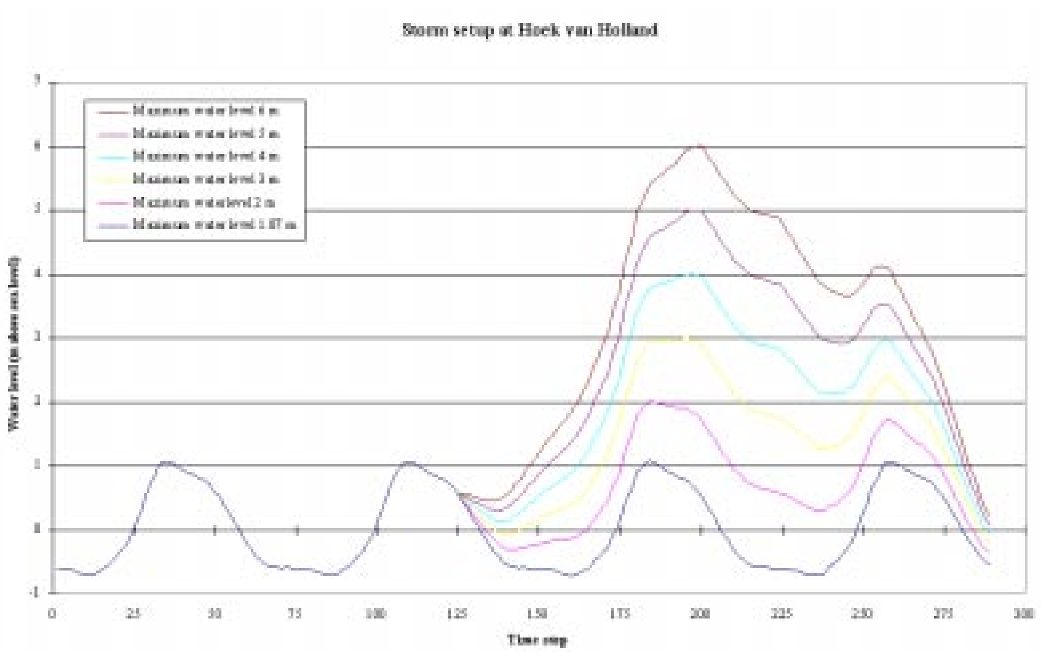

Figure 2. Change of sea-water level at Hoek van Holland for six storm conditions (Source: RIZA, 1999).

Rhine discharge at Lobith station (m^3/s)	Excess frequency (1/day)
600	0.481
2000	0.262
4000	0.069
6000	0.0139
8000	3.13E-3
10000	6.12E-4
13000	4.33E-5
16500	2.14E-6
19700	1.49E-7

Sea water level at Hoek van Holland (m above sea level)	Excess frequency (1/day)
1.07	0.237
2.00	0.006
3.00	1.20E-04
4.00	2.71E-06
5.00	1.24E-06
6.00	7.56E-09

Table 1. Frequency classes of Rhine discharge and sea water level in winter (discharge: excess frequency per day; sea-water level: excess frequency per high tide) (Source: RIZA, 1999).

Location	Acceptable inundation frequency ($year^{-1}$)	Corresponding high water level (m above sea level)
Rotterdam	1/10000	3.55
Schoonhoven	1/2000	4.20
Dordrecht	1/2000	3.00
Gorinchem	1/1250	5.75
Moerdijk	1/2000	2.75
Hedel	1/1250	6.40

Table 2. Acceptable inundation frequencies and corresponding high water levels for 6 locations in the study area (Source: Dienst Weg- en Waterbouwkunde, 1996).

Climate change will affect the high water level frequency distribution of the Rhine-Meuse delta. Increases in the peak discharge of the rivers Rhine and Meuse, and a rise in (mean) sea level are projected. Little is known about the effects of climate change on storm intensity and duration frequency distribution. This section deals with the effects of climate change on high water levels in the study area and uncertainty in the projections of climate change impacts which results from uncertainty in the effects of climate change on storm intensity and duration.

Future scenarios

To investigate the effects of climate change on high water levels, three scenarios are defined. The sea-level rise and increase in peak river discharge for these three scenarios are listed in Table 3.

Scenario		Sea-level rise	Increase in peak discharge (> 10,000 m^3/s) of the river Rhine	Increase in peak discharge (> 2,000 m^3/s) of the river Meuse
A	Lower estimate (no increase in temperature)	0.10 m	No change	No change
B	Central estimate (T + 1ºC)	0.25 m	+ 5%	+ 10%
C	Upper estimate (T + 2ºC)	0.45 m	+ 10%	+ 20%

Table 3. Three scenarios for relative sea-level rise and increase in peak discharge of the rivers Rhine and Meuse in 2050 (wrt the year 2000) (Source: Projectteam NW4, 1997).

Figure 3 shows the increase in high water levels in the study area for scenario C. The increase is presented for water levels occurring with a frequency of 1/2000 $year^{-1}$. The high water level increase resulting from climate changes varies from less than 0.1 m to more than 0.7 m, and is lowest in the Rotterdam area where high water levels are controlled by storm-surge barriers. The increase is highest in the eastern part of the study area, where high water levels are determined by peak river discharge.

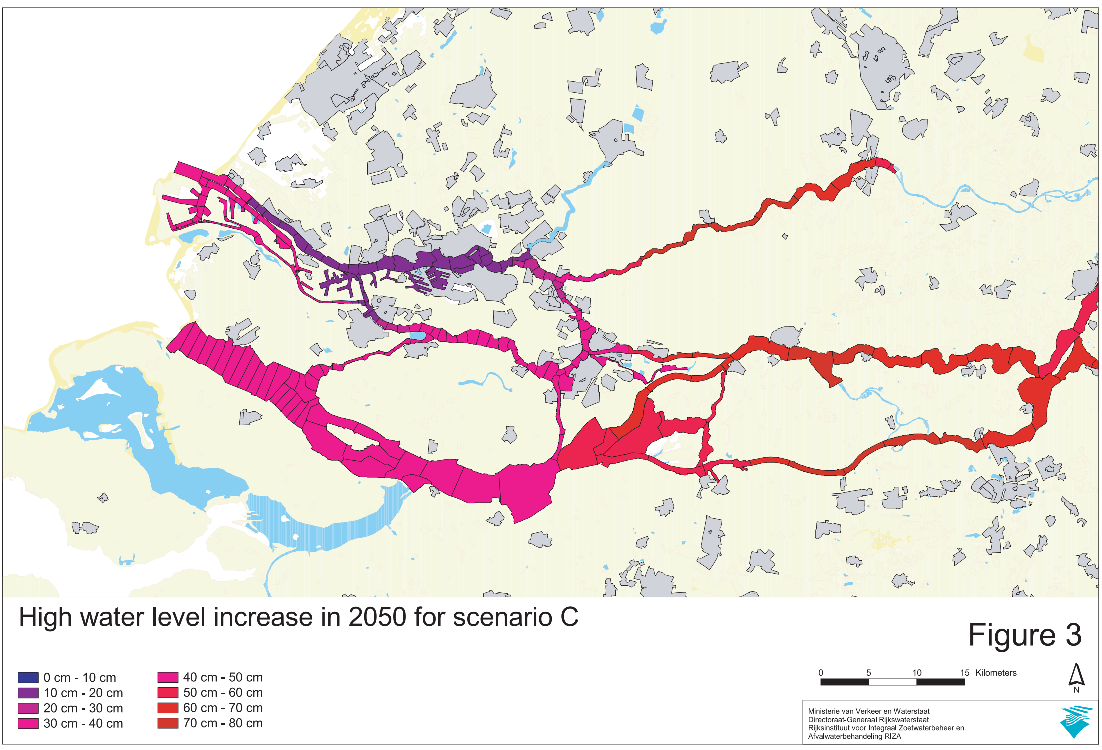

Figure 3. Increases in high water level for scenario C (wrt to the year 2000). The increase in water level occurs with a frequency of 1/2000 $year^{-1}$.

As stated above, little is known about the effects of climate change on storm intensities (wind speeds) and duration (storm lengths). At present, a standard of 29 hours is used for storm duration (based on historical information on the storm duration frequency distribution), and is approximately the mean storm duration in the present climate. The storm-surge frequency distribution is also based on historical information of wind speed and storm surges. To illustrate the effect of an increase in the (mean) storm duration and storm intensity, an increase of 4 hours in storm duration and an increase of 10% in wind speeds greater than 10 ms^{-1} was assumed. The effects of this simulated increase in storm intensity and duration are illustrated in Figure 4.

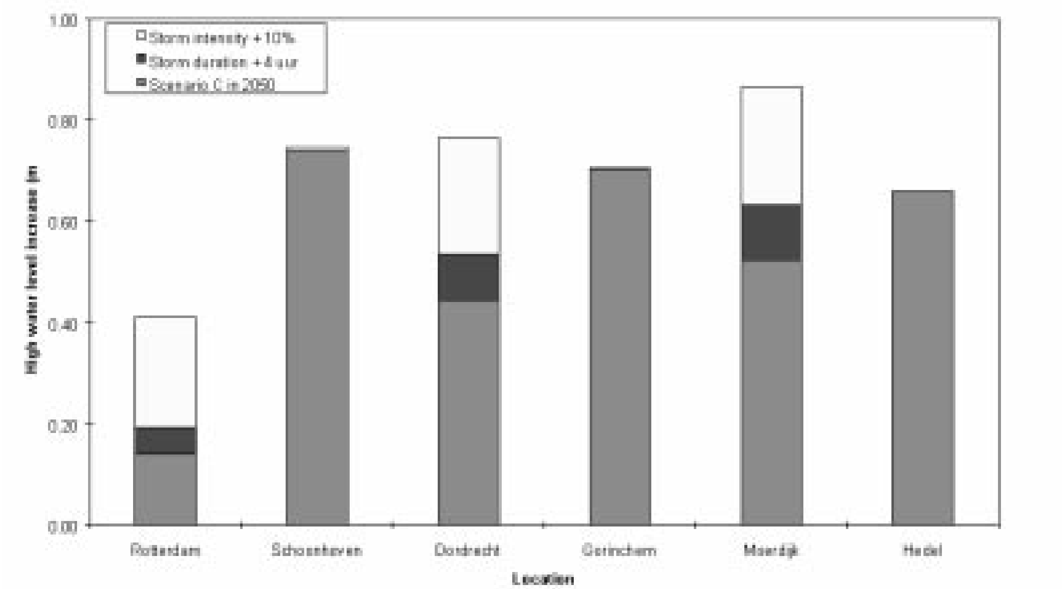

Figure 4. High water level increase in 2050 (wrt to the year 2000) for a frequency of 1/2000 year $^{-1}$ due to sea-level rise, an increase of the river discharge according to scenario C, and an increase in storm duration and intensity. The results are cumulative: the effects of an increase in storm duration are added to the increase due to climate scenario C only; the increase due to a higher storm intensity is added to the combined increase due to scenario C and an increase in storm duration.

Figure 4 shows that a rather small increase in storm duration and intensity can have a major effect on the simulated increase in high water levels. The effects are small in the eastern parts of the study area, but large in the western regions. The effects of an increase in storm intensity and duration are related to an increase in the frequency of situations in which discharge to the sea is limited by high seawater levels.

Discussion

The simulation results suggest that climate change could have a large effect on high water levels in the Rhine-Meuse delta. However, the high water level increase projected for the coming decades is rather uncertain. This is partly due to uncertainties in the projected temperature rise and resulting sea-level rise, as well as to uncertainties in the expected peak river discharge. Simulations of a hypothetical increase in storm intensity and duration show that relatively small changes in these variables have large effects on the simulated high water level increase, especially in the western part of the delta. These simulations illustrate the necessity of reliable estimates of the effects of climate change on wind speeds and storm length.

Previously, it was mentioned that high water level calculations are based on the assumption that river discharge and storm surges at sea are independent. The method only distinguishes between winter and summer seasons with two different sets of frequencies for specific discharge and storm surge values.

Climate change may result in a stronger correlation between river discharge and wind speed. Therefore, more information is required on probable changes in the relationship between wind and river discharge.

LOW RIVER DISCHARGE REGIME: CONSEQUENCES FOR SALT INTRUSION

Introduction

Under current climatic conditions, it is rare for salt intrusion, resulting from a combination of low river discharge and high seawater levels (due to a storm surge), to reach the drinking water abstraction points. Furthermore, the duration of the excess of salt concentration is never long enough to create serious problems for the water companies, since they have ample storage capacity to endure the period of saline excess. However, climate models project that, not only will an increase in low river discharge periods occur more often in the summer, they will also last longer each time. It is clear that this will threaten fresh water resource provision in some parts of the Rhine-Meuse delta.

The effects of these changes on salt intrusion are assessed using a probabilistic method, similar to the one used to determine the design water level on which the actual height of river dikes and dams is based (see also the previous section).

The two most important external factors that determine the extent of salt intrusion in the Rhine-Meuse delta are the upstream river discharge of the Rhine (measured at Lobith station) and the wind speed (including direction). Discharge is usually high in late winter and spring, and low in summer and autumn. To define the reference situation, we have used the discharge of the Rhine for the months May - October (inclusive). For wind speed, we used three years of daily averaged data measured at Hoek van Holland. These parameters have been divided into a number of classes (see Table 4). For each variable and class, the probability of occurrence has been determined. Note that the parameters wind speed and direction have been converted into the wind set-up.

Class of Rhine discharge (m^3s^{-1})	Probability of occurrence (%)
800-1000	4.8
1000-2000	52.1
2000-3000	33.0
3000-5000	9.4
5000-7000	0.8

Class of wind speed (ms^{-1})	Wind set-up (m)	Probability of occurrence (%)
0 - 2.5	0.02	1.8
2.5 - 5.0	0.09	33.0
5.0 - 7.5	0.21	34.9
7.5 - 10.0	0.37	19.4
10.0 - 12.5	0.58	8.1
12.5 - 15.0	0.83	2.5
15.0 - 17.5	1.13	0.3

Table 4. Probability of occurrence of river discharge and wind speed (wind set-up) for the months May-October.

The same one-dimensional model that was used for the high river discharge regime has been run for each of the possible 5*7=35 combinations (based on the advection-diffusion equation). Since the probability of occurrence of each parameter is known, the probability of occurrence of each of these combinations can be calculated, providing that the parameters are independent.

The reference situation: salt intrusion under average conditions

Salt intrusion in the Rhine-Meuse estuary can only occur via the Rotterdam Waterway, since, with the Haringvliet sluices closed at high tides, it is the only direct connection between the upstream rivers and the North Sea. Salt intrusion in this relatively narrow and deep channel manifests itself in the shape of a salt tongue that flows in an easterly direction underneath the (more or less continuous) fresh water outflow in the upper layer. In the one-dimensional representation used here, it is impossible to distinguish between the concentrations of the two layers. Instead, the model calculates an average concentration across the channel cross-section. Due to industrial activities, the background Cl- concentration of the river Rhine is of the order of 200 mgl^{-1} (the Cl- concentration of the North Sea is about 17,000 mgl^{-1}). Any increase in the concentration above the background level indicates the presence of a salt tongue, although it is impossible to say anything about the relative thickness of the underflow and of the concentration thereof.

Figure 5 shows the salt concentrations (Cl- in mgl^{-1}) under average conditions (an excess frequency of 50 times per year) for the reference situation. In the northern branch, the effects of the saline underflow reach Rotterdam (approximately 36 km from the sea boundary via the route: Rotterdam Waterway - Nieuwe Maas) while the salt intrusion via the Oude Maas extends somewhat further (beyond the junction of Oude Maas and Spui).

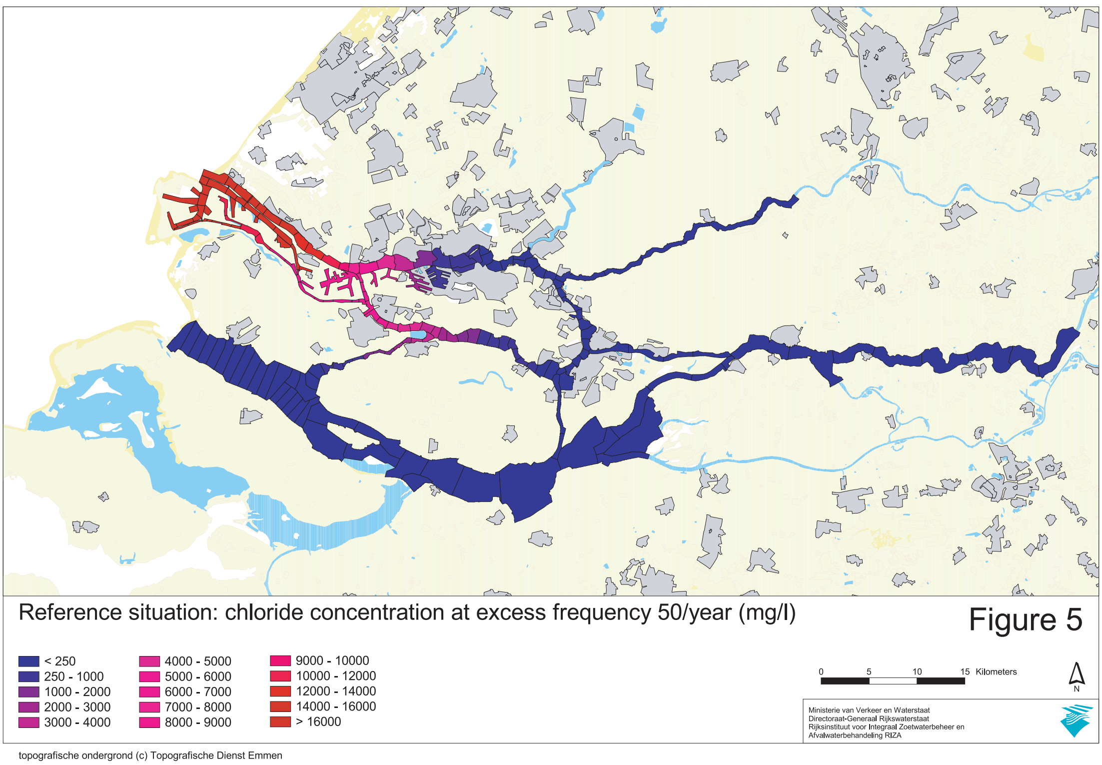

Figure 5. Reference situation: chloride concentration for the excess frequency of 50/year.

In more extreme cases (an excess frequency of once per year, see Figure 6), the salt tongue along the Nieuwe Maas does not reach much further than the reference situation, while intrusion along the Oude Maas extends beyond the southern mouths of the Spui and Dordtsche Kil rivers. Although the Haringvliet sluice gates are closed during high tides, and therefore no direct salt intrusion can occur via this connection to the sea, saline intrusion of the southern branch of the Rhine-Meuse estuary can still take place via the two north-south branches. The main reason for the observed differences between Nieuwe and Oude Maas is the tidal forcing of the salt tongue along the Oude Maas - Dordtsche Kil trajectory (in fact, the salt intrusion in this part of the estuary is strongly related to the difference in water levels between Hoek van Holland and Moerdijk). The salt intrusion in the Nieuwe Maas is associated more strongly with the upstream river discharge. This is partly due to the differences in bathymetry – while the Nieuwe Maas becomes increasingly shallow further east (a depth of less than 9 m east of Rotterdam), the Oude Maas remains deep (approximately 14-18 m) until the junction with the Dordtsche Kil river.

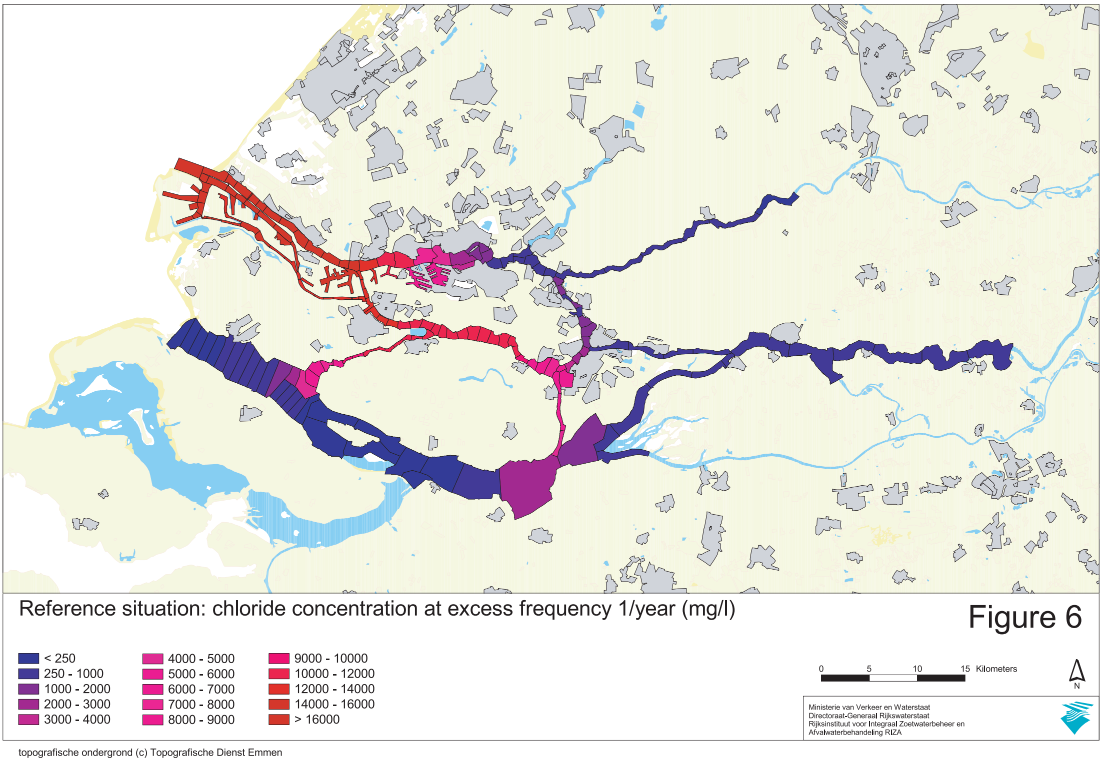

Figure 6. Reference situation: chloride concentration for the excess frequency of 1/year.

Future scenarios: impacts of decreased summer discharge and sea-level rise

The first future scenario considered involves the impacts of a global temperature increase of 2°C (corresponding to the extreme scenario C for the year 2050 - see Table 3) on summer discharge in the Rhine. In Table 5, the effects of this warming scenario on the hydrological regime of the Rhine basin are shown, together with the change from the reference situation. These results have been obtained from the RHINEFLOW model (Grabs *et al.*, 1997).

Class of Rhine discharge (m3s^{-1})	Probability of occurrence (%)	Change from reference (%)
800-1000	5.6	+0.8
1000-2000	57.6	+5.5
2000-3000	29.2	-3.8
3000-5000	7.3	-2.1
5000-7000	0.3	-0.5

Table 5. Frequency of occurrence of summer river discharge resulting from a 2°C increase in global temperature.

A second future scenario has been defined as the situation in which the mean sea level has risen 45 cm with respect to the reference situation (corresponding to the extreme climate scenario for 2050, IPCC, 1995). In the third scenario, the two effects (decreased river discharge and sea-level rise) have been combined. The results of these three different scenarios are shown in Table 6. First, the chloride concentrations corresponding to an excess frequency of once per year (extreme salt intrusion) are given. Second, the number of tides (per year) during which the maximum chloride concentration at a given station was higher than 250 mgl^{-1} (with an average duration of 12 hours and 25 minutes, there are 704 tidal periods in one year) are presented. This concentration has been chosen because it is the upper limit that a number of water companies use for abstracting fresh water.

Cl- concentration (mgl^{-1}) 1/year		Reference scenario ($00q_1$)	Decreased discharge scenario ($00q_2$)		Sea-level rise scenario ($45q_1$)		Combination scenario ($45q_2$)	
Station	Label (Figure 1)		Abs.	Diff.	Abs.	Diff.	Abs.	Diff.
Lekhaven	1	4,803	5,032	229	6,639	1,836	6,792	1,989
Beerenplaat	2	11,813	11,852	39	12,053	240	12,083	270
Brienenoord	3	895	941	46	1,304	409	1,400	505
Bernisse	4	8,061	8.092	31	8,033	-28	8,070	9
Alblasserdam	5	963	1,013	50	1,142	179	1,191	228
Wieldrecht	6	5,653	5,910	257	6,011	358	6,300	647

Excess frequency of 250 mgl^{-1}								
Station	Label (Figure 1)		Abs.	Diff.	Abs.	Diff.	Abs.	Diff.
Lekhaven	1	291	314	23	355	64	378	87
Beerenplaat	2	447	448	1	471	24	473	26
Brienenoord	3	27	29	2	39	12	44	17
Bernisse	4	70	71	1	89	19	89	19
Alblasserdam	5	8	8	0	8	0	9	1
Wieldrecht	6	19	20	1	30	11	33	14

Table 6. Results of scenario calculations for six stations (see Figure 1 for locations).

In general, the chloride concentrations increase at all stations due to decreased river discharge and even more so for sea-level rise. The 'combination' scenario results in the largest impacts of the scenarios considered. Note that the effects of the 'combination' scenario are not simply the sum of the effects of the separate scenarios for decreased summer discharge and sea-level rise (i.e., the effects are not linear).

For each scenario, the effects of climate change are largest for the stations located along the northern branch of the delta (stations 1,3 and 5 along the Nieuwe Maas). Stations 1 and 2, 3 and 4 and 5 and 6 are located pair-wise at roughly the same distance from the junction of Oude and Nieuwe Maas. As indicated above, salt intrusion in the reference situation reaches further along the Oude Maas than along the Nieuwe Maas (see also Table 6 by comparing stations 1-2, 3-4 and 5-6). Not only is there a higher frequency of salt intrusion, concentrations are also higher. Additional field measurements (Rijkswaterstaat, 1998) have shown that this situation is true when chloride concentrations at stations 1 and 2 are above approximately 2000 mgl^{-1}. Changes in boundary conditions (sea level or river discharge) make the incidences of extreme salt intrusion stronger (and make them occur more often – see the second part of Table 6), but the relative effects are small in the Oude Maas, since the concentrations (at an excess frequency of 1/year) are already high.

Figure 7 shows the difference in the once per year concentrations between the 'combination' scenario with decreased summer discharge and sea-level rise, and the reference situation. The figure clearly shows large effects along the Oude and Nieuwe Maas. Furthermore, it demonstrates that an increase in salt intrusion is expected in almost all river branches of the Rhine-Meuse delta.

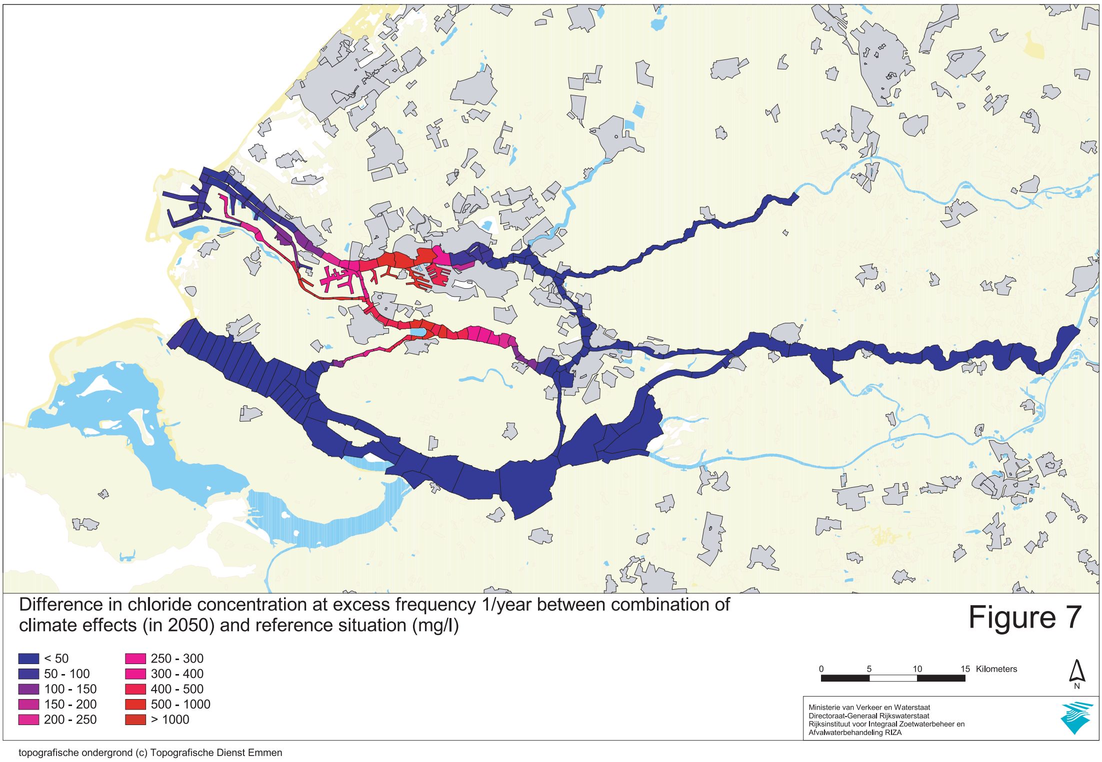

Figure 7. Difference in chloride concentration at an excess frequency of 1/year between the combination scenario (2050) and the reference situation.

Sensitivity to estimates of sea-level rise

Since the effects of sea-level rise were generally almost one order of magnitude greater than those of the decreased river discharge, we have tested the sensitivity of the results to the rise in sea level expected for the year 2050 in the extreme scenario. Calculations for the combined climatological effects were repeated for an increase in average sea level of 50 cm rather than 45 cm (extreme scenario + 10%). Table 7 shows the results for the same stations as before. The differences between the 50 cm sea-level rise and the 45 cm sea-level rise are generally smaller than the extra 10% increase at the sea boundary.

Cl- concentration (mgl^{-1}) 1/year		Combination with a 45 cm sea-level rise ($45q_2$)	Combination with a 50 cm sea-level ($50q_2$)	
Station	Label (Figure 1)	Abs.	Abs.	Diff.
Lekhaven	1	6,792	6,897	105
Beerenplaat	2	12,083	12,153	70
Brienenoord	3	1,400	1,498	98
Bernisse	4	8,070	8,070	0
Alblasserdam	5	1,191	1,242	51
Wieldrecht	6	6,300	6,499	199

Excess frequency of 250 mgl^{-1}				
Station	Label (Figure 1)	Abs.	Abs.	Diff.
Lekhaven	1	378	383	5
Beerenplaat	2	473	475	2
Brienenoord	3	44	47	3
Bernisse	4	89	91	2
Alblasserdam	5	9	9	0
Wieldrecht	6	33	34	1

Table 7. Results of calculations to determine the sensitivity of sea-level rise estimates.

Discussion

Calculations have shown that changes in boundary conditions due to projected climatic changes by the year 2050 will result in a large increase in salt intrusion in the Rhine-Meuse delta area. As a result, a larger area will be affected by salt intrusion, and average chloride concentrations will increase in those areas currently affected by salt intrusion. There are important consequences for water management in this area, particularly for the abstraction points which supply drinking and agricultural water (compare the locations of the six salt reference stations in Figure 1 with those of the abstraction points). For a number of the chosen salt reference stations, the excess frequency of the 250 mgl^{-1} concentration increases by more than 50%.

Although the results do not seem to be very sensitive to estimates of sea-level rise, the applied increase of 5 cm for climate scenario C (+45 cm) should be viewed in the light of the uncertainties present in climate change scenarios. It is clear that estimates ranging from 10 to 45 cm will have a large impact on the expected salt intrusion.

CONCLUSIONS AND RECOMMENDATIONS

Climate has a large influence on water systems in deltaic areas such as the Rhine-Meuse estuary in the Netherlands. We have shown the extent of the effects of three future climate change scenarios. Two major features of the estuarine water system are highlighted: flood protection and the supply of fresh water. The projected changes in mean sea level, storm duration, storm intensity and river discharge (a winter increase and a summer decrease) represent a serious threat to the ways in which the water system is currently used for the activities mentioned above.

The simulations described highlight the need for reliable estimates of the effects of climate change on sea level, peak river discharge, wind speed and storm duration. Furthermore, the dependency of some of these parameters on one and another is, in the present situation, assumed to be rather weak but may increase in the future. It is clear that future calculations of design levels for dams and dikes require further information on likely changes in these dependencies.

Simulations of future salt intrusion indicate that for the highlighted water system operations, reliable estimates of sea-level rise and changes in (summer) river discharge are also required. In this paper, we have only considered the combined effects of these two controlling factors. If climate has a discernible effect on the distribution of storms throughout the year (and on their duration and intensity), then these aspects will also have to be taken into account. At present, no information is available on possible changes in the concurrent periods of low river discharge and storms, which would result in maximum salt intrusion. If climatologists are able to shed some light on these changes, anticipatory actions for maintaining a well-managed delta will be more easily implemented.

Acknowledgements

We thank Sacha de Goederen for taking care of the calculations, Aad Fioole for producing some of the graphs and Dik Ludikhuize for stimulating discussions and for carefully reading the manuscript.

References

DBW/RIZA (1987a) **Het optreden van hoogwaterstanden in het noordelijk deltagebied**, DBW/RIZA document no. 87.018, Lelystad, the Netherlands.

DBW/RIZA (1987b) **Effect variatie opzetduren op de hoogwaterstanden in het noordelijk deltabekken**, DBW/RIZA document no. 87.054, Lelystad, the Netherlands.

Dienst Weg- en Waterbouwkunde (1996) **Hydraulische randvoorwaarden voor primaire waterkeringen**, ISBN-90-3693-718-3, Delft, the Netherlands.

Grabs, W., Daamen, K., Gellens, D., et al. (1997) **Impact of climate change on hydrological regimes and water resources management in the Rhine basin**. CHR report no. I-16, CHR, Lelystad, the Netherlands.

IPCC (Intergovernmental Panel on Climate Change) (1995) Second Assessment Report of Working Group 1. Cambridge University Press, Cambridge, U.K.

Projectteam NW4 (1997) **Klimaatverandering en bodemdaling: gevolgen voor de waterhuishouding van Nederland.**

Rijkswaterstaat (1998) **Zout in het Noordelijk Deltabekken in 1997**, Directorate Zuid-Holland, document no. APS/98-211, Rotterdam, the Netherlands.

RIZA (1991) **Gebruikershandleiding ZWENDL**.

RIZA (1995) **Het optreden van hoogwaterstanden in het noordelijk deltagebied in de situatie met toekomstige infrastructurele aanpassingen**. RIZA document No. 94.014X, Lelystad, the Netherlands.

RIZA (1999) **Hydraulische verkenning IVB, Resultaten 2000-2050, Autonome variant**. RIZA document No. 98.130X, Lelystad, the Netherlands.

WL|Delft Hydraulics (1990) **Synthese waterloopkundig systeem-onderzoek Noordelijk Deltabekken**, Report No. Z244, Delft, the Netherlands.

Keynote Paper 3

Scenarios for Extra-Tropical Storm and Wave Activity: Methodologies and Results

Eigil Kaas and Uffe Andersen

Danish Climate Centre, Danish Meteorological Institute (DMI), Lyngbyvej 100, DK-2100 Copenhagen Ø, Denmark (ek@dmi.dk)

INTRODUCTION

Coastal impacts in Europe are closely linked to severe extra-tropical storms, which constitute the basic physical process producing high waves and surges. Over the past 10-20 years or so there has been increasing public as well as scientific concern, that storm activity is increasing in Northwest Europe and that this change is related to global warming. Due to its large influence, any change in storm activity in the Northeast Atlantic (NEA) region could be the most important manifestation of climate change and variation in the European region. This realisation has motivated a number of European projects dealing with observed trends/variations and future scenarios of extra-tropical storms and their impacts. Relevant web-links to these projects can be found in Appendix 3.

This paper begins by providing a brief overview of the observational evidence for changing storm and wave activity in the NEA region. This is followed by a discussion of the physical mechanisms related to possible changing storm statistics in a warmer climate. A few of the most recent climate model estimates of future changes in severe extra-tropical storms are then presented and interpreted in terms of changing wave statistics. The paper concludes with a discussion of the findings.

OBSERVATIONAL EVIDENCE

The question of trends in storminess in the NEA region may seem trivial as wind and pressure observations have been made on a routine basis for more than 100 years. This means that one could in principle, calculate trends from individual station data of wind or pressure, or from weather maps (analyses) of for example, pressure. However, the challenge with analysing such historical data is to discriminate between signals reflecting real trends in the climate system as opposed to artificial trends related to inhomogeneities (i.e., changing instrumental accuracies, local environmental conditions, spatial and temporal data density, observational practices, and analysis routines). Several papers (e.g., Schinke, 1993; Lambert, 1996) have reported a strong upward trend in storm activity in the North Atlantic from around 1970. These statements were investigated in the WASA (1998) project and it was concluded that the reported extreme trends mainly represented the use of inhomogenous data.

From its inception, the WASA project (see Appendix 3) realised that inhomogeneities make the observed wind data generally useless for determining trends in storminess. The most severe inhomogeneity arises from the fact that the observations were not real measurements prior to 1950-60, but subjective, visual judgements of wind speed made by the observer. Mean sea level pressure (Pmsl) is related to wind via the geostrophic balance and therefore one may be tempted to use analysed weather maps, but these are also highly inhomogenous due to changes in the number of stations used to produce the maps and changes in the analysis routine. For reanalysis data, the objective analysis routine is fixed but these data sets generally cover less than 50 years and suffer from the problem of varying numbers and types of basic observations. WASA, therefore decided to use quality controlled Pmsl data for a fixed set of individual stations. These data were used in two different ways: (i) to calculate percentiles of geostrophic winds from the geostrophic triangle method (Alexanderson *et al.*, 1998), and (ii) to calculate percentiles of the 24 hour absolute tendency (Schmith *et al.*, 1998). While the triangle method could potentially be weakly inhomogenous (as discussed in WASA 1998), this is very unlikely for the 24 hour absolute tendency. Both methods indicate a modest rise in extreme storm activity during the last 20-30 years mainly at locations from the North Sea to the Faroe Islands. The recent increase in storm activity is comparable to that experienced towards the end of the 19th century. Hence, one cannot state that the trend after 1970 is extraordinary. Figure 1 shows variations in the standardised annual quantile time series based on the triangle method for Fenno-Scandinavia and the NEA region.

Figure 1. Standardised (to 0 mean and standard deviation 1) annual 95% (circles and full line) and 99% (crosses and dotted line) quantile time series (1880-1995) of geostrophic wind estimated from pressure triangles in the Scandinavian, Finish and Baltic Sea region (left) and in the British-Isles, North Sea and Norwegian Sea region (right). Lines are obtained from yearly data by applying a Gaussian filter with a standard deviation of 3 years. From Alexandersson et al. (1998; 2000).

WASA also investigated trends in ocean wave activity. Since only a few in situ measurements are available, a special reconstruction of the wave climate in the 40-year period 1955-1994 (Günther *et al.*, 1998) was undertaken. This was based on a full 40-year simulation from the WAM wave model with atmospheric wind forcing estimated from a high-resolution set of Pmsl analyses. Contamination of this driving data set by inhomogeneities was examined. It was concluded that the series was only weakly inhomogenous over data dense regions but suffered from an artificial deterioration of the storm climate in data-sparse areas. The hindcast wave climate - given the inhomogeneities in the driving wind - generally shows negative 40-year trends in the intra-annual 90% quantiles over the region southwest of the British Isles and positive trends further northeast (see Figure 2).

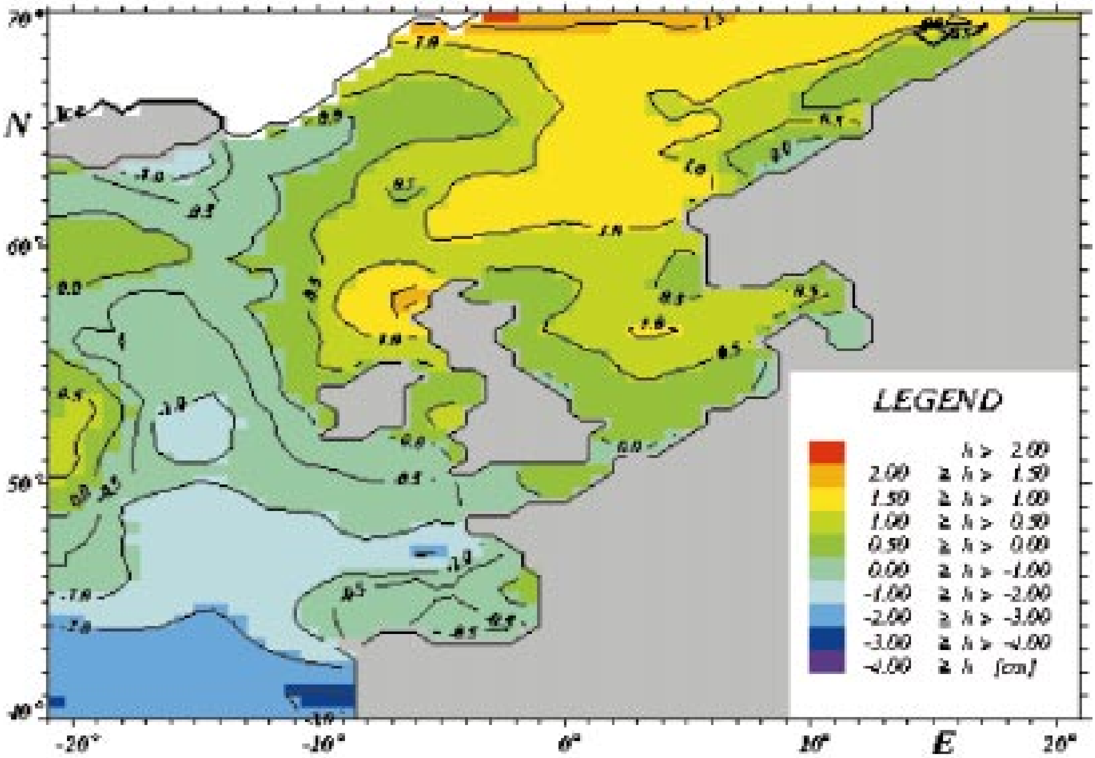

Figure 2. Map of the 1955–94 trends in the intraannual 90% quantiles of significant wave height, as derived from the 40-yr hindcast executed with the WAM wave model within the WASA project. Units: cm yr^{-1} (From Günther et al., 1998).

MECHANISMS

Changes in extra-tropical storm activity due to enhanced greenhouse effects are related to changes in the long-term mean atmospheric flow. The development of a given extra-tropical depression is influenced by changes in the background atmospheric flow characteristics:

- Decreased horizontal temperature gradients in the lower troposphere. Most global coupled ocean-atmosphere climate models (O-A-GCMs) simulate the largest warming over the extreme northern regions in winter (DJF), although this excessive warming may be reduced by the direct and indirect effects of increasing sulphate aerosol concentrations (Mitchell and Johns, 1997; Roeckner *et al*., 1998). This is illustrated in Figure 3, which shows the typical warming pattern in simulations forced by increased concentrations of greenhouse gases. The polar warming is associated with a reduction in the north-south temperature gradient, i.e., the baroclinicity in the lower troposphere. From an isolated point of view, this change should lead to a reduced intensity of extra-tropical storm activity, according to the theory of baroclinic instability (Holton, 1992).

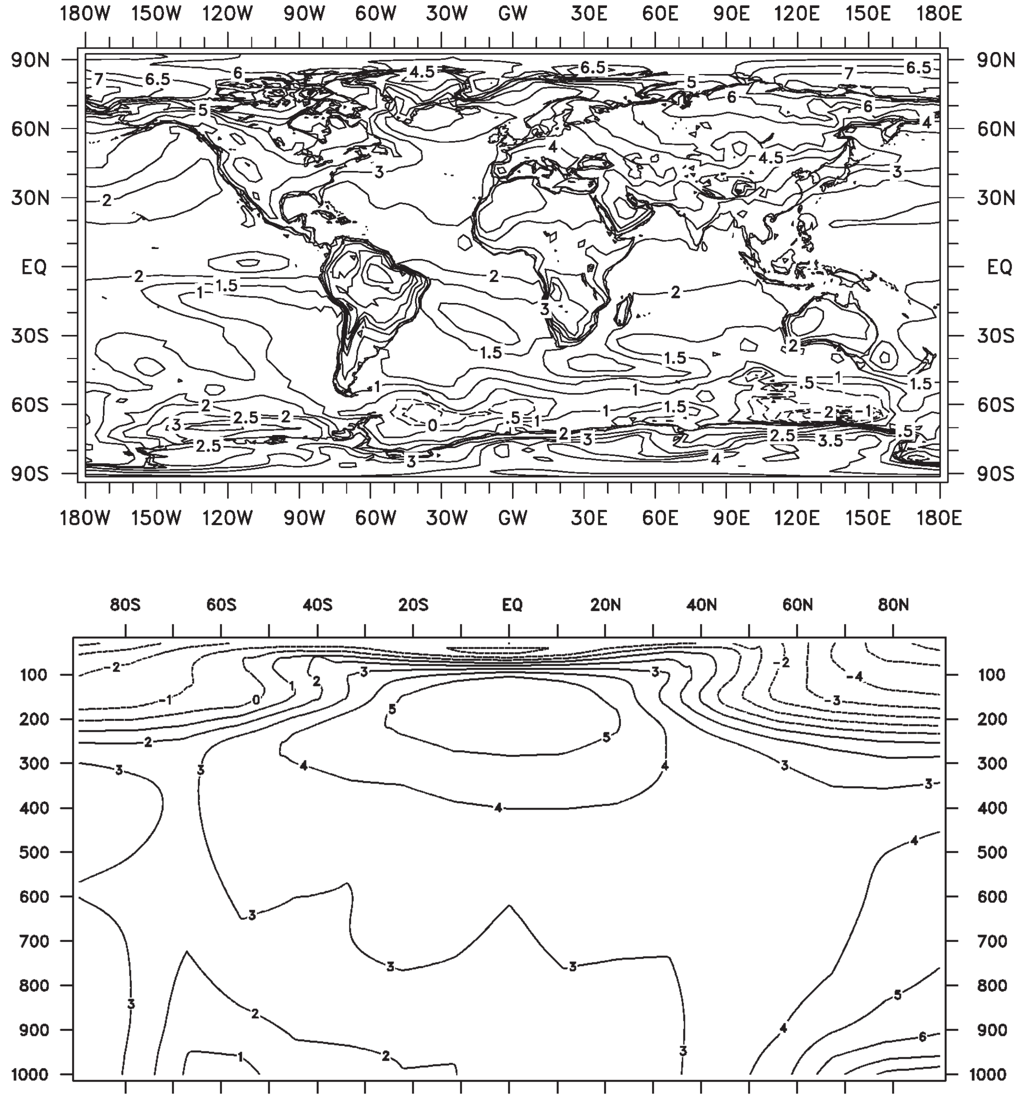

Figure 3. Simulated change due to increased greenhouse gas forcing in annual mean temperature (C) at 2m level (top) and the corresponding zonal mean temperature change in DJF (bottom) as function of pressure (hPa) and latitude. Adopted from May (1999).

- Increased baroclinicity in the upper troposphere. While the baroclinicity in the lower troposphere decreases, an increase is simulated aloft. This is because temperatures in the tropical regions increase more than the polar regions where they actually decrease at high altitudes, as can be seen from Figure 3. This change in background flow is - from an isolated point of view - associated with an increase in extra-tropical storm activity.

- Increased amounts of moisture available for condensation. The water vapour content of the lower part of the atmosphere generally increases as temperature increase; this is also the case in GCM scenarios. The latent heat released with condensation in extra-tropical low pressure systems, will lead to increased conversion rates of potential to kinetic energy and thereby to faster development rates relative to what would occurs in a dry atmosphere (e.g., Gutowski *et al.*, 1992; Kuo and Low-Nam, 1990; Langland *et al.* 1996). Therefore, one would expect increased amounts of water vapour available for condensation to produce more intensive extra-tropical storms. Moreover, this effect may tend to influence small-scale phenomena rather than large-scale phenomena, Sardia and Warner (1983).

- Decreasing static stability. Figure 3 shows another feature that appears in many climate models: an increasing lapse rate north of approximately 50°N. This suggests that static stability decreases at high northern latitudes when concentrations of greenhouse gases are increased. An increased lapse rate affects the process of baroclinic instability, since the horizontal scale of those atmospheric waves that are most unstable (i.e., growing most rapidly) is decreased and at the same time, these smaller scale weather systems grow faster (see e.g., Holton, 1992). Thus, the isolated effect of the simulated decrease in static stability is a shift towards smaller scale and more intensive low-pressure systems at high latitudes.

One may be tempted to consider changes in atmospheric long-term background conditions as the main cause of changes in extra-tropical storm activity. This point of view would be erroneous since it can be argued that the background flow (and its change) is a consequence just as much as a cause of the actual extra-tropical storm activity and the associated eddy heat and momentum transport. A complete description of the problem must therefore consider the mutual balance between the equator-to-pole heating gradient, the convergence of poleward eddy heat flux, and the eddy momentum flux convergence (and associated indirect circulations - see e.g., Holton, 1992) which determine the meridional temperature gradient and thus the strength of the eddies. In connection with this, it is important to note (e.g., Zhang and Wang, 1997) that water vapour - in addition to an enhancing effect - also plays a very important indirect role that tends to weaken extra-tropical storm activity. This is because the increase in moisture content is more abundant at low latitudes than at high latitudes. Associated with the increased meridional moisture gradient, there is a tendency for enhanced poleward transport of moisture, i.e., latent heat. The release of latent heat leads to a decreased meridional temperature gradient and thus, from an isolated point of view, to reduced baroclinicity.

In the above list of background flow changes, the first item is associated with decreased extra tropical storm activity while the last three are associated with increased activity. Theoretical considerations, diagnostic budget calculations and idealised model experiments can help in assessing their relative importance. With regard to the different changes in meridional temperature gradient at low and high altitudes (items 1 and 2) it has been suggested by Held and O'Brien (1992), using an idealised quasi-geostrophic model, that eddy heat flux is more sensitive to the lower level than to the upper level mean temperature gradient. The implication could be a net decrease in storm activity that is also indicated in results by, for example, Branscome and Gutowski (1992).

The relative role of local moisture processes (item 3) has been investigated by various diagnostic approaches (e.g., Manobianco, 1989), and by dry and moist sensitivity experiments using atmospheric models (e.g., Kuo and Low-Nam, 1990), while Langland *et al.* (1996) used an adjoint technique to identify locations of particular sensitivity to the release of latent heat. These studies have revealed that the effect of condensation amounts to 25-50% or more of the total deepening rate of explosive extra-tropical storms. As the specific humidity in the extra tropics is increased by approximately 7% per degree of warming (assuming unchanged relative humidity - which is reasonable in the extra-tropics, DelGenio *et al.*, 1991; Frei *et al.* 1998), a simple linear estimate gives increased deepening rates of up to 10% assuming a 3°C warming and no other changes in the background flow. Note, however, that non-linear feedback mechanisms, like enhanced surface evaporation may enhance the developments further. Note also, that since the horizontal scale of the additional development due to latent heat release is small, one may expect the effect to be rather large in terms of surface wind speeds. Figure 4 shows a 48-hour 'forecast' of a storm simulated with the HIRHAM regional climate model (Christensen et al., 1998). The initial atmospheric conditions were taken from a global high-resolution time slice simulation (see below) using the ECHAM4 model. The left panel shows the mean sea level pressure in the standard simulation, while the middle panel is the result of a 'forecast' with a modified version of HIRHAM, where the impact of latent heat release on the model dynamics is switched off. This is achieved by simply setting the latent heat released in the first equation of thermodynamics to zero; otherwise there are no differences between the simulations. For this particular storm, the latent heat effect is dramatic with almost no development in the middle panel. For other cases, however, the effect is more modest, although always positive.

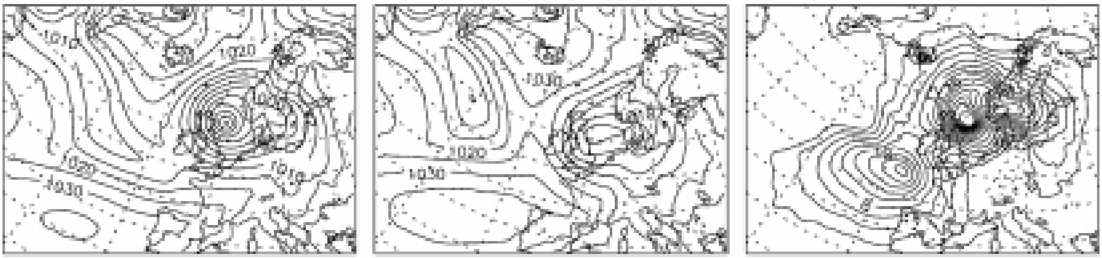

Figure 4. Mean sea level pressure of a storm simulated with the HIRHAM regional climate model at a 30 km horizontal resolution. Left panel: standard 48 hour 'forecast'. Middle panel: 'forecast' without latent heat release. Right: difference between the middle and left panel. The contour interval is 5 hPa in the two left panels and 2 hPa in the right panel with negative contours dashed.

Although the scaling effect of an increased lapse rate (item 4) may be of importance, it has not yet been investigated in detail for small-scale intensive cyclones in connection with climate change.

The above considerations have all been quite general and relevant to the broader view of extra tropical storm activity. However, from a regional impact perspective, climatic changes in the position and strength of the quasi-stationary planetary waves are likely to be more relevant, although causality is complicated since these large-scale waves interact with the smaller scale transient eddies (i.e., the storms). It is thus well known that the large-scale flow anomalies – such as the so called North Atlantic Oscillation (NAO) – interact and are mutually dependent on organised variations in the small-scale high frequency eddies, i.e., storm tracks (e.g., Nakamura *et al.*, 1997 and references therein).

There have been a number of empirical studies (e.g., Rogers, 1997; Kaas *et al.*, 1996; Schmith *et al.*, 1998) identifying these physical relationships. These findings indicate that climatic changes in storm activity closely correspond to changes in, for example, the NAO and in its more low-frequent hemispheric counterpart, the Arctic Oscillation (AO). It is difficult to judge which basic mechanisms may lead to greenhouse gas forced changes in the AO. It has been suggested by Shindell *et al.* (1999), that radiatively forced changes in the stratosphere may change the characteristics of the dynamic wave interactions between the stratosphere and troposphere in such a way as to strengthen the AO, i.e., decrease/increase the surface pressure in the arctic/subtropical areas. Another possible mechanism leading to increased AO is a thinning/melting of the arctic sea ice. From the atmospheric point of view, this will act as a large lower boundary-heating anomaly that tends to decrease the surface pressure via mechanisms equivalent to those in monsoon circulations. As mentioned in the previous section there has been a moderate upward trend in the storm activity in the northeast Atlantic during the last 30 years or so. It is unclear whether this change and the associated increase in the NAO and AO indices is caused by increasing greenhouse gas concentrations, but it is at least consistent with many (but not all) of the climate model scenario simulations described in the following section.

SCENARIOS OF STORMS AND WAVES

Simulations with O-A-GCMs are widely accepted as the best tool available to estimate climatic changes in the large- and medium-scale flow of the atmosphere that are due to anthropogenic emissions (Houghton *et al.*, 1995). There have been several investigations based on such simulations (some of them only with mixed layer oceans) or on corresponding time-slice simulations (see below) to assess changes in extra-tropical storm activity. Most of these report an increase in storm activity (storm track) in the eastern North Atlantic and in western Europe, for example: Hall *et al.* (1994), Carnell *et al.* (1996), Lunkeit *et al.* (1996), Cubasch *et al.* (1997), Schubert *et al.* (1998), and Ulbrich and Christoph (1999). However, there are also reports of an overall reduction in synoptic activity in this region (e.g., Stephenson and Held, 1993; Lambert, 1995; Zhang and Wang, 1997; Carnell and Senior, 1998). The measure of storm activity used in these studies has generally been (2.5-6 day) band-passed filtered standard deviations of the 500 hPa height (Blackmon, 1976) or equivalent measures. These measures provide good descriptors of general storm activity, but not necessarily of the most intensive and therefore most interesting developments from an impact point of view. Thus, while Lambert (1995) found a decreasing total number of Northern Hemisphere winter cyclones he also found an increase in the frequency of intense cyclones in an enhanced greenhouse gas experiment with the CCC Canadian GCM. Carnell and Senior (1998) analysed the number of storms in the HadCM2 model for both greenhouse gas experiments and for simulations that include the combined effects of increased greenhouse gases and a simple parameterisation of the direct radiative forcing due to anthropogenic sulphate aerosols. Their results are qualitatively similar to Lambert (1995), since they found a general decrease in the number of storms but an increase in the number of deep cyclones.

In conclusion, simulations with global coarse mesh models give somewhat varying answers to the question of whether storm conditions near Europe will worsen as global warming takes place. There seems to be some indication that intense storms could become more severe. The discussion in the previous section concluded that the increased release of latent heat in a warmer climate could be a key mechanism for the development of more intense cyclones, while the decreasing equator-to-pole gradient could work in the opposite direction. Some of the regional differences between the O-A-GCM simulations are undoubtedly related to the different simulated changes in the AO at the time of CO2 doubling. While most coupled models, such as the first Hadley Centre coupled model (Carnell *et al.*, 1996), HadCM3 (Nathan P. Gillett and Ruth Mc Donald, personal communication) and the ECHAM4/OPYC3 model (Roeckner *et al.*, 1998), simulate a considerable decrease in the arctic surface pressure (increased AO), others such as the HadCM2 model, show no clear change in the AO as shown by Figure 3b of Carnell and Senior (1998). Figure 5 shows an example of a typical change in the mean sea level pressure pattern relative to the corresponding control simulation.

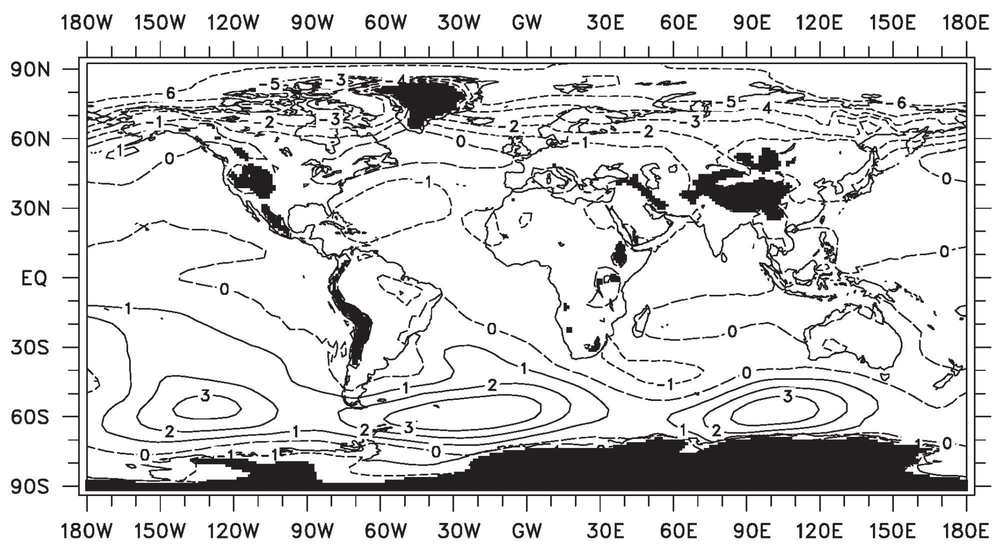

Figure 5. Simulated change in mean sea level pressure in DJF. The contour interval is 1 hPa, negative contours are dashed. Adopted from May (1999).

Intense depression systems and downscaling

From an impact point of view, there is no doubt that any change in the strength and frequency of extreme storm events is much more important than a change in, for example, the total number of storms or the overall level of 500 hPa high frequency variability. This is because it is the extreme storms that, in addition to their devastating effects on land, result in large ocean surges, wave events and consequently coastal erosion. In addition, the wind effect itself is sometimes of importance to coastal morphology (see reference to the STORMINESS project in Appendix 3). As argued above, the spatial resolution of state of the art O-A-GCMs is not sufficient to simulate small scale and very intense storm events. Examples of such storms are those that battered Western Europe in December 1999. These storms were typical baroclinic waves at the large scale, but their inner cores were very intense and small scale. To produce reasonable forecasts of such storms operational weather prediction models, such as the HIRLAM model, need an order of magnitude finer spatial resolution than that used in state of the art O-A-GCMs (Jes U. Jørgensen, DMI, personal communication). The inability of the coarse mesh O-A-GCMs to simulate small-scale extra-tropical storms has been a main motivation for devising different methodologies to downscale global climate change scenarios. In this context downscaling is simply a smaller scale interpretation of flow on the larger scale. Three different methods have been used so far:

- Global Time SLice simulations (G-TSL's). These simulations (Bengtsson *et al.*, 1995, 1996) cover a number of years and are performed with a high-resolution atmospheric global climate model (A-GCM) that is forced, at its lower boundary, by the sea-surface temperature and sea-ice conditions simulated in O-A-CGM simulations. Furthermore, a given G-TSL is forced by the same anthropogenic forcing used in the underlying O-A-GCM. The timing of synoptic weather events is essentially decoupled from the O-A-GCM, since the atmospheric dynamics of the G-TSL are free. The resolution of G-TSLs have so far been 2 to 3 times finer than in O-A-GCMs. This resolution is sufficient to simulate rather intensive systems, but is still not fine enough to adequately simulate, for example, the December 1999 storms in Europe. However, certain G-TSLs (stretched spectral models, Déqué *et al.*, 1998) have been run at a variable horizontal resolution, with a resolution comparable to R-TSLs (see below) for a specified region and coarser resolution elsewhere. Note, that if the A-GCM used in a given G-TSL experiment has a different climate sensitivity (i.e., degree of response) than the atmospheric component of the underlying O-A-GCM, this will be difficult to detect in the G-TSL experiment because its large-scale climate change is more or less restricted to the change of oceanic conditions in the O-A-GCM. This means that if a simulated climatic change in meridional heat transport associated with transient eddies (the storms) is different in the two models, which is a rather reasonable assumption, this will not be fully reflected in the G-TSL. Therefore, the only way to estimate the full effect of the finer resolution is to run the O-A-GCM at a high resolution.

- Regional Time SLice simulations (R-TSL's). These simulations (see e.g., Christensen *et al.* 1997, 1998) are similar to G-TSL's but are performed at considerably higher resolution (presently approximately 20 km in the horizontal grid-point distance) and cover only limited geographical domains. The lateral (vertical) boundary conditions are typically provided every 6 hours by the underlying O-A-GCM. Regional climate models are able to simulate most of the intensive and small-scale extra-tropical storms but are not able to feed back into large-scale flow. For this reason they are well suited to perform process studies of extreme events, while any R-TSL simulated climate change on a larger scale should not be considered anything other than a deviation from the O-A-GCM. In other words, the R-TSL simulation cannot 'improve' the larger scales in a physically consistent way.

- Empirical downscaling. This method (see e.g., Zorita and Storch, 1999) utilises present day observed statistical relationships between large-scale atmospheric flow and small-scale or local features. For example, when the NAO for a given set of years is in its positive phase (lower than normal pressure near Iceland), it is well known that there are associated shifts in storm activity in the North Atlantic, with more storms observed in northern areas of the North Sea. The identified relationships are used to interpret the (large-scale) flow in the O-A-GCM. Therefore, if a long-term shift in NAO towards its positive phase is part of the O-A-GCM response to an increased greenhouse effect, then empirical downscaling of the O-A-GCM will give enhanced storm activity in northern regions of the North Sea. In general, Empirical downscaling must be used with care since it assumes that the physical mechanisms linking large- and small-scale flow remain the same in a changed climate.

The coastal effects of storms are largely related to surges and waves. The issue of changing surge statistics is dealt with in the accompanying article by Flather (2000). Wave statistics can be obtained by forcing a wave model with winds simulated in O-A-GCMs. However, since many coastal features are not resolved by O-A-GCMs, particularly near steep topography such as in the Mediterranean area, downscaling of the forcing wind field is generally required. This can be achieved via all three methods mentioned above. Another option is to perform an empirical downscaling of the O-A-GCM (or a corresponding set of G-TSL simulations) directly into local wave statistics.

Certain impact-oriented studies require very long time series of climate variables. In these cases, one may generate synthetic time series using weather or wave generators. Normally, these are first order auto-regressive models, built from observed data. When such generators are applied to climate change scenarios, the relevant regression parameters (mean value and autocorrelation) must be constrained by the large-scale flow simulated in the O-A-GCM or subsequent G-TSL or R-TSL simulations (see e.g., Pfizenmayer and von Storch, 2000).

Storm and wave scenarios in WASA and STOWASUS-2100

In addition to examining the observed trends in storms, waves, and surges, the WASA project also produced climate change scenario simulations of waves and surges for the North Atlantic region. These were based on wind and pressure forcings from a set of G-TSL simulations (Bengtsson *et al*., 1995, 1996) using the ECHAM3 model run at a spectral truncation of T106 corresponding to a grid distance of approximately 125 km. Some of the above considerations, concerning the importance of model resolution for correctly simulating extreme extra-tropical storm events, were the basic motivation for performing the wave and surge simulations in WASA. Beersma *et al.* (1997) investigated the extra-tropical storms in the G-TSL simulations used in WASA and they concluded that there were certain differences between the storm climate of the control (present day) and the $2xCO_2$ simulation. However, the simulations were too short (only 5 years) to dismiss the possibility that these differences merely reflect sample (year-to-year) variations unrelated to the deterministic signals caused by changes in atmospheric composition.

The main reason for the follow-up project to WASA, STOWASUS-2100 (see link in Appendix 3), was to re-estimate the scenario simulations produced in WASA for much longer time-slice periods, giving greater attention to extreme storm, wave and surge events along European coasts including the Mediterranean. The backbone of the project is two time-slice simulations using the ECHAM4 model at T106 truncation (May, 1999), covering a 30-year control period, corresponding to the present day climate, and a 30-year scenario with an approximately doubled greenhouse gas forcing. The SST and sea ice lower boundary conditions were taken from a transient O-A-GCM greenhouse gas sensitivity simulation using the ECHAM4/OPYC3 model (Roeckner *et al*., 1998). The O-A-GCM simulation was performed at a horizontal resolution (T42) about 2.5 times coarser than in the G-TSL. Figures 3 and 5 show the long-term mean differences between the two G-TSL simulations for temperature and mean sea level pressure, respectively. The temperature difference in the lower troposphere between the experiments is about 3°C near Europe and the difference in the vertically integrated specific humidity is 20-25%. The additional moisture is potentially available for condensation in extreme extra-tropical storms in the scenario period.

Figure 6 shows the simulated climate change in storm activity in both the G-TSL and the underlying O-A-GCM, estimated as the standard deviation of the 2.5-6 day band-pass filtered 500 hPa variability. The figure also includes the corresponding 'observed' values, calculated from the ECMWF 15-year reanalyses. It can be seen that the pattern of variability is reasonably well simulated in both models, but that the maximum values are underestimated by approximately 20% in the O-A-GCM and by 10% in the G-TSL control simulations. There are strong similarities between the G-TSL and the O-A-GCM simulated climate change patterns (the two right-hand panels), although the maximum increase in storm activity tends to be considerably stronger in the O-A-GCM simulations. The reason for this is not entirely clear, but may be related to different changes in the meridional transient eddy transport of latent heat. This transport is likely to be more efficient at the T106 resolution and therefore, as specific humidity increases, the meridional heat transport (which tends to break down meridional temperature gradients) could increase more rapidly at the T106 resolution. In fact, the temperature increase in the lower troposphere of the polar area is somewhat stronger in the G-TSL than in the O-A-GCM (May, 1999), which is consistent with this argument. Figure 7 shows the simulated change in extreme winds estimated as the average of all occurrences of winds exceeding the 99.9 percentile level (6-hourly data). The pattern is very noisy but seems to be reasonable consistent with the change in 500 hPa high frequency variability. The general signal can be characterised as a modest increase in wind speeds near the northwestern European coasts and a somewhat larger decrease in areas further to the west and south. In the Mediterranean, changes are either small, or there is a tendency for storm activity to decrease.

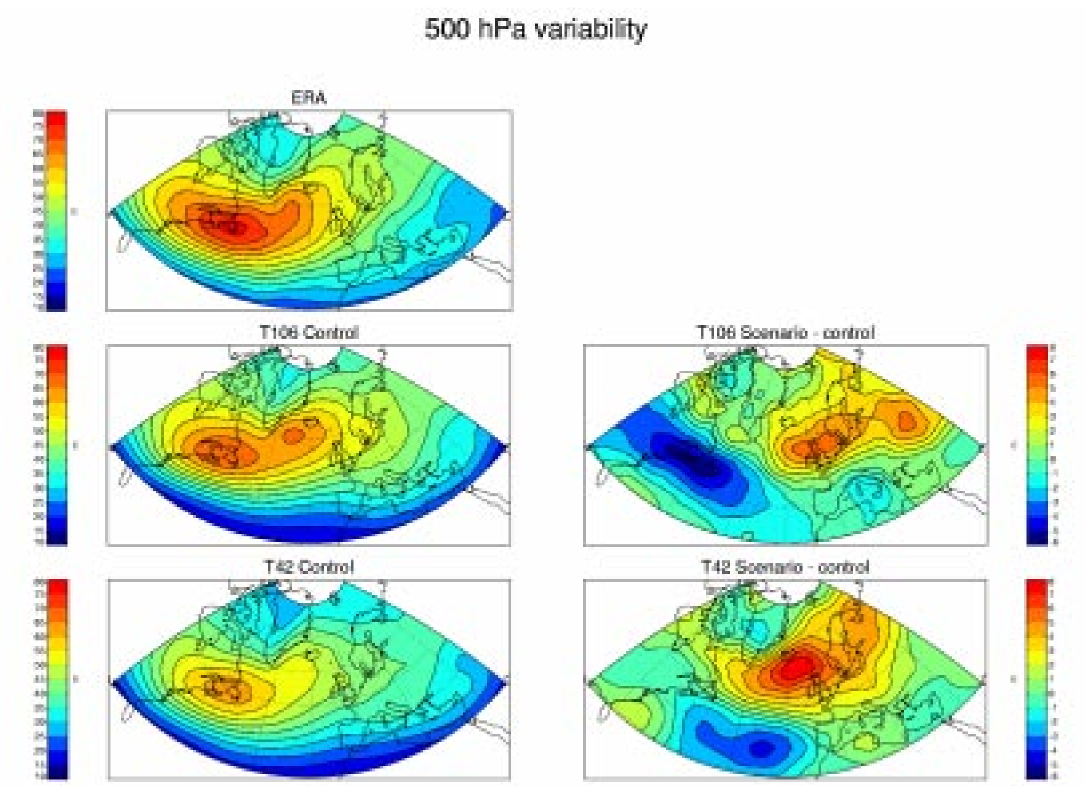

Figure 6. The storm track intensity estimated as a standard deviation of the 2.5-6 day band-pass filtered 500 hPa height in the northern winter (NDJFM). ERA indicates the 'observed' values as estimated in the 15-year European reanalyses 1979-1993; T106 Control: the G-TSL values in the 30-year control period; T42 Control: the values in the global O-A-GCM providing SST and sea ice for the G-TSL; and scenario minus control: the corresponding differences between the 30-year scenario and the control period.

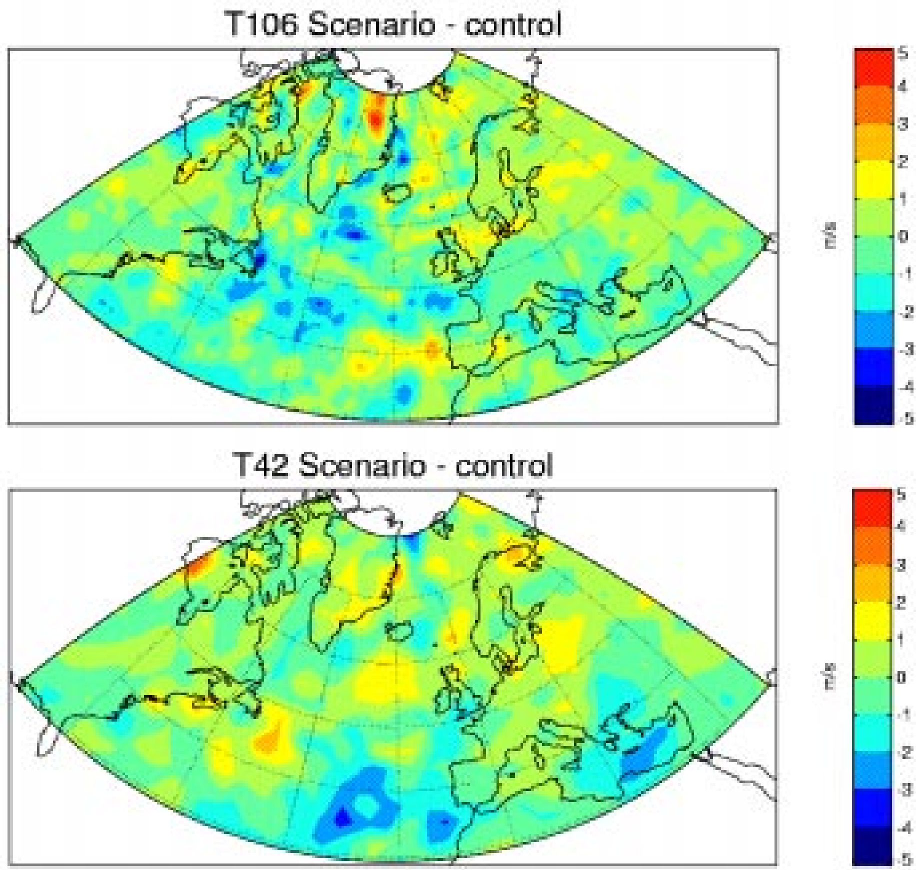

Figure 7. Mean value of the 10m wind speeds exceeding the 99.9 percentile level. Upper panel: Difference between the 30-year G-TSL scenario and the control. Lower panel: Difference between the 30-year O-A-GCM scenario and the control.

As mentioned above, STOWASUS-2100 also includes simulations of waves (and surges). Figure 8 and Table 1 show results from two 30-year wave simulations with the WAM ocean wave model. The grid resolution is 0.7° or approximately 77 km. There are 2767 sea points in the grid. The model is set up with 25 frequencies, logarithmically spaced from 0.042 to 0.411 Hz, and 24 directions, equally spaced (the integration area is larger than that shown in Figure 8). Figure 8 shows the difference between the average significant wave height in the 30-year 2xCO_2 run and the wave height in the control run. The general pattern, with increases in the northeast and decreases in the southwest, seems consistent with the change in atmospheric storm activity. It is interesting to note that this pattern is also consistent with the hindcasted trend, during the 1955-94 period (Figure 2). While Figure 8 only shows differences in the average significant wave height, Table 1 also presents statistics for different percentiles at selected locations, and observed values for two locations. The general picture of increased extreme values in the northeast and decreased values further southwest is quite clear.

Figure 8. Difference between average significant wave height in the 30-year 2xCO_2 run and the wave height in the corresponding control run as simulated with the WAM model. The contour interval is 0.05m. From the Norwegian contribution to the second status report of the STOWASUS-2100 project (Kaas et al., 2000).

One of the objectives in STOWASUS-2100 is to perform a number of case-study simulations with the regional climate model HIRHAM (see Christensen et al., 1996) at a 30 km horizontal resolution or higher. These are mainly process studies aimed at investigating the influence of changing background flow (baroclinic structure and latent heat effects) on extreme storm developments. It is obviously important to assess whether a particularly high spatial resolution is needed to capture the enhanced latent heat effect associated with explosive cyclogenesis. So far, the total deepening effect of latent heat (compared to a dry atmosphere) has been estimated (using HIRHAM) to be different to that of individual intense cyclones. Generally the effect is about 20-50% but for certain developments (as in Figure 4) it is much more dramatic. Climate change process studies using HIRHAM are currently being undertaken and cannot therefore be discussed. HIRHAM is also used in STOWASUS-2100 to produce high-resolution wind fields for case studies with wave and surge models. Currently, approximately 50 cases from the control and scenario periods are being re-simulated in 60-hour simulation windows. Some of these cases intend to include polar lows which are highly influenced by latent heat release (Sardia and Warner, 1983) but which cannot be simulated at a T106 resolution.

Wave height statistics Ekofisk (56.5°N, 3.2°E)

	Mean	50%	90%	99%
Ctr. year 1-30	2.09	1.7	4.1	6.7
CO_2 year 1-30	2.19	1.8	4.3	7.0
Obs. 1980-98	2.07	1.8	3.8	6.2

Wave height statistics Gullfaks (61.2°N, 2.3°E)

	Mean	50%	90%	99%
Ctr. year 1-30	2.89	2.5	5.4	8.5
CO_2 year 1-30	3.02	2.6	5.6	8.8
Obs. 1980-98	2.74	2.4	4.9	7.6

Wave height statistics Mike (66.0°N, 2.0°E)

	Mean	50%	90%	99%
Ctr. year 1-30	2.87	2.5	5.3	8.2
CO_2 year 1-30	3.00	2.6	5.5	8.9

Wave height statistics Ami (71.5°N, 19.0°E)

	Mean	50%	90%	99%
Ctr. year 1-30	2.42	2.0	4.5	7.6
CO_2 year 1-30	2.53	2.1	4.7	8.3

Wave height statistics Charlie (52.5°N, 33.5°W)

	Mean	50%	90%	99%
Ctr. year 1-30	3.33	2.9	5.8	9.3
CO_2 year 1-30	3.22	2.8	5.7	8.9

Wave height statistics Lima (56.5°N, 20.0°W)

	Mean	50%	90%	99%
Ctr. year 1-30	3.45	3.0	6.1	9.7
CO_2 year 1-30	3.42	3.0	6.1	9.9

Wave height statistics Juliette (52.5°N, 20.0°W)

	Mean	50%	90%	99%
Ctr. year 1-30	3.27	2.9	5.7	9.1
CO_2 year 1-30	3.19	2.8	5.7	8.9

Wave height statistics India (59.0°N, 19.0°W)

	Mean	50%	90%	99%
Ctr. Year 1-30	3.41	3.0	6.1	9.7
CO_2 year 1-30	3.41	2.9	6.1	10.0

Table 1. Statistics of significant wave height (m) for WAM simulations: Mean values, 50, 90 and 99 percentiles for the 30-year control and 2xCO_2 runs. Observations for 1980-1998 are also given for Ekofisk and Gullfaks. Source: Norwegian contribution to the second status report of the STOWASUS-2100 project (Kaas et al., 2000).

More details about STOWASUS-2100 can be found on the project web site (see Appendix 3).

DISCUSSION AND CONCLUSION

Although the potential impacts of changing extreme storm statistics can be dramatic, there are still large uncertainties in the climate model estimates of such changes. The reason for these uncertainties can be attributed to differences in the climate response to the changing atmospheric composition of different O-A-GCMs. From an isolated standpoint, it seems obvious that the higher availability of water vapour in a warmer climate would tend to produce more intense storms. However, storm activity is an integrated part of the general circulation of atmosphere: the convergence of eddy meridional heat and momentum transport associated with these storms are, in addition to radiative processes, fundamental in shaping the north-south temperature gradient and the zonal mean flow which basically defines the level of storm activity. Since coarse mesh general climate models cannot simulate extreme, small-scale, extra-tropical storm events sufficiently well, these models may have problems simulating possible changes in the overall balance between processes. Furthermore, the simulated regional climate change varies between different O-A-GCMs, and therefore the regional change in storm activity also varies. The difference in the simulated arctic sea-level pressure response is very important in this context. It is uncertain whether this difference is related to vertical resolution, and therefore the simulation of vertically propagating Rossby waves breaking into the stratosphere as suggested by Shindell *et al.* (1999), or to differences in the simulation of processes defining thinning of arctic sea ice, or to other processes (involving transient eddies).

Most but not all modern climate models appear to simulate some increase in storm activity near northwestern European coasts due to anthropogenic emissions. Global high-resolution time-slice simulations seem to give similar results.

Extreme storms constitute the driving mechanism for extreme ocean wave and storm surge events. Simulations using a wave model forced with atmospheric winds from a set of global high-resolution time-slice simulations resulted in an increase in high waves in the northeastern part of the North Atlantic and decreases further southwest.

REFERENCES

Alexandersson, H., Schmith, T. Iden K. and Tuomenvirta, H. (1998) Long-term trend variations of the storm climate over NW Europe, **The Global Atmosphere and Ocean System** 6, 97-120.

Alexandersson, H., Schmith, T. Iden K. and Tuomenvirta, H. (2000) Trends of storms in NW Europe derived from an updated pressure data set, **Climate Research** 14, 71-73.

Beersma, J. Rider, K. Komen, G. Kaas E. and Kharin, V. (1997) An analysis of extra-tropical storms in the North Atlantic region as simulated in a control and 2CO2 time-slice experiment with a high resolution atmospheric model, **Tellus** 49A, 347-361.

Bengtsson, L., Botzet, M. and Esch, M. (1995) Hurricane-type vortices in a general circulation model, Part I, **Tellus** 47A, 175-196.

Bengtsson, L., Botzet, M. and Esch, M. (1996) Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes?, **Tellus** 48A, 57-73.

Blackmon, M. (1976) A climatologic spectral study of the 500mb geopotential height of the northern hemisphere, **Journal of Atmospheric Science** 33, 1607-1623.

Branscome, L.E., and Gutowski (Jr.), W.J. (1992) The impact of doubled CO2 on the energetics and hydrologic processes of mid-latitude transient eddies, **Climate Dynamics** 8, 29-37.

Carnell, R.E., Senior, C.A. and Mitchell, J.F.B. (1996) An assessment of measures of storminess: simulated changes in northern hemisphere winter due to increasing CO2, **Climate Dynamics** 12, 467-476.

Carnell, R.E., and Senior, C.A. (1998) Changes in mid-latitude variability due to increasing greenhouse gases and sulphate aerosols, **Climate Dynamics** 14, 369-383.

Christensen, J.H., Christensen, O.B., Lopez, P., van Meijgaard, E. and Botzet, M. (1996) The HIRHAM4 Regional Atmospheric Climate Model, **DMI Scientific Report** 96-4 [Available from DMI, Lyngbyvej 100, Copenhagen Ø, DENMARK].

Christensen J.H., Machenhauer, B. Jones, R.G. Schär, C. Ruti, P.M. Castro, M. Visconti, G. (1997) Validation of present-day regional climate simulations over Europe: LAM simulations with observed boundary conditions, **Climate Dynamics** 13, 489-506.

Christensen O. B., Christensen, J.H. Machenhauer B. and Botzet, M. (1998) Very high-resolution regional climate simulations over Scandinavia – **Present climate, Journal of Climate** 11, 3204-3229.

Cubasch, U., Caneill, J.-Y., Filiberti, M., Hegerl, G., Johns, T., Keen, A,. Parey, S., Thual, O., Ulbrich, U., Voss, R., Waszkewitz, J., Wild, M. and van Ypersele J. (1997) **Anthropogenic Climate Change**. Project No. EV5V-CT92-0123 Final Report. Office for Official Publications of the European Commission EUR 17466EN Luxembourg, ISBN92-827-9728-7, 73 pp.

DelGenio, A.D., Lacis, A.A. and Ruedy, R.A. (1991) Simulations of the effect of a warmer climate on atmospheric humidity, **Nature** 351, 382-385.

Déqué, M., Marguet P. and Jones, R.G. (1998) Simulation of climate change over Europe using a global variable resolution general circulation model, **Climate Dynamics** 14, 173-189.

Flather, R. (2000) **Climate Change Effects on Storm Surges: Methodologies and Results**. Keynote Paper 4 in this book.

Frei, C., Schär, C., Lüthi, D. and Davies, J.C. (1998) Heavy precipitation processes in a warmer climate, **Geophysical Research Letters** 25, 1431-1434.

Günther, H., Rosenthal, W., Stawarz, M., Carretero, J.C., Gomez, M., Lozano, I., Serano O. and Reistad, M. (1998) The wave climate of the Northeast Atlantic over the period 1955-94: the WASA wave hindcast. The **Global Atmosphere and Ocean System** 6, 121-163.

Gutowski, (Jr.), W.J. Branscome, L.E. and Stewart, D.A. (1992) Life cycles of moist baroclinic eddies, **Journal of Atmospheric Science** 49-4, 306-319.

Hall, N.M.J, Hoskins, B.J. Valdes P.J. and Senior, C.A. (1994) Storm tracks in a high resolution GCM with doubled CO_2, **Quarterly Journal of the Royal Meteorological Society** 120, 1209-1230.

Held, I.M. and O'Brien, E. (1992) Quasi-geostrophic turbulence in a three-layer model: Effects of vertical structure in the mean shear. **Journal of Atmospheric Science** 49, 1861-1870.Holton, J.R. (1992) An Introduction to Dynamic Meteorology. Third Edition, Academic Press, 511pp.

Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg A. and Maskell K. (eds.) (1996) **Climate Change 1995: The Science of Climate Change**. Cambridge University Press, Cambridge, Great Britain.

Kaas, E., Li, T.-S. and Schmith, T. (1996) Statistical hindcast of wind climatology in the North Atlantic and northwestern European region, **ClimateResearch** 7, 97-110.

Kaas, E., Andersen, U., Flather, R., Williams, J., Lionello, P., Malguzzi, P., Pfizenmayer, A., von Storch, H., de Ronde, J., Philippart, M., Holtermann, S., Reistad, M., Helge Midtbø, K., Vignes, O., Haakenstad, H., Hackett B. and Fossum, I. (2000) STOWASUS 2100, Regional Storm, Wave and Surge Scenarios for the 2100 Century: Progress report for the second project year. **DMI Technical Report** No. 00-01. (http://intranet.dmi.dk/f+u/publikation/Tr00-01.pdf).

Kuo, Y.-H. and Low-Nam, S. (1990) Prediction of nine explosive cyclones over the western Atlantic ocean with a regional model, **Monthly Weather Review** 118, 3-25.

Lambert, S.J. (1995) The effect of enhanced greenhouse warming on winter cyclone frequencies and strengths. J**ournal of Climate** 8, 1447-1452.

Lambert, S.J. (1996) Intense extratropical northern hemisphere winter cyclone event: 1899-1991, **Journal of Geophysical Research** 101, 21319-21325.

Langland R.H., Elsberry, R.L. and Errico, R.M. (1996) Adjoint sensitivity of an idealized extratropical cyclone with moist physical processes, **Quarterly Journal of the Royal Meteorological Society** 122, 1891-1920.

Lunkeit, F., Ponater, M., Sausen, R., Sogalle, M., Ulbrich, U. and Windelband, M. (1996) **Cyclonic activity in a warmer climate**, Beitr. Phys. Atmosph. 69, 393-407.

Manobianco, J. (1989) Explosive east coast cyclogenesis: Numerical experimentation and model-based diagnostics, **Monthly Weather Review** 117, 2384-2405.

May, W. (1999) A time-slice experiment with the ECHAM4 A-GCM at high resolution: The experimental design and the assessment of climate change as compared to a greenhouse gas experiment with ECHAM4/OPYC at low resolution. **DMI Scientific Report**, 99-2, ISBN 87-7478-389-0.

Mitchell, J.F. B. and Johns, T.C. (1997) On Modification of Global Warming by Sulfate Aerosols, **Journal of Climate** 10, 245-267.

Nakamura, H., Nakamura, M. and Anderson, J.L. (1997) The role of high- and low-frequency dynamics in blocking formation. **Monthly Weather Review** 125, 2074-2093.

Pfizenmayer A. and von Storch, H. (2000) **Signature of changing wave climate in the North Sea**. GKSS report, in press.

Roeckner, E., Bengtsson, L., Feichter, J., Lelieveld, J. and Rodhe, H. (1998) Transient climate change simulations with a coupled atmosphere-ocean GCM including the tropospheric sulfur cycle, **Journal of Climate** 12, 3004-3032.

Rogers, J.C. (1997) North Atlantic storm track variability and its association to the North Atlantic Oscillation and climate variability of Northern Europe, **Journal of Climate** 10, 1635-1647.

Sardia, J.M. and Warner, T.T. (1983) On the mechanism for the development of polar lows, **Journal of Atmospheric Science** 40, 869-881.

Schinke, H. (1993) On the occurrence of deep cyclones over Europe and the North Atlantic in the period 1930-1991, **Beitr. Phys. Atmosph**. 66(3), 223-237.

Schmith, T., Kaas E. and Li, T.-S. (1998) Northeast Atlantic storminess re-analysed: No trend during past 100 year period, **Climate Dynamics** 14, 529-536.

Schubert, M., Perlwitz, J., Blender, T., Fraedrich, K. and Lunkeit, F. (1998) North Atlantic cyclones in CO2-induced warm climate simulations: Frequency, intensity, and tracks, **Climate Dynamics** 14, 827-837.

Shindell, D.T., Miller, R.L., Schmidt, G.A. and Pandolfo, L. (1999) Greenhouse gas forcing of Northern Hemisphere winter climate trends, **Nature** 399, 452-455.

Stephenson, D. and Held, I. (1993) GCM response of northern winter stationary waves and storm tracks to increasing amounts of carbon dioxide, **Journal of Climate** 6, 1859-1870.

Ulbrich, U. and Christoph, M. (1999) A shift in the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing, **Climate Dynamic**s 15, 551-559.

WASA (1998) Changing waves and storms in the Northeast Atlantic? **Bulletin of the American Meteorological Society** 79, 741-760.

Zhang, Y. and Wang, W.-C. (1997) Model-simulated northern winter cyclone and anticyclone activity under a greenhouse warming scenario, **Journal of Climate** 12, 2474-2489.

Zorita, E., and von Storch, H. (1999) The analog method as a simple statistical downscaling technique: comparison with more complicated methods, **Journal of Climate** 10, 2474-2489.

Keynote Paper 4

Climate Change Effects on Storm Surges: Methodologies and Results

Roger Flather and Jane Williams

Proudman Oceanographic Laboratory, Bidston Observatory, Bidston Hill, Prenton, CH43 7RA, Cheshire, U.K. (raf@pol.ac.uk)

ABSTRACT

Climate-related changes in sea level, in particular high water levels, are important because coastal defence structures which protect areas susceptible to flooding, have lifetimes comparable with the timescale of significant changes in atmospheric CO_2. Undoubtedly, most research effort on sea levels goes into studies of mean sea level with the aim of understanding and explaining its variability and identifying trends. However, the behaviour of high or extreme water levels is of greater practical importance.

Extreme water levels generally result from a combination of the high water of a spring tide and a storm surge. An increase in mean sea level will of course, directly affect extreme levels, but changes in the mean level and hence water depth can also influence the tidal component by changing its wavelength and modifying the propagation and dissipation of tidal energy. Increased water depth also affects the generation, propagation and dissipation of the storm surge component, perhaps slightly reducing the surge magnitude. In addition, the surge climate can change if the storm climate, for example, storm tracks, intensity and frequency of occurrence, alters.

This paper discusses recent work to estimate changes in storm components, concentrating on the influence of changing storm climate on surges, largely in northwest Europe. Such work has been carried out or is in progress in a number of research centres, in various national programmes, and was a component of the EU 'WASA' project (1994-1996) continued in 'STOWASUS-2100' (1997-2000). Approaches and methodologies are described and results and remaining problems discussed. Most results suggest some enhancement of extreme surge heights with a doubling of CO_2, but difficulties remain, for example, in distinguishing greenhouse gas induced change from natural variability.

INTRODUCTION

Coastal floods caused by a combination of high tides, storm surges and storm generated wind waves are a major natural hazard in many parts of the world. Low-lying, densely populated and poorly defended coastal areas such as the northern Bay of Bengal are particularly susceptible. Where defences against coastal flooding and erosion exist, they are designed to withstand storm situations that may occur on average once in a given number of years. Rising sea levels and changing storminess will reduce the effectiveness of coastal defences increasing the likelihood of more frequent, extensive and damaging floods in the future, and are consequently a major concern.

This paper aims to provide an overview of the relevant mechanisms and approaches by which the impact of climate change on the factors causing coastal flooding can be understood and quantified. Mean sea level change has been studied intensively, and results presented in numerous papers and summarised in IPCC reports (e.g., 1996). We concentrate on changes in high water levels and in particular on the storm surge component. Such work has been carried out or is in progress in a number of research centres, in various national programmes, and was a component of the EU 'WASA' project (1994-1996) continued in 'STOWASUS-2100' (1997-2000).

The layout of the paper is as follows: First, we give a brief review of the background of sea-level change. Second, we discuss the mechanisms through which sea-level change can modify the tide and surge response. Third, investigations of the effects of changes in storminess are described. Fourth, we describe some of the on-going work in STOWASUS-2100, followed by discussion and conclusions.

BACKGROUND - SEA LEVEL CHANGE

Generally, observed sea level at a given location and time can be considered as the sum:

sea level = mean sea level + tide + storm surge + interactions

Where, mean sea level (MSL) is the mean over some suitably long period (including steric, i.e., density-induced effects), tide is the astronomically generated component, storm surge is the meteorologically generated component due to storms, and interactions occur between the other components due to non-linear dynamical processes in shallow water. This separation is useful but imperfect because, for example, MSL also includes the averaged effects of storm surges, long-period tides also include meteorologically generated contributions, so that care is needed to avoid some double accounting. Tide gauges measure sea level relative to benchmarks fixed to the land and so the measurements include vertical land movements, which may be due to geological processes (e.g., glacial rebound, tectonic activity) or anthropogenic changes (e.g., ground water extraction). Land movements need to be understood and quantified in order to relate local observed sea level changes to 'absolute' sea level change.

Correcting for land movements, global MSL is estimated (from in situ gauges) to have risen at a rate of 1.0 to 2.5 mm y^{-1} in the past hundred years, with a 'central best value' of 1.8 mm y^{-1} (IPCC, 1996). A recent review of trends in MSL observed in the British Isles (Woodworth *et al.*, 1999) suggests a figure closer to 1 mm y^{-1}, consistent with secular trends observed elsewhere in northwest Europe. From the longest records, an acceleration of 0.4 to 0.8 mm y^{-1} per century is inferred, apparently beginning in the 19th century with a possible contribution from accelerated glacier melt after the Little Ice Age (Dowdeswell *et al.*, 1997). This acceleration is similar to that (~0.4 mm y^{-1} per century) in long European records (Stockholm, Amsterdam and Brest) obtained by Woodworth (1990). It is less apparent in 20th century records alone, but is much less than considered possible in the 21st century (IPCC, 1996).

Various studies of tide-gauge records have found small but not statistically significant trends in non-tidal sea-level variability (Zhang *et al.*, 1997; Bijl *et al.*, 1999; Pugh and Maul, 1999; Woodworth, 1999). After removing effects of local vertical land movements, trends in UK extreme sea levels have been found to be nearly uniform, ~ 1.1 mm/y, closely matching mean sea-level trends (Dixon and Tawn, 1992). There is evidence of changes in tidal range, usually attributed to coastal engineering, dredging etc. On millennial scales, changed sea levels and (e.g., North Sea) basin morphology also have a large impact on tides (Shennan *et al.*, 2000).

MECHANISMS AND SENSITIVITY STUDIES

Tides in shelf and coastal seas are the response to oscillations primarily generated in the deep oceans. The response of a shelf sea depends on its size, shape and water depth. Large tides occur near resonance where a natural model of oscillation for part of the region has a period close to that of a constituent of the tide. A simple resonant case occurs where the shelf width or length of a basin corresponds to a quarter wavelength of the tide. This is approximately so for the Bay of Fundy (Canada), which has the world's largest tidal range, and for the Bristol Channel, which has the world's second largest tidal range. Generally, each tidal constituent propagates as a wave forming a linked system, losing energy in shelf seas through dissipation by bottom friction and by transferring energy to harmonics and other tidal frequencies through non-linear shallow water processes and interactions.

In the depth-averaged formulation generally used to describe tide–surge dynamics, the meteorological forcing terms generating storm surges are wind stress / water depth, and the horizontal gradient of sea surface atmospheric pressure, Pmsl. Wind stress increases in importance in shallow water whereas the pressure gradient term does not depend on water depth. Consequently, pressure forcing dominates in the deep ocean, but wind stress is the most important parameter in shallow water. Major surges therefore occur in shallow water.

Changes in water depth due to MSL rise will modify the dynamics of tides and surges. An increase in MSL and hence water depth will increase the tidal wavelength, modifying the system of tidal waves. Both increases and decreases in tidal range may result. For example, for near-resonant cases, tidal elevations may increase if the system moves closer to resonance or decrease if it moves away from resonance. Increased water depths will also modify bottom friction and hence the dissipation of tidal energy, so in general changes may be more complex. The generation, propagation and dissipation of storm surges will also be affected by rising sea level and increased water depth, reducing the effective forcing and surge elevations.

Figure 1 shows for the northwest European Shelf, the change in mean tidal high water (MHW), mean low water (MLW) and tidal range due to a 50cm rise in MSL, computed using the POL 'CS3' tide-surge model (used operationally in the UK for storm surge prediction). These changes show higher MHW, lower MLW and increased tidal range in the German Bight, Skagerrak and Kattegat probably due to reduced dissipation; more tidal energy reaches the Kattegat from the Atlantic with deeper water. Substantial (10cm) increases in MHW also occur in the Bristol Channel and eastern Irish Sea and decreases of a similar magnitude in the Gulf of St Malo. These are near resonant areas with large amplitudes for the main M2 harmonic. Therefore, if MSL rises by 50cm, MHW level will increase by 40 – 60cm on northwest European coast

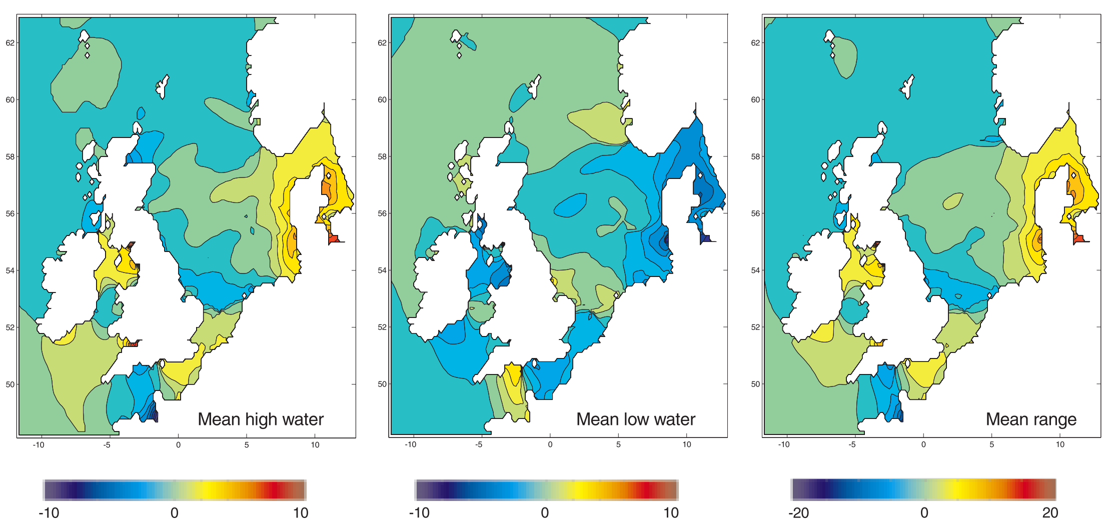

Figure 1. Change in mean tide parameters caused by a sea-level rise of 50cm, from the POL 'CS3' model.

Flather and Khandker (1993) investigated these effects in the northern Bay of Bengal using simple model experiments. With a 2m-rise in sea level, the amplitude of the largest harmonic (M2) increased by about 10cm in the northeast and decreased by about 15cm in the northwest of the bay (~10% of the amplitude), consistent with resonance arguments. The effect on surge elevations during a cyclone in May 1995 was to reduce their maximum by about 30cm, roughly 10% of the peak surge computed. For total water levels (tide and surge), the change is determined by a combination of the above processes, further complicated by the relative timing of the tide and surge components. Maximum total water level increased in some areas (by up to +25cm) and decreased in others (by up to –50cm). Therefore, the effect of the 2m-rise in MSL would be to increase maximum water levels by between 1.5m and 2.25m depending on location (see Figure 2).

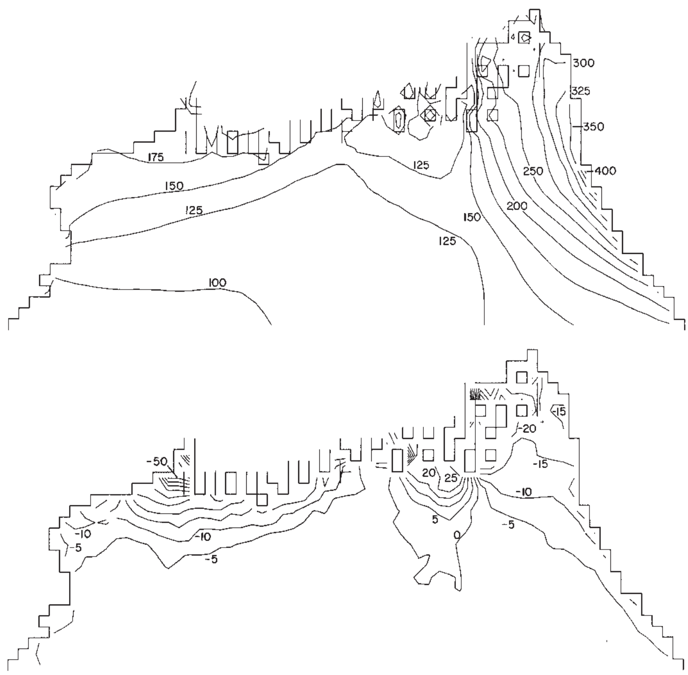

Figure 2. Contours of maximum computed elevation (cm) due to tide and surge in the period 1200Z 24 May to 1200Z 25 May 1985 (top) and the change (cm) in the maximum computed tide + surge elevation produced by a +2m rise in MSL (from Flather and Khandker, 1993).

Sensitivity studies based on the catastrophic 1953 storm surge in the North Sea have been carried out in the UK (Flather, 1992). Changes in maximum surge elevations during this event were investigated using numerical tide-surge model simulations. These changes are caused by increases in storm intensity, changes in storm track, changes in water depth (mean sea level) and changes in the timing of the passage of the storm relative to tidal high water. For a single extreme storm, these results provide an indication of the change in the surge response caused by the assumed changes in storm characteristics. Similar studies for the Dutch coast (de Ronde, 1993) suggested that a 5m rise in MSL would have only a small effect (-20 to + 10cm) on surge elevations. Bijl (1997) showed that an increase in storm intensity would have a relatively large effect on surge maxima whereas a shift in track of 2 to the north would produce only a small effect.

EFFECTS OF CHANGES IN STORMINESS ON STORM SURGE EXTREMES

More recent studies have attempted to understand and quantify changes in the storm surge climatology and in particular surge extremes. The approach is to run long model hindcast simulations of surges for 10-year periods, forced by gridded meteorological data sets, to provide regional storm surge climatologies in the form of, for example, hourly model elevation fields (and current). These can be analysed in the same way as observations to provide estimates of surge extremes. In particular, the N-year return value, defined as that which is exceeded on average once in N years, can be derived.

In the EU project ‘WASA’, Flather *et al.* (1998) showed that this approach could produce good estimates of extreme surges given accurate meteorological data. A 40-year (1955-1994) simulation with a 2D 35km grid tide-surge model (CSX) of the northwest European shelf was forced by 6-hourly meteorological analyses from the Norwegian Meteorological Institute (Reistad and Iden, 1995). A second 40-year run without meteorological forcing provides model tide predictions, which are subtracted from the ‘tide + surge’ solution to give the surge component. A comprehensive data set of surge elevations derived from long tide gauge records was assembled and used to validate the model results. Comparisons with the observed surges showed that the accuracy of the model results was in the order of 10cm (RMS).

For every model grid point, the N-year return period surge elevations were derived using an approach based on the ‘r largest’ method described by Smith (1986) and Tawn (1988). This is an extension of the classical ‘annual extremes’ method of Gumbel (1958) using the r largest independent values, where r is typically O(10), rather than the single largest value from each calendar year. The selected surge maxima should exceed a chosen threshold value and be separated from any other selected maximum by a minimum time interval, so that they can assumed to be independent. The cumulative probability distribution is then computed from the selected maxima (number of years of data r values), and a suitable theoretical distribution fitted to it, allowing extrapolation to the required return period.

Flather *et al.* (1998) took r = 7, the minimum time interval 34h, and used the ‘generalised extreme value’ distribution GEV (, , k), which has three adjustable parameters, the location, the scale and k the shape parameter. Model derived 50-year return period surges (Figure 3) closely correspond to values derived from tide gauge observations except where the model resolution was too coarse to represent surges accurately (e.g., in the Bristol Channel and eastern Irish Sea).

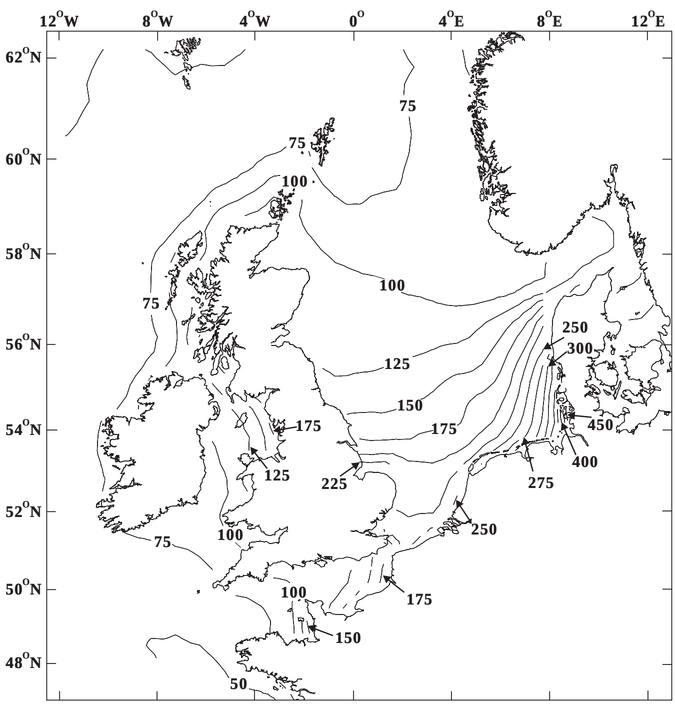

Figure 3. Distribution of 50-year surge elevation (cm) based on analysis of model surges (from Flather *et al.*, 1998).

In a first attempt to determine the change in storm surge extremes caused by a doubling of atmospheric CO_2, Flather and Smith (1998) applied the same approach with meteorological forcing. This comprised two 5-year data sets, a 'control' representing present-day conditions, and a '2xCO_2' scenario from a time-slice experiment run with the ECHAM3 climate model at spectral resolution T106 (Bengtsson *et al.*, 1995; 1996). The supplied met data resolution was about 100km and 12 h in time, rather course for use in surge calculations. 5-year return period surges were derived as above but with r = 10 and using the simpler Gumbel (two parameter) distribution to fit the data. Comparison with equivalent results from the DNMI forced hindcast showed that the control surge extremes were substantially underestimated by up to 60%. Changes in 5-year surge ('2xCO_2' - 'control') gave small negative differences west and northwest of Ireland, and differences of up to +15cm in the Irish Sea and Bristol Channel. Larger differences (+10 to +25cm) occurred in the English Channel, and surge elevation changes in the North Sea were typically +10 to +40cm, increasing in the shallow water of the German Bight to a maximum of about +65cm.

It remained to determine whether these changes were significant and due to increasing CO_2. Issues to be considered included the underestimate of the 'control' surge climate, errors in estimates of extremes (from fitting the Gumbel distribution function to the cumulative probability data), and whether the changes could be due to the natural variability in estimating 5-year surges from 5-year data sets. The natural variability in surge estimates was examined by analysing 5-year sub-sets of the 40-year hindcast run with DNMI forcing. A measure of the natural variability in 5-year surge was obtained by taking, for each grid point, the difference between the largest and smallest estimate obtained, indicating the range or uncertainty in the estimates resulting from the different storm samples. The natural variability was quite large, up to 65cm in the Irish Sea, and typically 30 - 60cm in the North Sea increasing to almost 120cm in the German Bight.

Finally, to compensate for the underestimated 'control' surge extremes, simple up-scaling was applied to the extremes derived from the 'control' and '2xCO_2' forced runs to enable direct comparisons with the 'present-day' extreme surges. For each grid point, the 'control' and '2xCO_2' values were multiplied by the corresponding ratio (DNMI / 'control'). Comparing the resulting scaled differences ('2xCO_2' - 'control') with the estimated range of natural variability in 5-year surge (Figure 4), most surge elevations remain within the normal range of variability. There are a few exceptions in the southern North Sea, the eastern English Channel and off the west coast of Denmark where the effect of increased CO_2 may be significant.

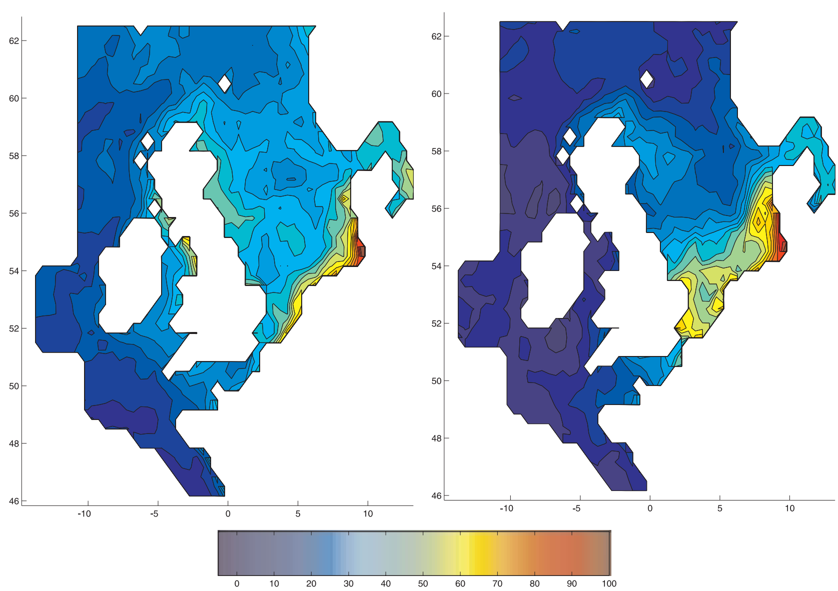

Figure 4. Range of natural variability (left) and scaled change in 5-year surge ('2xCO_2' minus 'control').

Von Storch and Reichardt (1997) and Langenberg *et al.* (1999) have carried out related studies using the same ECHAM3 data set. Von Storch and Reichardt (1997) used a two-step statistical downscaling method to generate a scenario for future changes in water level at Cuxhaven. A dynamical downscaling of ECHAM3 data was used to estimate expected changes in monthly mean Pmsl distributions over the northeast Atlantic and western Europe, which were then related to intra-monthly percentiles of high water level at Cuxhaven. No significant difference was found between the 'control' and '2xCO_2' scenarios.

Langenberg et al. (1999) used a similar statistical approach complemented by runs of a tide-surge model covering the northwest European shelf and Baltic Sea forced by DNMI Pmsl analyses and the ECHAM3 data. The analysis concentrated on the coast of mainland Europe from Vlissingen to Smogen (Sweden). Results suggested a continuing increase in mean water levels due to increasing CO_2, but the high frequency variability was affected much less. The natural variability in the system was too large to attribute changes to anthropogenic development.

STOWASUS-2100: WORK IN PROGRESS

The range of uncertainty/variability in extreme estimates should be reduced if they are based on longer periods of data. This, amongst other things, was the motivation for continued work in STOWASUS-2100.

Two 30-year time slice simulations with ECHAM4 at T106 resolution run by DMI (May, 1999; Kaas and Andersen, 2000) provided meteorological forcing for a 'control' period corresponding to the present day (1970-1999) and an approximate '2xCO_2' scenario (2060-2089). The data supplied were at ~125km and 6h resolution. Using these data, studies of storm surge climatology are being carried out for the northwest European coasts by CCMS-POL, DNMI, RIKZ and for the Adriatic by the University of Padua.

For the northwest European work, two new surge models were set up by CCMS-POL: 'NEAC' covering the northeast Atlantic and European shelf seas from northern Spain to northern Norway with a ~35km grid, for the large-scale; and 'NISE' covering the North and Irish Seas and English Channel at a ~12km resolution to provide more detail in these areas. Both models include 26 tidal harmonics, and open boundary surge input for NISE is interpolated from the NEAC results. Figure 5 shows the ECHAM4 points superimposed onto the NEAC model grid.

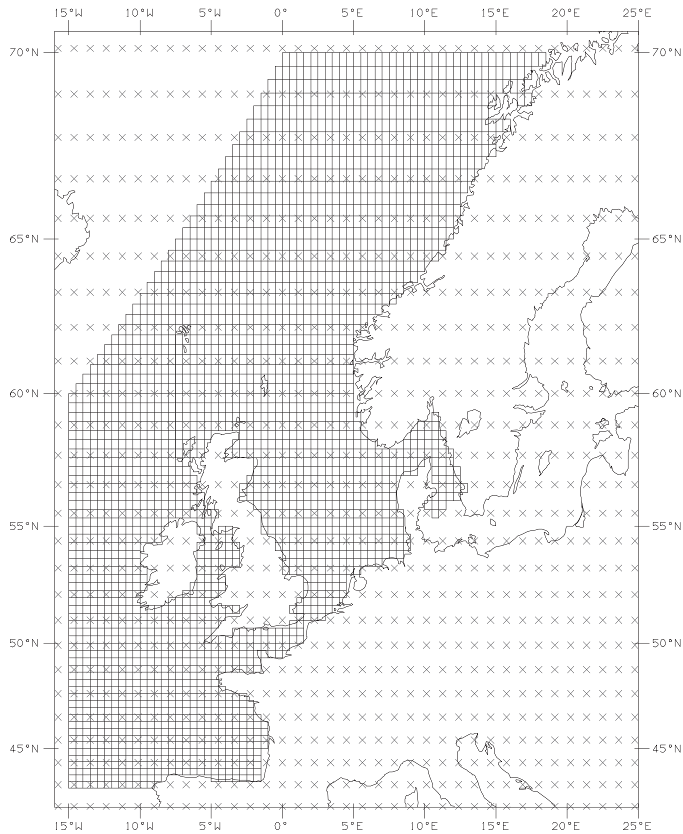

Figure 5. NEAC model grid (~35 km) with ECHAM4 (T106) output points.

The models were run for the following cases:

- Tide only for (a) 1955-1999, and (b) 2060-2089.
- 'Tide + surge' with DNMI met forcing for 1955-1997 (to determine 'present-day' surge climate).
- 'Tide + surge' with ECHAM4 'control' forcing for 1970-1999.
- Tide + surge' with ECHAM4 '2xCO_2' forcing for 2060-2089.

From each run, hourly model fields were stored for analysis and surge components computed by subtracting 'tide' from 'tide + surge' solutions. NEAC surges were validated by comparing DNMI forced surges with the corresponding results from WASA. Extreme surge elevations were derived as above using r = 10 and the Gumbel distribution for the 'present day', 'control' and '2xCO_2' runs of NEAC. The 50-year return period surge elevation was considered as a reasonable extrapolation from the 30-year data sets.

The 'present-day' NEAC 50-year surge distribution was consistent with the equivalent from WASA and hence in good agreement with observed estimates. The NEAC 'present-day' and 'control' 50-year surge distributions, shown in Figure 6, agree much more closely than corresponding results in WASA, probably due to the 6h time resolution of the ECHAM4 forcing. The largest differences occur in the coastal zone, possibly due to the effect of the coarse resolution of land and sea on ECHAM4 winds. This is a very encouraging result, showing that the ECHAM4 'control' meteorological fields are statistically a good approximation to the real 'present-day' weather.

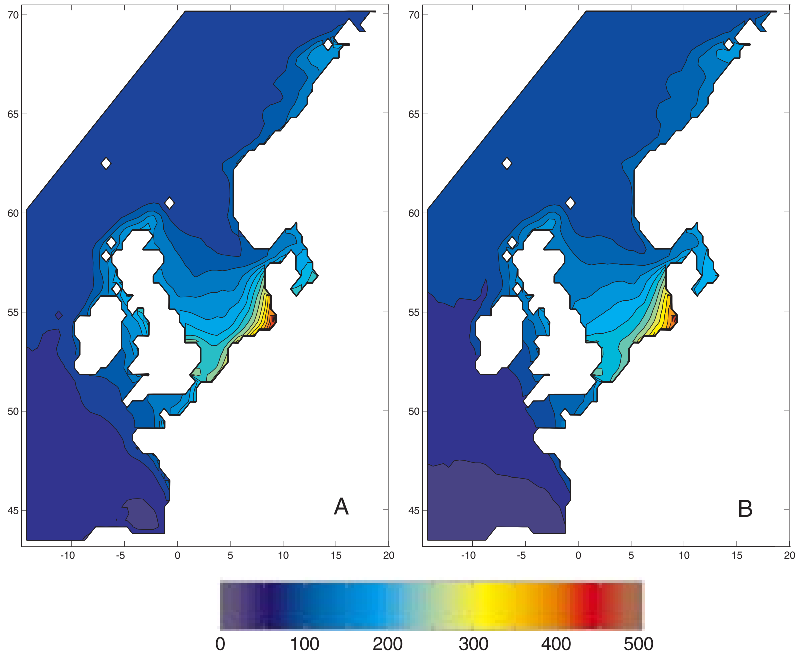

Figure 6. Distribution of 50-year surge elevation (cm) from (a) 'present-day' and (b) 'control' solutions.

The difference in 50-year surge ('2xCO_2' minus 'control'), shown in Figure 7a, is largest (about +30cm) for the Dutch and Danish coasts but is spatially noisy. A possible source of the noise is in fitting the theoretical distribution (Gumbel in this case) to the cumulative probability distribution of the data. Tests using the alternative GEV function (Figure 7b) and using Gumbel with numbers of maxima per year of between 5 and 20, gave different but still noisy distributions. Figure 7c shows the result for r = 20. Although the individual 50-year surge distributions appear sensible, differences between them are very sensitive to the choice of distribution function and t number of maxima per year.

Further tests were carried out on hourly time series of surges extracted from the NEAC results for a selection of coastal locations. The 10 largest maxima in each year were extracted using a 60-hour surge event window. Gumbel and GEV distributions were fitted and 50-year return period surge elevations and standard errors derived (see Table 1). For a given location, differences between 50-year values depend more on the function used than on which run, 'control' or '2xCO_2', the data analysed came from. Accounting for standard errors, the 50-year extreme surges for the '2xCO_2' run are not significantly different from those for the 'control' run.

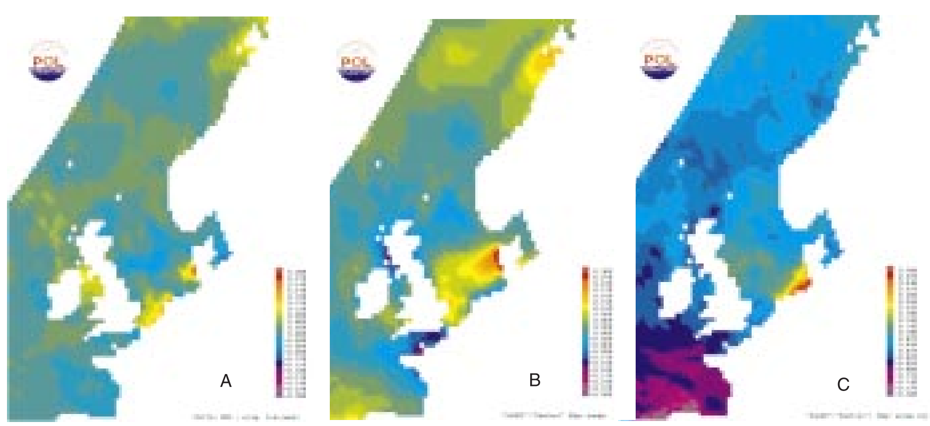

Figure 7. Difference in 50-year surge elevation '2xCO_2'-'control', using (a) Gumbel with r=10, (b) GEV with r=10, and (c) Gumbel with r=20.

Port	Gumbel		GEV	
	'Control'	'$2xCO_2$'	'Control'	'$2xCO_2$'
Bergen	1.01 (0.04)	1.01 (0.03)	0.78 (0.02)	0.78 (0.03)
Brest	0.69 (0.03)	0.69 (0.03)	0.61 (0.05)	0.52 (0.03)
Esberg	3.44 (0.14)	3.46 (0.13)	2.43 (0.09)	2.88 (0.15)
Galway	0.88 (0.03)	0.85 (0.03)	0.75 (0.05)	0.73 (0.04)
Hook of Holland	2.36 (0.09)	2.37 (0.09)	2.13 (0.17)	2.26 (0.19)
Lowestoft	2.20 (0.09)	2.21 (0.09)	1.93 (0.14)	2.08 (0.16)
Liverpool	1.52 (0.06)	1.64 (0.06)	1.30 (0.08)	1.34 (0.08)
Newlyn	0.75 (0.03)	0.75 (0.03)	0.64 (0.04)	0.59 (0.03)
Sheerness	2.39 (0.10)	2.42 (0.10)	2.14 (0.16)	2.26 (0.18)
Wick	1.35 (0.05)	1.32 (0.05)	1.14 (0.07)	1.14 (0.06)

Table 1. 50-year surge heights (m), based on the 10 largest yearly maxima with a 60-hour event window, the standard error is given in brackets.

However, changes can be seen in the tail of the surge frequency distributions representing larger events (see Figure 8). At Bergen, the largest computed surge occurred in the 'control' run with more frequent, smaller surges, in the '$2xCO_2$' run. However, at Esbjerg the maximum surge in the '$2xCO_2$' solution is much bigger than the maximum surge in the 'control' and there are generally more large surges with the '$2xCO_2$' simulation, which tends to support the increase in surge extremes west of Denmark in the WASA results and in Figure 7.

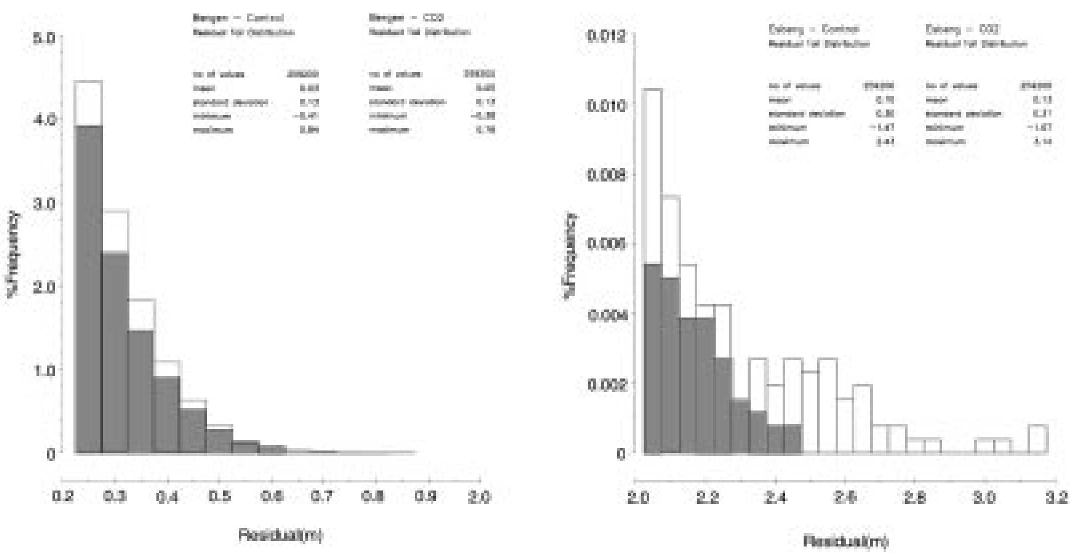

Figure 8. Extreme statistics for Bergen and Esbjerg from 'control' (shaded) and '$2xCO_2$' NEAC scenarios.

Percentile analysis, which avoids the difficulties associated with fitting a theoretical distribution to the data described above and so gives a much more robust result, has also been applied to the NEAC results. The 99th percentile is the surge elevation exceeded in 1% of the samples, i.e., on average about 90 hours per year, so is much smaller than the 1-in-5 year or 1-in-50 year extreme value, but has a similar distribution. Figure 9 shows the distribution of differences between 99th percentiles from the 'control' and '$2xCO_2$' runs. This is somewhat similar to the difference in 50-year extreme surges using a Gumbel distribution with r=20 (Figure 7c).

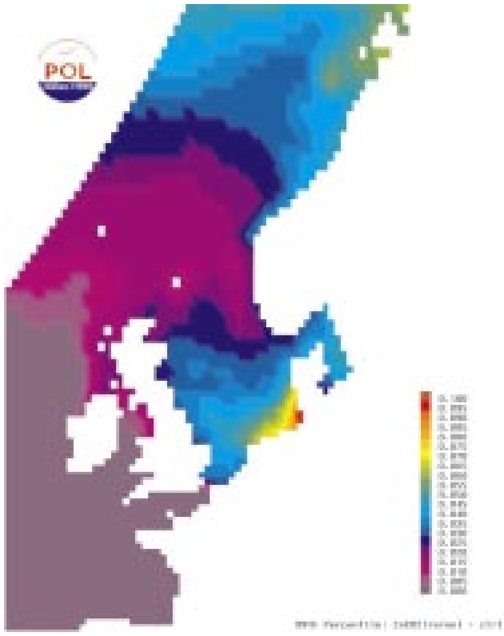

Figure 9. Difference in 99th percentile storm surge elevation '2xCO_2' 'Control' from NEAC model runs.

The work in STOWASUS-2100 is ongoing.

DISCUSSION AND CONCLUSIONS

We have given a brief outline of some of the work undertaken on sea-level change, and have discussed some of the mechanisms relevant to understanding changes in tide, storm surge and water levels, specifically the effects resulting from a change in water depth with rising MSL. For a given change in depth, these effects can be estimated with some confidence. In morphologically active areas, the assumption that MSL rise is equal to water depth change may not be valid, but in areas with well defended coasts such as northwest Europe it is probably a reasonable first approximation.

Changes in surge elevation and water level resulting from changes in storminess are more difficult to quantify. Useful insights can be derived from sensitivity studies, but for practical applications, reliable estimates in extremes are required. An approach in which tide-surge models are run for a few decades, forced by meteorological data from routine analyses and climate model simulations, provides regional surge or water level climatologies as hourly model fields of elevation (and current). These can then be analysed in the same way as observations to provide estimates of extremes.

In practice, the success of this approach depends on a number of factors. These include such questions as - does the meteorological forcing used represent the true storm climate, i.e., resolve storm development in space and time and with the correct statistics (frequency etc.)? If this is not the case, then the computed surges will not provide a good approximation to the true surge climate, making interpretation difficult. Studies using meteorological data from high-resolution regional climate models will improve these aspects. The other main issue is in interpretation of results. Can changes or trends be distinguished from the natural variability? If so, are they caused by climate change or by some other mechanism? These issues must arise in other aspects of climate research and it is possible that solutions can be adapted from other areas of work. Natural variability can be assessed from long hindcast simulations forced by routine meteorological analyses. These extend back almost 50 years and are extremely valuable, but may contain inhomogeneities which reduce their value, as do long O(100y) observational records (see e.g., WASA, 1998). Finally, estimates of changes in extreme values appear to be very sensitive to aspects of the analysis method used; including the sampling of data and assumed theoretical distribution used to fit and extrapolate the cumulative probability distribution of the data. More sophisticated statistical techniques may be able to address some of these issues.

ACKNOWLEDGEMENTS

Some of the work described here was funded by the EU in the projects WASA EU-EV5V-CT94-0506 and STOWASUS-2100 ENV4-CT97-0498; by the UK Ministry of Agriculture, Fisheries and Food (FD0313), and by the UK Natural Environment Research Council.

REFERENCES

Bengtsson, L., Botzet, M. and Esch, M. (1995) Hurricane-type vortices in a general circulation model, **Tellus** 47A, 175-196.

Bengtsson, L., Botzet, M. and Esch, M. (1996) Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes? **Tellus** 48A, 57-73.

Bijl, W. (1997) Impact of wind climate change on the surge in the southern North Sea, **Climate Research** 8, 45-59.

Bijl, W., Flather, R., de Ronde, J.G. and Schmith, T. (1999) Changing storminess? An analysis of long-term sea level data sets, **Climate Research** 11, 161-172.

Dixon, M.J. and Tawn, J.A. (1992) Trends in UK extreme sea-levels: a spatial approach, **Geophysical Journal International** 111, 607-616.

Dowdeswell, J.A., Hagen, J.O., Björnsson, H., Glazovsky, A.F., Harrison, W.D., Holmlund, P., Jania, J., Koerner, R.M., Lefauconnier, B., Ommanney, C.S.L. and Thomas, R.H. (1997) The mass balance of circum-Arctic glaciers and recent climate change, **Quaternary Research** 48, 1-14.

Flather, R.A. (1992) Tidal range and storm surges. In, **Global warming and climate change**. Seminar Report of the Irish Sea Forum, held at University of Liverpool, 26 April 1992. Liverpool University Press, Liverpool, pp 29-40.

Flather, R.A. and Khandker, H. (1993) The storm surge problem and possible effects of sea level changes on coastal flooding in the Bay of Bengal. In, Warrick, R.A. M. Barrow, E. and Wigley, T.M.L. (eds.), **Climate and sea level change: observations, projections and implications**. Cambridge University Press, Cambridge, pp 229245.

Flather, R.A. and Smith, J.A. (1998) First estimates of changes in extreme storm surge elevations due to the doubling of CO2, **The Global Atmosphere and Ocean System** 6, 193-208.

Flather, R.A., Smith, J.A., Richards, J.D., Bell, C. and Blackman, D.L. (1998) Direct estimates of extreme storm surge elevations from a 40-year numerical model simulation and from observations, **The Global Atmosphere and Ocean System** 6, 165-176.

Gumbel, E.J. (1958) **Statistics of Extremes**. Columbia University Press, New York.

IPCC (1996) **Climate change 1995. The Science of Climate Change. Contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change**, Houghton, J.H., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K. (eds.). Cambridge University Press, Cambridge.

Kaas, E. and Andersen, U. (2000) Scenarios for extra-tropical storm and wave activity: methodologies and results. Paper presented at ECLAT-2 workshop EW-3: **Climate Scenarios for Water-Related and Coastal Impacts**. de Bilt (KNMI), the Netherlands, May 10-12th 2000.

Langenberg, H., Pfitzenmayer, A., von Storch, H. and Sündermann, J. (1999) Storm-related sea level variations along the North Sea coast: natural variability and anthropogenic change, **Continental Shelf Research** 19, 821-842.

May, W. (1999) A time-slice experiment with the ECHAM4 A-GCM at high resolution: The experimental design and the assessment of climate change as compared to a greenhouse gas experiment with ECHAM4/OPYC at low resolution, **DMI Scientific Report** 99-2, ISBN 87-7478-389-0.

Pugh, D.T. and Maul, G.A. (1999) Coastal sea level prediction for climate change. In: **Coastal Ocean Prediction, Coastal and Estuarine Studies** 56, 377-404. American Geophysical Union, Washington D.C.

Reistad, M. and Iden, K.A. (1995) Updating, correction and evaluation of a hindcast data base of air pressure, winds and waves for the North Sea, Norwegian Sea and the Barents Sea. **Det Norske Meteorologiske Institutt Tech**. Rep. No.9.

de Ronde, J.G. (1993) What will happen to the Netherlands if sea level rise accelerates? In, Warrick, R.A. M. Barrow, E. and Wigley, T.M.L. (eds.), **Climate and sea level change: observations, projections and implications**. Cambridge University Press, Cambridge, pp 322-335.

Shennan, I., Lambeck, K., Flather, R., Horton, B., McArthur, J., Innes, J., Lloyd, J., Rutherford, M. and Wingfield, R. (2000) Modelling western North Sea palaeogeographies and tidal changes during the Holocene. In, Shennan, I.and Andrews, J. (eds.), **Holocene Land-Ocean Interaction and Environmental Change around the North Sea**. Geological Society, London, Special Publications, 166, 299-319.

Smith, R.L. (1986) Extreme value theory based on the r largest annual events, **Journal of Hydrology** 86, 27-43.

Tawn, J.A. (1988) An extreme value theory model for dependent observations, **Journal of Hydrology** 101, 227-250.

Von Storch, H. and Reichardt, H. (1997) A scenario of storm surge statistics for the German Bight at the expected time of doubled atmospheric carbon dioxide concentration, Journal of Climate 10, 2563-2662.

WASA (1998) Changing waves and storms in the Northeast Atlantic, **Bulletin of the American Meteorological Society** 79(5), 741-760.

Woodworth, P.L. (1990) A search for accelerations in records of European mean sea level, **International Journal of Climate** 10, 129-143.

Woodworth, P.L. (1999) A study of changes in high water levels and tides at Liverpool during the last two hundred and thirty years with some historical background. **Proudman Oceanographic Laboratory Report**, No. 56.

Woodworth, P.L., Tsimplis, M.N., Flather, R.A. and Shennan, I. (1999) A review of the trends observed in British Isles mean sea level data measured by tide gauges, **Geophysical Journal International** 136, 651-670.

Zhang, K., Douglas, B.C. and Leatherman, S.P. (1997) East coast storm surges provide unique climate record. EOS, **Transactions of the American Geophysical Union** 78, 389-397.

Development of Daily Precipitation Scenarios at KNMI

Adri Buishand and Björn Beckmann

Royal Netherlands Meteorological Institute (KNMI), P.O. Box 201, 3730 AE De Bilt, the Netherlands (buishand@knmi.nl and beckmann@knmi.nl)

ABSTRACT

The use of statistical relationships is a noticeable feature of daily precipitation scenarios produced at KNMI. Recently, atmospheric moisture has been included as predictor variable. Separate models are used to describe rainfall occurrence (probability of a wet day) and the wet-day rainfall amounts. Relationships for daily rainfall at Berne (Switzerland) are presented using atmospheric moisture and circulation variables from the NCEP reanalysis data. Perturbation of the observed record and stochastic time series simulations are examined as methods of scenario production. An application is given with data from a time-dependent greenhouse gas forcing experiment using the ECHAM4/OPYC3 model for the periods 1968-1997 and 2070-2099. The estimated changes in the annual and seasonal mean rainfall amounts from the fitted statistical relationships are compared with those in the simulated rainfall of ECHAM4/OPYC3. It is shown that these changes are sensitive to the choice of moisture variables in the statistical relationship for the wet-day precipitation amounts. Besides changes in the mean precipitation amount, the 90th percentile of the distributions of the N-day annual maximum precipitation amounts is considered to assess daily precipitation scenarios. The representation of the coefficient of variation of the wet-day precipitation amount strongly influences the quality of the reproduction of this extreme-value characteristic and its changes.

INTRODUCTION

A daily precipitation scenario is defined here as an artificial time series of daily precipitation that can be used to assess the impacts of increased atmospheric greenhouse gas concentrations. Several methods have been proposed to obtain such time series, ranging from the perturbation of a record of observed precipitation to statistical downscaling techniques using the dependence of local precipitation on large-scale variables. In the latter approach the emphasis has been on the link between local precipitation and atmospheric flow characteristics (Bárdossy and Plate, 1992; Zorita and von Storch, 1999). Although long-term variations in precipitation in the past may be explained by fluctuations in atmospheric circulation, it is questionable whether potential future systematic changes in precipitation resulting from the global warming can be derived from the changes in the atmospheric circulation alone. Various experiments with general climate models (GCMs) suggest that this is not the case (Matyasovszky *et al.*, 1993; Jones *et al.*, 1997; Wilby and Wigley, 1997).

Early work on precipitation scenarios at KNMI focussed on the use of the dependence of precipitation on temperature. This dependence can partly be attributed to the fact that warm air can contain more moisture than cold air. Shower activity also depends on temperature. For De Bilt (the Netherlands) these phenomena can easily be identified by plotting the mean wet-day precipitation amounts versus the daily mean or daily maximum 2-metre temperature (Können, 1983; Buishand and Klein Tank, 1996). However, a similar analysis for some sites in England, Switzerland, Portugal and Italy, showed that the temperature effect on precipitation is often obscured by other meteorological factors (Brandsma and Buishand, 1996). Because the correlation between daily precipitation and temperature is generally weak in the observed data, it is quite difficult to use temperature as a covariate in stochastic models for daily precipitation.

The recent availability of reanalysis data from numerical weather prediction models has offered new opportunities to incorporate upper-air variables in statistical downscaling models. A number of authors (e.g., Crane and Hewitson, 1998; Charles *et al*., 1999) have advocated the use of a measure of upper-air humidity. The correlation between precipitation and atmospheric moisture is generally stronger than that between precipitation and temperature. However, it is not clear which moisture variable is the most appropriate one to use.

Since 1998, KNMI has participated in the European project WRINCLE (Water Resources: the INfluence of Climate change in Europe). Improved statistical downscaling using reanalysis data is an important part of that project. Generalised additive models are used to explore the relationship between daily precipitation and the predictor variables. These models are an extension of the standard linear model for data from a normal distribution, covering both non-linearity and a variety of distributions (Hastie and Tibshirani, 1990). They were successfully applied to describe the dependence of the wet-day precipitation amounts on 2-metre temperature and circulation variables in earlier work (Brandsma and Buishand, 1997). In the WRINCLE project, generalised additive models are also used to describe rainfall occurrence.

This paper presents results for Berne (Switzerland) from the work done under WRINCLE. Results from a time-dependent greenhouse gas forcing experiment of the ECHAM4/OPYC3 model are used to estimate changes in precipitation for 2070-2099. The statistical models for rainfall occurrence and wet-day precipitation amounts are discussed. Reproduction of the annual cycle of precipitation is addressed. Calculation of changes in the annual and seasonal mean precipitation amounts for given changes in the predictors are explained, and methods to construct daily precipitation scenarios are presented.

MODELLING RAINFALL OCCURRENCE

The key parameter in rainfall occurrence modelling is the probability P of a day being wet (here a day with 0.1 mm or more). In the additive logistic model this probability is represented as:

$$\operatorname{logit}(P) = \ln\left(\frac{P}{1-P}\right) = a_0 + \sum_{i=1}^{p} f_i(x_i) \qquad (1)$$

where the $f_i(x_i)$ are arbitrary smooth functions of the predictor variables x_i. The logit transformation ensures that P lies in the interval between 0 and 1. The functions $f_i(x_i)$ have been estimated by the iterative back-fitting algorithm (Hastie and Tibshirani, 1990) using a locally weighted running-line smoother with a span of 0.5 (the proportion of the data entered in the local fit). To exclude free constants the fitted values for each function $f_i(x_i)$ are adjusted to average zero. In the case of a linear function, this implies that, $f_i(x_i) = a_i(x_i - \bar{x}_i)$ where a_i is a regression coefficient and $\bar{x}_i$ is the average of the variable x_i.

Data for the 30-year period 1968-1997 have been analysed. The predictor variables were derived from 6-hourly analyses at 2.5° resolution in the NCEP data set (Kalnay *et al*., 1996). Daily averages were calculated from the four consecutive values at 12, 18, 00, 06 UTC. These hours are within the sampling interval of a daily precipitation measurement. It emerged that the daily averages of the predictors explained a much larger proportion of the daily precipitation variance than the 00 UTC or 12 UTC value alone.

Akaike's information criterion was used to find a suitable set of predictor variables (Hastie and Tibshirani, 1990). A predictor variable was only entered into the model if the correlation with other predictors was less than 0.6. This led to a model with seven predictors (in decreasing order of statistical significance): the relative humidity at 700 hPa (*rh*), the south component of the geostrophic wind (*v*), the west component of the geostrophic wind (*u*), the baroclinicity at 700 hPa (*b*), the 1000-500 hPa thickness (*thick*), the height of the 1000 hPa level (*h*), and the geostrophic relative vorticity (ζ). Both the velocity components and the vorticity were derived from the 1000 hPa heights at the grid points nearest to Berne. The baroclinicity was taken as the absolute value of the temperature gradient at the 700 hPa level. The choice of relative humidity as a moisture variable instead of a measure of absolute humidity is in agreement with Charles *et al.* (1999). Although the amount of rain depends on the absolute humidity, the probability of rain is related more to the degree of saturation. GCM simulations suggest that the changes in the relative humidity of a warmer world are much less significant than those in the absolute humidity (Del Genio *et al.*, 1991).

The model explains 47% of the variance in daily rainfall occurrence. The functions $f_1(rh)$, $f_4(b)$ and $f7(\zeta)$ were taken as linear. Figure 1 shows the estimates of $f_1(rh)$ and $f_2(v)$.The rainfall probability on the right-hand side of each panel is given by:

$$P = \frac{1}{1 + \exp\left[-a_0 - f_i(x_i)\right]} \qquad (2)$$

As expected P increases with increasing rh. Furthermore, P tends to be high if v is negative (northerly flow) and low if v is positive (southerly flow).

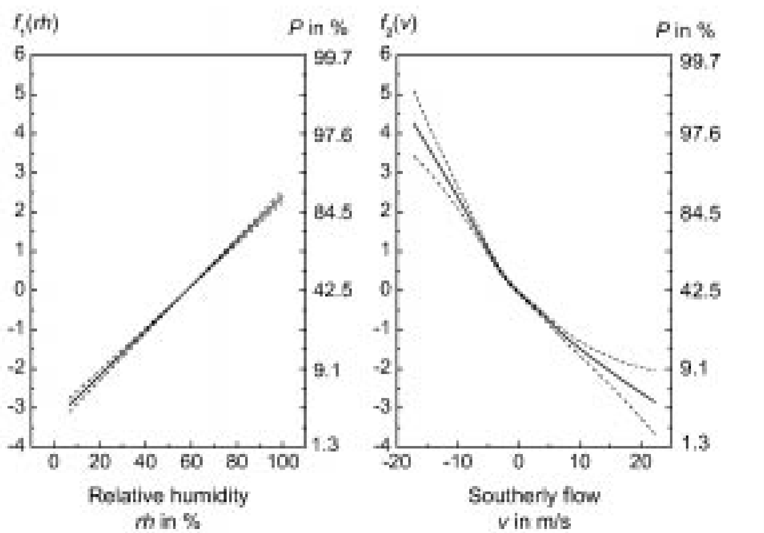

Figure 1. Estimates of the functions $f_1(rh)$ and $f_2(v)$ in the additive logistic model for rainfall occurrence at Berne. The dashed lines mark pointwise 2 x standard-error bands.

MODELLING RAINFALL AMOUNT

The generalised additive model with constant coefficient of variation and log link function has been adopted to analyse the wet-day precipitation amounts R at Berne. The log link function specifies the mean of R as:

$$E(R) = \exp\left[a_0 + \sum_{i=1}^{p} f_i(x_i)\right] \qquad (3)$$

E(R) cannot become negative with this representation, and the log link is also convenient for scenario construction (see the section below on 'Time series perturbation'). A constant coefficient of variation implies that the variance of R increases with the mean, which for wet-day precipitation is much more realistic than the more familiar assumption of a constant variance. As in Equation (1) the $f_i(x_i)$ are arbitrary smooth functions of the predictor variables x_i.

The predictor variables were the same as those chosen for modelling rainfall occurrence, except that *rh* and *thick* were replaced by the specific humidity at 700 hPa (*q*). The predictor variables can be ranked in decreasing order of statistical significance as: *q, v, b, h, u* and ζ. The functions $f_2(v)$, $f_3(b)$ and $f_6(\zeta)$ were taken as linear. Figure 2 presents the estimates of $f_1(q)$ and $f_2(v)$. The rainfall amount on the right-hand side of each panel is given by:

$$R = \exp[a_0 + f_i(x_i)] \tag{4}$$

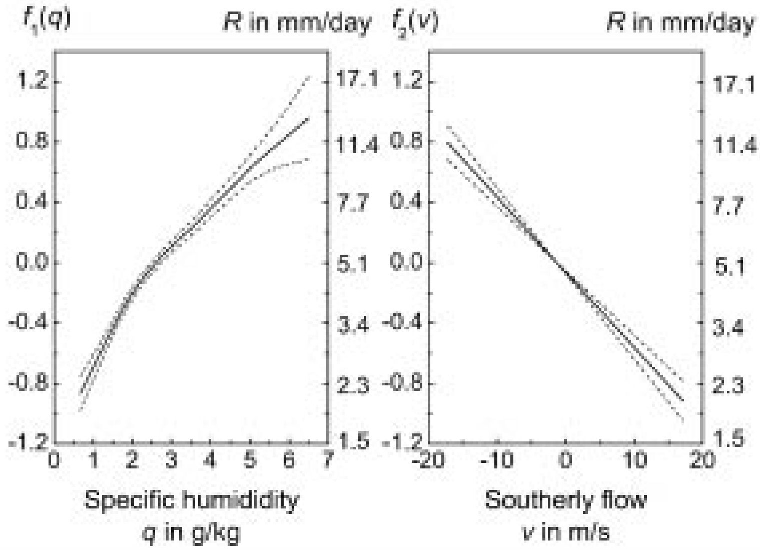

Figure 2. Estimates of the functions $f_1(q)$ and $f_2(v)$ in the generalised additive model for wet-day rainfall at Berne. The dashed lines mark pointwise 2 x standard-error bands.

From the figure it follows that E(*R*) increases with increasing *q*. As in Figure 1, the function $f_2(v)$ decreases with increasing *v*. Estimates of the functions $f_i(x_i)$ for *h*, *u*, ζ and *b* also show similar behaviour for rainfall occurrence and rainfall amount.

The model explains only 21% of the daily variance. A small improvement of 2% is possible by replacing *q* with *rh* and precipitable water (*pw*). However, the latter is usually not available in GCM output.

REPRODUCTION OF THE ANNUAL CYCLE

The relationships presented in the previous two sections were assumed constant over the year. A quick test of this assumption is possible by comparing the observed rainfall probability and mean wet-day precipitation amount for each calendar month with that expected from the model. The expected monthly mean wet-day precipitation amount is easily obtained by replacing the observed precipitation amount of each wet day with its estimate from Equation (3).

Figure 3 shows that the models describe the observed annual cycles well. For the rainfall amount, this is largely attributed to temperature dependent predictors like *q* or *pw*. Nevertheless, for some calendar months the discrepancies are about twice the standard errors of the observed monthly means. For both rainfall occurrence and the wet-day precipitation amount a small systematic overestimation is found for spring and an underestimation for the second half of the year. A two-sided *t*-test on the differences between the observed and modelled values shows that several of these discrepancies are statistically significant at the

5% level [1]. Seasonally varying relationships may reduce the observed discrepancies. The discrepancies could, however, also be regarded as a warning that a statistical model with six or seven predictor variables only provides a crude description of daily precipitation.

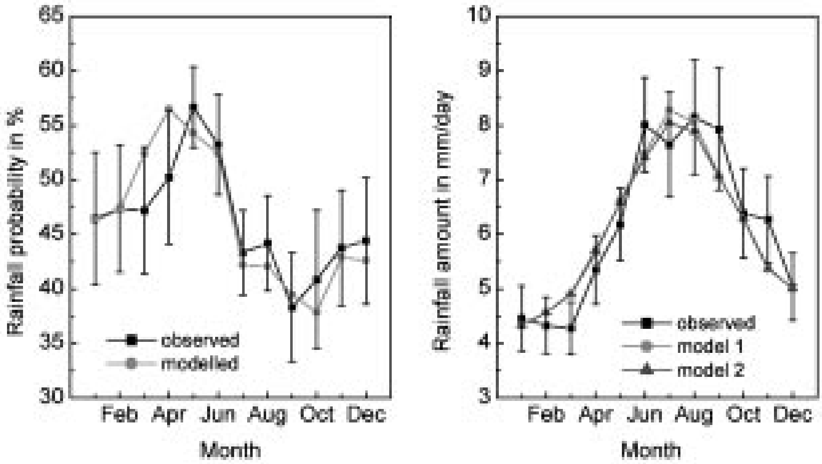

Figure 3. Observed and modelled annual cycle of daily rainfall probability (left panel) and mean wet-day precipitation amount (right panel) at Berne. In model 1 atmospheric moisture is represented as specific humidity, and in model 2 as relative humidity and precipitable water. The error bars indicate twice the standard error of the observed means.

The observed monthly mean wet-day probabilities explain only 1% of the variance of daily rainfall occurrence. For the monthly mean wet-day precipitation amounts, the proportion of explained variance is 3%. These figures are small compared to those for the fitted generalised additive models.

CHANGES IN ANNUAL AND SEASONAL MEANS

For given values of the predictor variables the expected annual number of wet days N_{wet} and the expected annual total rainfall R_{tot} can be easily calculated as:

$$N_{\text{wet}} = \sum_t P_t \, / J \tag{5}$$

$$R_{\text{tot}} = \sum_t (P_t R_t) / J \tag{6}$$

where P_t is the probability of precipitation for day t, R_t is the expected precipitation amount for day t given that it is wet, and J is the number of years. The summation is over all days in the period concerned. Seasonal means are obtained in a similar manner by restricting the summation over the season of interest. For the period 1968-1997 the estimated mean annual number of wet days from Equation (5) matches that of the observed data; for Equation (6) the differences between the estimated and observed annual means are not more than 2%. Differences are largely due to the fact that the model fitted to the wet-day precipitation amounts is also applied to the dry days.

In this section, the annual and seasonal means at Berne are derived for the potential future climate of 2070-2099, using the results from the time-dependent greenhouse gas (GHG) forcing experiment with the coupled global atmosphere-ocean model ECHAM4/OPYC3 of the Max-Planck Institute for Meteorology and the Deutsche Klimarechenzentrum (both in Hamburg). A steadily growing concentration of greenhouse

[1] For rainfall occurrence, differences between the monthly values were considered to avoid problems of autocorrelation, whereas for the wet-day precipitation amounts the test was performed on the differences of the daily values

gases, as observed between 1860 and 1990 and according to IPCC scenario IS92a from 1990 onward, was prescribed in that experiment (Arpe and Roeckner, 1999; Roeckner *et al.*, 1999). Figure 4 presents the annual means of *q*, *thick*, *u* and *v* for the grid point nearest to Berne.

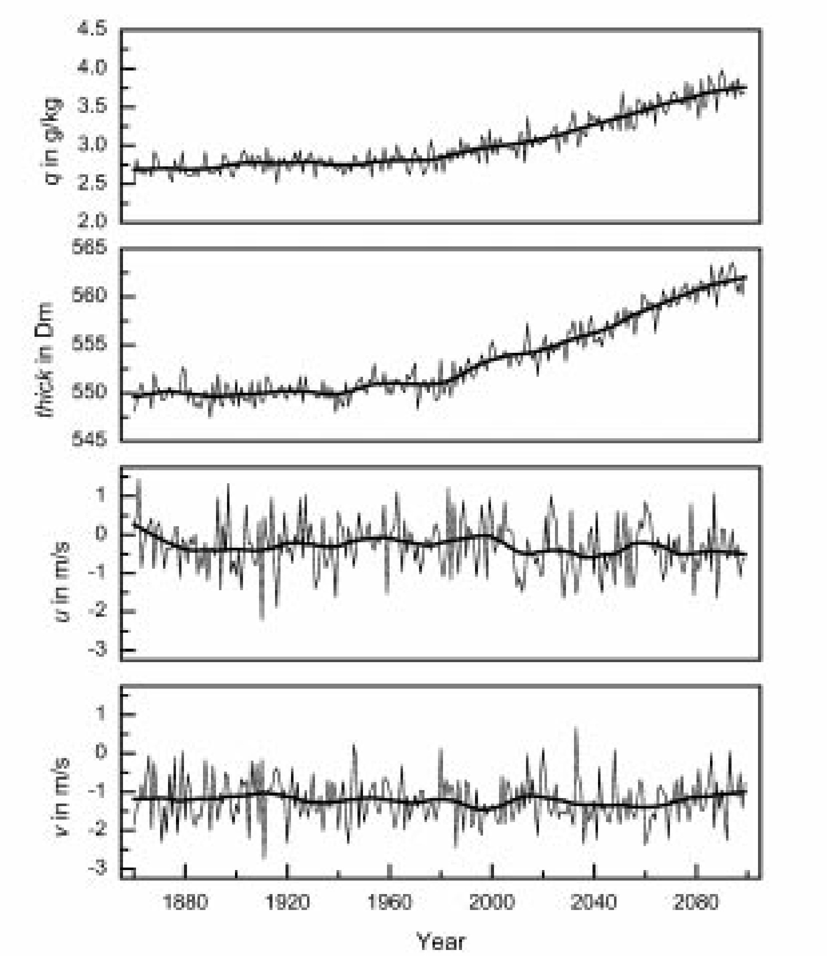

Figure 4. Temporal evolution of the annual mean values of the specific humidity at 700 hPa (*q*), the 1000-500 hPa thickness (*thick*), and the *u* and *v* components of the geostrophic flow (derived from 1000 hPa heights) over Switzerland in the time-dependent GHG forcing experiment with the ECHAM4/OPYC3 model (grid point 46.04ºN, 8.44ºE). The bold line is a weighted regression smoothed for each year using data from the 30 nearest years.

The observed increases in specific humidity and thickness are related to the increase in temperature (4.5 °C for the next hundred years over Switzerland). There is little change in relative humidity (not shown). The summer means of the *u*-velocities show a clear decrease during the period 1860-2099, which is to some extent masked in Figure 4 by the winter values. The *v*-velocities in the summer half of the year are relatively high during the last 30 years of the simulation run.

Monthly values from the GHG experiment were made available. To estimate the mean number of wet days N^*_{wet} and the mean annual or seasonal amount R^*_{tot} at the end of the 21st century for Berne, Equations (5) and (6) were applied to the perturbed predictor variables:

$$x^*_{ti} = x_{ti} + \Delta x_i \qquad (7)$$

where $\mathbf{x}_{ti}$ is the value of the *ith* predictor for day *t* in the period 1968-1997 and $\Delta\mathbf{x}_i$ is the change in the mean of $\mathbf{x}_i$ between the periods 1968-1997 and 2070-2099 in the GHG experiment. Different values of $\Delta\mathbf{x}_i$ were used for the winter half (October – March) and summer half (April – September) of the year[2]. In order to make extrapolations beyond the range of the observed values $\mathbf{x}_{ti}$, the smooth estimates of non-linear functions in Equations (1) and (3) were replaced by piecewise linear functions. For instance, the non-linearities in $f_2(v)$ in Figure 1 and $f_1(q)$ in Figure 2 could be approximated as:

$$f_i(x_i) = a_i + b_i x_i + c_{1i}(x_i - s_{1i})_+ \tag{8}$$

Here, $(\mathbf{x}_i - s_{1i})_+ = \mathbf{x}_i - s_{1i}$ if $\mathbf{x}_i > s_{1i}$ and 0 otherwise. The location of the knot s_{1i} was chosen at –2.1 m s^{-1} for $f_2(v)$ in Figure 1 and at 2.25 g/kg for $f_1(q)$ in Figure 2.

The results are summarised in Table 1. The decrease in the number of wet days is mainly due to the increased 1000-500 hPa thickness in the warmer climate and the changes in the west and south components of the flow in the summer half of the year. The mean winter rainfall amount increases because of the increase in specific humidity. This effect is counterbalanced in the summer half of the year by changes in *u*, *v* and *thick*. There is a marked difference between a model for the wet-day precipitation amounts that uses *q* as a measure of humidity (model 1) and a model that uses *rh* and *pw* (model 2). The changes in the simulated mean precipitation amounts of the ECHAM4/OPYC3 model are approximately in the same range as those derived from the statistical models.

	Year	Winter	Summer
Number of wet days			
Observed	169	82	87
Change (%)	–15	–9	–21
Rainfall amount			
Observed (mm)	1040	417	623
Change (%)			
• Model 1	2	10	–3
• Model 2	–3	3	–7
• ECHAM4/OPYC3	2	4	0

Table 1. Observed mean number of wet days and mean rainfall amounts at Berne, and their estimated changes for the end of the 21st century (in model 1 atmospheric moisture is represented as specific humidity in the relationship for the wet-day precipitation amounts, and in model 2 as relative humidity and precipitable water).

DAILY PRECIPITATION SCENARIOS

Two different methods of scenario construction are presented: (1) perturbation of the observed daily precipitation record at Berne, and (2) conditional simulation of daily precipitation using a Monte Carlo method. The two methods are compared by computing the 90th percentile of the distributions of the *N*-day annual maximum precipitation amounts (‘10-year event’). Only one model for the wet-day precipitation amount is considered, namely that with specific humidity.

[2] However, the daily values of the relative humidity were derived from the perturbed daily values of the specific humidity and temperature at 700hPa. For the application of the model of rainfall amount with *rh* and *pw* as moisture variables, the changes in *pw* were derived from a regression of the seasonal means of *pw* on those of *q*.

Time series perturbation

Daily precipitation scenarios have often been obtained by multiplying the observed precipitation amounts by a constant factor, for example, the ratio between the seasonal means of the future and present climate in a GCM experiment. The mean number of wet days then remains unaltered in the future climate. In order to produce a scenario with less wet days, Klein Tank and Buishand (1995) suggested randomly replacing wet days by dry days using the probabilities of precipitation from the logistic model. Let ΔM denote the expected decrease in the number of wet days from Equation (5). To achieve such a decrease in the future climate, a wet day τ is replaced by a dry day with probability Π_τ, given by:

$$\Pi_\tau = \Delta M \left(1 - P_\tau^*\right)^\theta / \sum_\tau \left(1 - P_\tau^*\right)^\theta \qquad (9)$$

where, P_τ^* is the probability of rain in the future climate. Here, the summation is over all wet days in the observed record. The parameter θ was taken as 1 by Klein Tank and Buishand (1995). The probability Π_τ then increases linearly with the probability $1 - P^*_\tau$ that day τ is dry. To ensure that $\Pi_\tau < 1$ for all τ, ΔM may not exceed $\sum_\tau \left(1 - P_\tau^*\right)^\theta$

Precipitation amounts on the remaining wet days are then scaled by the ratio between the expected values

$$R_t^* / R_t = \exp\left\{ \sum_{i=1}^{p} \left[f_i\left(x_i^*\right) - f_i\left(x_i\right) \right] \right\} \qquad (10)$$

Because of the log-link function in the model for the wet-day precipitation amounts the adjustment only depends on the changes in the $f_i(x_i)$. The scaling factor reduces to a constant if these functions are linear.

Although the method reproduces the changes in the mean number of wet days in Table 1, this is not necessarily true for the changes in mean annual and seasonal precipitation. The latter are influenced by the choice of θ in Equation (9). For Berne, a reasonable agreement with the estimated changes in mean precipitation amounts could be achieved by setting θ equal to 1 for the winter half of the year and 0.5 for the summer half of the year.

Conditional simulation

Here, the term conditional simulation implies that daily precipitation is generated conditional on the values of the predictor variables. This can be undertaken for both present and future climates.

For present climate conditions, a synthetic sequence can be generated as follows. For each day t a binary variable Y_t is drawn, taking the value 0 (dry day) with probability $1 - P_t$ and 1 (wet day) with probability P_t. In the latter case a random amount is generated as:

$$R_{\mathrm{sim},t} = \omega_t R_t \qquad (11)$$

where R_t is the expected mean precipitation amount for day t from Equation (3) and ω_t is a positive random variable with mean 1, for example,

$$\omega_t = \frac{1}{\kappa} \mathrm{Gam}(\kappa) \qquad (12)$$

with Gam(κ) a standard gamma variable with shape parameter κ. The gamma distribution has often been used in unconditional simulations of daily precipitation (Wilks and Wilby, 1999). It is also the standard distribution in generalised additive models with constant coefficient of variation *CV*. The following relationship exists between κ and *CV:*

$$\kappa = 1 / CV^2 \tag{13}$$

It is therefore possible to preserve both the mean and *CV* of the wet-day precipitation amounts.

The simulation of future climates is undertaken in the same way. The expected changes in the mean number of wet days and the annual and seasonal mean precipitation amounts are the same as those derived from Equations (5) and (6). However, the annual cycles of the monthly means of the generated sequences show the same discrepancies as that observed in Figure 3. In addition, extreme-value properties may not be preserved, as demonstrated in the following section.

Evaluation based on *N*-day annual maximum precipitation amounts

Percentiles of the distribution of annual maximum precipitation amounts over different time-intervals have often been used in hydrological design. From an engineering point of view, it is therefore more meaningful to study these percentiles than the frequency distribution or exceedance frequencies of the daily precipitation amounts. Here the 90th percentile of the distribution of the *N*-day annual maximum precipitation amounts is considered for *N* = 1, 3, 10 and 30. In the hydrological literature, this percentile is usually denoted as the 10-year event because it is exceeded on average once in 10 years. The 10-year events were derived by fitting Gumbel distributions to the annual maxima using probability-weighted moments (Landwehr *et al.*, 1979).

Table 2 compares the 10-year events of simulated sequences for present conditions with those of the observed data at Berne. In the method of Hay *et al.* (1991) ω_t is generated as the product of a uniformly distributed random number between 0 and 2 and a standard exponential variable. The extremes are too large in the resulting scenario, mainly because *CV* is not preserved (CV^2 is always 5/3 in that method). The 10-year events are still too large if ω_t is generated from a gamma distribution with the same *CV* as that of the observed data.

Method of Generating ω_t	*CV*	10-year event (mm) *N* = 1	*N* = 3	*N* = 10	*N* = 30
Hay et al. (1991)	1.29	128	184	269	381
Gamma	1.16	96	133	218	328
Gamma	variable	70	106	188	299
Observed	1.16	65	99	149	258

Table 2. Estimates of the 90th percentile (10-year event) of the *N*-day annual maximum precipitation amounts at Berne from the observed data and simulated sequences (average of 20 runs for each simulation method).

The problem is that *CV* decreases with the expected wet-day precipitation amount R_t (Figure 5). A marked improvement in the reproduction of the 10-year events is achieved by incorporating this dependence in the simulation algorithm (Table 2). The smooth curve in Figure 5 was approximated by a piecewise linear function like the non-linear functions in the models for *P* and *R*.

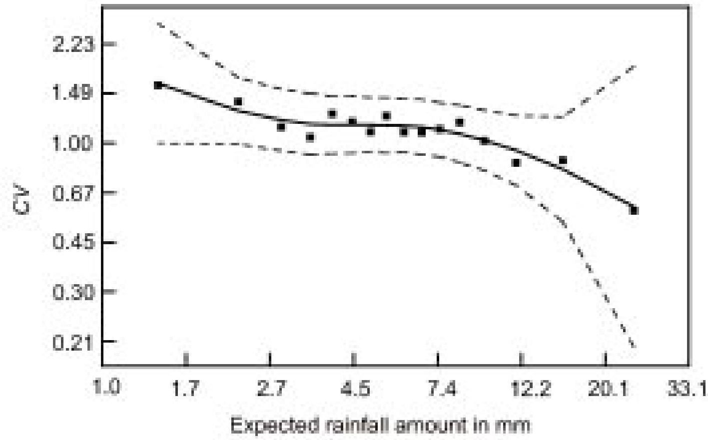

Figure 5. Coefficient of variation *CV* of the wet-day rainfall amounts as a function of the expected rainfall amount from Equation (3). The solid line is obtained using a locally weighted running line smoother with a span of 0.5 mm; the dashed lines mark pointwise 2 x standard error bands.

Table 3 presents the estimated changes in the 10-year events between the periods 1968-1997 and 2070-2099. All scenarios show an increase in this extreme-value characteristic. In contrast to the change in the mean annual amount, the effect of the higher wet-day precipitation amounts resulting from the increase in specific humidity now dominates that of the decrease in the number of wet days. For time series perturbation, the changes are comparable with those for conditional simulation with a constant CV. Smaller changes are found if the decrease of *CV* with R_t is taken into account, in particular for $N = 1$ and $N = 3$.

Change in 10-year event (%)				
Scenario	$N = 1$	$N = 3$	$N = 10$	$N = 30$
Perturbed record	15	16	11	9
Simulated sequences, constant *CV*	15	14	12	11
variable *CV*	6	7	7	8

Table 3. Percentage changes in the 10-year event of the N-day precipitation amounts at Berne for different scenarios for the end of the 21st century (averages of 20 runs for each simulation method and ω_t generated from a gamma distribution).

Both the reproduction of the 10-year events and their changes in a potential future climate are thus influenced by the representation of *CV*. The crucial aspect is the change in *CV* for large values of R_t and Figure 5 shows that this change is quite uncertain. The estimated *CV* for days with $R_t > 20$ mm was 0.58, which is considerably lower than the values for other days with large expected rainfall amounts. This low value of *CV* is accompanied by a strong over-prediction of the true wet-day precipitation amounts by the fitted statistical model (Figure 6). A similar discrepancy was found for Neuchâtel, but it was less evident for a third station analysed, Payerne. A crude way to eliminate the bias at large values of R_t is to remove the baroclinicity from the statistical model for the wet-day precipitation amounts (Figure 6). This also leads to a less rapid decrease in *CV* for large values of R_t than that observed in Figure 5. The use of alternative expressions for $f_3(b)$ was not successful.

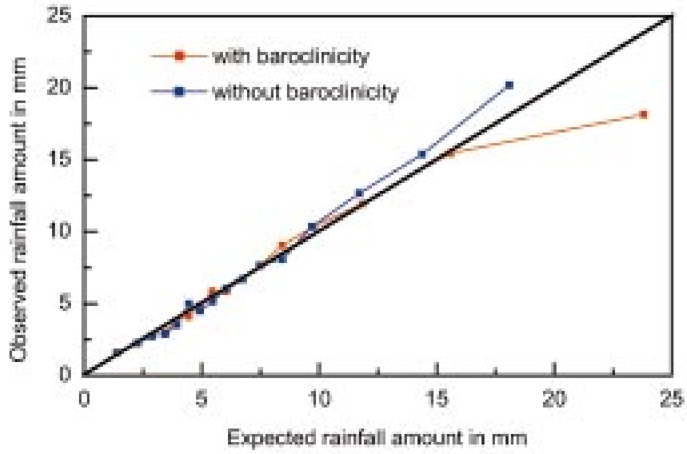

Figure 6. Observed mean wet-day rainfall amounts versus the expected wet-day rainfall amounts from the fitted relationships with (red) and without baroclinicity (blue).

Table 4 presents the changes in the 10-year events for the case that there is no baroclinicity in the statistical models for rainfall occurrence and rainfall amount. The differences between the scenarios are smaller than those shown in Table 3.

	Change in 10-year event (%)			
Scenario	***N* = 1**	***N* = 3**	***N* = 10**	***N* = 30**
Perturbed record	12	9	9	6
Simulated sequences, constant *CV*	13	12	8	5
variable *CV*	10	12	6	3

Table 4. Same as Table 3 but now for statistical models without baroclinicity as predictor variable.

CONCLUSIONS

Generalised additive models have been used at KNMI to explore the dependence of daily rainfall on other meteorological variables. Within this modelling framework, it is convenient to analyse rainfall occurrence and wet-day rainfall amounts separately. In this paper, daily rainfall at Berne and upper air variables from the NCEP reanalysis data were considered. Relative humidity at 700 hPa was used as a moisture variable in the model for rainfall occurrence, whereas for the description of the wet-day rainfall amounts a measure of the absolute humidity was included. The magnitude of the changes in precipitation in a potential future climate proved to be sensitive to the choice of the latter. Small discrepancies in the modelled annual cycles of rainfall occurrence and the mean wet-day rainfall amounts were observed. Possible non-homogeneities in the NCEP data set and biases in the GCM output were not addressed. In particular, the quality of moisture variables requires more attention.

Despite many queries regarding the potential benefits of statistical downscaling procedures, the fitted relationships produced plausible estimates of changes in mean precipitation amounts and the 10-year events of the *N*-day precipitation amounts at the end of the 21st century, using results from the GHG forcing experiment of the ECHAM4/OPYC3 model for the periods 1968-1997 and 2070-2099. The observed daily precipitation was perturbed by replacing a proportion of the wet days by dry days and scaling the amounts on the remaining wet days. The estimated changes in the 10-year events of the *N*-day precipitation amounts with this perturbation method agreed quite well with those obtained from conditional simulation of daily rainfall sequences provided that the wet-day precipitation amounts have constant *CV*. Smaller changes were obtained if *CV* varies with the expected wet-day precipitation amount R_t in the simulation algorithm. However, this is partly caused by a rapid decrease in *CV* for larger values of R_t, resulting from a bias in the statistical model for wet-day precipitation. Assumptions influencing the magnitude of large precipitation amounts should be carefully checked if extreme-value properties are of interest.

ACKNOWLEDGEMENTS

The authors thank H.Thiemann and M.Lautenschlager of the Deutsche Klimarechenzentrum (DKRZ), Hamburg for their efforts to make the ECHAM4/OPYC3 data available. The daily rainfall data for Berne were provided by the Swiss Meteorological Institute, Zürich. The WRINCLE project is in part supported by the EU Environment and Climate Research Programme (contract: ENV4-CT97-0452, Climate and Natural Hazards).

REFERENCES

Arpe, K. and Roeckner, E. (1999) Simulation of the hydrological cycle over Europe: Model validation and impacts of increasing greenhouse gases, **Advances in Water Resources** 23, 105-119.

Bárdossy, A. and Plate, E.J. (1992) Space-time model for daily rainfall using atmospheric circulation patterns, **Water Resources Research** 28, 1247-1259.

Brandsma, T. and Buishand, T.A. (1996) KNMI contribution to the European project POPSICLE, **Technical Report TR-194, Royal Netherlands Meteorological Institute**, De Bilt, 44 pp.

Brandsma, T. and Buishand, T.A. (1997) Statistical linkage of daily precipitation in Switzerland to atmospheric circulation and temperature, **Journal of Hydrology** 198, 98-123.

Buishand, T.A. and Klein Tank, A.M.G. (1996) Regression model for generating time series of daily precipitation amounts for climate change impact studies, **Stochastic Hydrology and Hydraulics** 10, 87-106.

Charles, S.P., Bates, B.C., Whetton, P.H. and Hughes, J.P. (1999) Validation of downscaling models for changed climate conditions: case study of southwestern Australia, **Climate Research** 12, 1-14.

Crane, R.G. and Hewitson, B.C. (1998) Doubled CO2 precipitation changes for the Susquehanna basin: down-scaling from the Genesis general circulation model, **International Journal of Climatology** 18, 65-76.

Del Genio, A.D., Lacis, A.A. and Ruedy, R.A. (1991) Simulations of the effect of a warmer climate on atmospheric humidity, **Nature** 351, 382-385.

Hastie, T.J. and Tibshirani, R.J. (1990) Generalized additive models. Chapman and Hall, London, 335 pp.

Hay, L.E., McCabe, G.J., Wolock, D.M., and Ayers, M.A. (1991) Simulation of precipitation by weather type analysis, **Water Resources Research** 27, 493-501.

Jones, R.G, Murphy, J.M., Noguer, M. and Keen, A.B. (1997) Simulation of climate change over Europe using a nested regional-climate model. II: Comparison of driving and regional model responses to doubling of carbon dioxide, **Quarterly Journal of the Royal Meteorological Society** 123, 265-292.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgens, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R. and Joseph, D. (1996) The NCEP/NCAR 40-year reanalysis project, **Bulletin of the American Meteorological Society** 77, 437-471.

Klein Tank, A.M.G. and Buishand, T.A. (1995) Transformation of precipitation time series for climate change impact studies, **Scientific Report WR 95-01, Royal Netherlands Meteorological Institute, De Bilt**, 63 pp.

Können, G.P. (ed.) (1983) **Het weer in Nederland**. Thieme, Zutphen, 143 pp.

Landwehr, J.M., Matalas, N.C. and Wallis, J.R. (1979) Probability weighted moments compared with some traditional techniques in estimating Gumbel parameters and quantiles, **Water Resources Research** 15, 1055-1064.

Matyasovszky, I., Bogárdi, I., Bárdossy, A., Duckstein, L. (1993) Space-time precipitation reflecting climate change, **Hydrological Sciences Journal** 38, 539-558.

Roeckner, E., Bengtsson, L., Feichter, J., Lelieveld, J. and Rodhe,H. (1999) Transient climate change simulations with a coupled atmosphere-ocean GCM including the tropospheric sulfur cycle, **Journal of Climate 12, 3004-3032.**

Wilby, R.L. and Wigley, T.M.L. (1997) Downscaling general circulation model output: a review of methods and limitations, **Progress in Physical Geography** 21, 530-548.

Wilks, D.S. and Wilby, R.L. (1999) The weather generation game: a review of stochastic weather models, **Progress in Physical Geography** 23, 329-357.

Zorita, E. and von Storch, H. (1999) The analog method as a simple statistical downscaling technique: comparison with more complicated methods, **Journal of Climate** 12, 2474-2489.

Working Groups

page numbers

Working Group 1A

Needs and Availability of Climate Scenarios for Hydrological Impacts

Participants: András Bárdossy, Elaine Barrow, Adri Buishand, Timothy Carter, João Corte-Real, Martin Dubrovsky, Linda Mortsch, Mark New, Serge Planton, Andreas Schumann, UweUlbrich, David Viner (chair), Rob Wilby (rapporteur)

Report by: Rob Wilby

Terms of Reference

The Working Group was given a series of issues to discuss and decided to address the following specific questions:

- What are the minimal climate data requirements for hydrological impact assessment?
- Do global–scale hydrological assessments provide useful insights?
- Can more 'realistic' hydrological scenarios be generated?
- What constitutes a 'dangerous' climate-change scenario?

A further aim was to identify clear recommendations for future research and policy. These outcomes are listed in the final section of this report.

What are the Minimal Climate Data Requirements?

As a starting point, the group was provided with a list of daily mean variables from the HadCM3 experiment that are currently available to the community through the Climate Impacts LINK Project (see Table 1).

Specific Humidity 1.5m	Wind Speed 10m	Soil Moisture Content
Snow amount	Large Scale Rainfall Rate	Geopotential Heights
Mean Sea Level Pressure	Total Downward Surface Short Wave Flux	Large Scale Snowfall Rate
Surface Heat Flux (Sensible Heat)	Convective Rainfall Rate	Net Downward Short Wave Flux
Surface Moisture Flux (Evaporation)	Convective Snowfall Rate	Relative Humidity at all Pressure Levels
Temperature 1.5m (Mean, Max, Min)	Surface Runoff	Mean Temperature at all Pressure Levels
Relative Humidity 1.5m	Sub-surface Runoff	Total Cloud in Long Wave Radiation

Table 1. Daily mean variables from HadCM3 held by the Climate Impacts LINK Project.

In order to maximise the value of such data for hydrological impact assessment the following practical issues were noted:

- There should be timely and cost free access to archived climate model output. Ideally, climate data should be consistent between ensembles, held in a unified format or accessible through user–friendly archive interfaces (as in the case of the Data Distribution Centre). However, it is appropriate that the use of the data should be monitored and properly acknowledged (as in the case of LINK data).

- Climate model output should be available on a daily basis, for ensemble runs, different emissions scenarios, and ideally for several different models. The impacts community should also have some mechanism for requesting data that are not routinely included in standard parameter lists (like Table 1).

- High quality meta–data should be provided to precisely define all archived data. For example, soil moisture was identified as a particularly ambiguous variable. Confidence measures should also be provided for all climate-model fields, although it was recognised that a universally acceptable set of diagnostics would be difficult to define.

- Baseline climate and non–climatic data sets (such as emissions scenarios or global vegetation distributions) should be available at spatial and temporal scales comparable to climate model output.

- Bench–mark hydrological data sets should be established and/or key river basins identified to facilitate inter–comparison studies. Precipitation, evapotranspiration, and snowmelt/snow–cover were identified as the most critical hydrological variables. However, it was also recognised that the most sensitive components are region and problem specific.

Do Global–Scale Hydrological Assessments Provide Useful Insights?

The group next considered the scientific merit and policy value of coarse (spatial and temporal) resolution, global–scale hydrological assessments. Lists of arguments for and against such studies were assembled.

Arguments in favour:

- Global studies can help identify regional ‘hot spots’ for more detailed case study.

- Hydrological feedbacks to the climate system (such as soil-moisture changes) are currently represented only at global scales.

- Global studies help elucidate the wider significance of climatic versus non–climatic factors to regional water–balances.

- Global studies provide results of complex issues in a format that is more easily understood by policy makers.

- Global patterns of hydrological stress help inform policy negotiations and highlight the fact that water is a global security issue.

Arguments against:

- Socio-economic units are more informative scales for hydrological impact assessment.

- Global studies can conceal significant regional or sub-grid-box scale variations.

- Hydrological extremes (such as floods) are not properly addressed by the time–scales (typically monthly, seasonal or annual) of global studies.

- A wider issue of semantics: global studies address changes in water–balance rather than catchment hydrology per se.

Can More 'Realistic' Hydrological Scenarios be Generated?

Given the aforementioned limitations of global-scale water-balance studies the group then discussed ways in which more realistic hydrological scenarios might be generated. The following points were identified:

- Once again, there was a consensus surrounding the need for high quality meta-data since realistic hydrological scenarios presuppose that the observational data (used for statistical downscaling and hydrological model calibration) are equivalent to the climate model data used for future scenario generation.

- There is also a need for common diagnostics with which to verify hydrological 'realism' and to inter-compare alternative hydrological models. The chosen diagnostic should incorporate some level of physical understanding, for example, modelled dry-spell persistence as a diagnostic for hydrological drought. Diagnostics should also distinguish between point and areal extremes.

- Generating realistic hydrological extremes (i.e., droughts and floods) presupposes the existence of long, homogeneous data sets of daily resolution or less. Palaeo data may provide insight into the frequency and severity of extremes during periods of rapid climate change, as well as over longer time horizons (centuries to millennia, rather than years to decades).

- An understanding of the physical mechanisms under-pinning hydrological extremes in global models should be sought and compared to those acting in the real world. This will favour the selection of the most appropriate climate model output(s) for more detailed hydrological studies. Rather than using continuous hydrological series it may be better to composite hydrological data using physically sensible climate variables.

- Stochastic weather generators should be used for hydrological risk analysis.

What Constitutes a 'Dangerous' Climate Change Scenario?

Finally, the working group considered the factors that define a dangerous climate change:

- It was concluded that the definition of system vulnerability is stakeholder specific. By involving stakeholders in the design of impact experiments, studies will have greater relevance to mitigation discussions. Stakeholders should present very specific questions to the climate modelling community.

- There are widely differing definitions of risk according to the chosen (scientific, economic, political or environmental) perspective. Probabilistic statements are often of greater value than estimates of mean conditions.

- There is a place for stakeholder 'visioning' exercises in the assessment of dangerous climate changes.

Main Recommendations

From the Working Group discussions it was possible to identify a number of key recommendations to address the data needs of the hydrological impacts community:

- The European Commission should establish a 'European Climate Data Centre (ECDC)' to facilitate the efficient archiving and distribution of observed and climate model data. By assembling a central data bank there may be long-term gains in project efficiency (in terms of time and cost savings) through the exchange of generic data sets amongst groups. The ECDC should also develop bench–mark data sets and establish a common protocol for data formatting, meta-data and archiving. This would allow more time to be spent on impact assessment and less time spent on data processing.

- There is an urgent need for inter-comparisons of different downscaling methods, hydrological models and impact scenarios using generic data sets or bench-mark data. This presupposes the existence of widely accepted diagnostics for model validation. In turn, these diagnostics should have a physically meaningful basis — the 'mean' statistic alone is seldom adequate.

- Hydrological impact assessments should be stakeholder driven. This will inevitably favour a 'bottom-up' approach as well as a greater emphasis on the most significant (local- to regional-scale) physical processes. By inverting the problem and identifying critical processes/limiting factors, the impacts community is better placed to ask more specific questions of the climate modelling community. At the same time, the climate modelling community should continue to evaluate the realism of large-scale model processes compared to real world processes.

Working Group 1B

Climate Needs and Availability of Climate Scenarios for Coastal Impact Assessments

Participants: Thomas Beckmann (chair), Henk van den Brink, Iain Brown, Richenda Connell, DennisDoortmont, Roger Flather, Eigil Kaas, Jason Lowe, Miroslaw Mietus, Kathy McInnes, John de Ronde (rapporteur) and Joost de Wolff

Report by: John de Ronde

INTRODUCTION

A large proportion of the world's population lives in coastal and deltaic areas and it is expected that this will increase in the future. About 10 % of the coastal area has a population density of over 100 inhabitants per square kilometre. At high tide, large parts of these areas are located only a few meters above sea level. Shallow coastal waters represent the richest areas of the world's seas, both with regard to biomass and in their wealth of species. So coastal impacts due to climate change are of great global importance.

The main task of the Coastal Impacts working group was to investigate and describe the minimum scenario requirements of coastal impact studies: What information is needed and at what spatial and temporal resolution? Is only the change from a certain baseline required, or is it the entire development in time, and at what time step? Is it enough to have information for one point, or is spatial information needed and at what grid size? A key question is what accuracy is needed, taking into account the accuracy of the impact models used and the accuracy of the socio-economic scenarios. It is less important to obtain accurate climate change scenarios, if through socio-economic change a given impact changes by almost 100 percent.

The workgroup began by looking at the problem in two different ways. First, the important parameters were assessed and second, an inventory was made of the most important coastal impacts. Relationships between the relevant parameters and potential impacts were then discussed. Finally, issues of uncertainty and accuracy were addressed and some concluding remarks made.

Important Input Parameters for Coastal Impact Studies

The following parameters have been identified:

- Sea-level rise — regional variation
- Storm surges — height and duration
- Waves — height, period and direction
- Wind — strength, duration and direction
- Temperature — water temperature, air temperature
- Sea ice — extension and duration

Important Coastal Impacts

In this section, relevant parameters for different potential impacts in coastal areas (see Table 1) are discussed while taking into account the spatial and temporal resolution.

Impact	Relevant parameters					
	Sea-level rise	Storm surges	Waves	Wind and Pressure	Temperature	Sea ice
Direct wind damage				X		
Flooding	X	X	X	v		s
Coastal erosion	X	X	X	v		
Water management	X	s				
Salt intrusion	X	s				
Shipping (dredging)	X			s		s
'Wet' environment	X	s	s	v	X	s
Tourism					X	

X = Important parameter
v = Impact of this parameter works via other parameters. In the case of flooding, wind is one of the most important parameters, but the surges and waves cause the impact.
s = Parameter with small importance

Table 1. Relevant parameters for different potential impacts in coastal areas.

Direct Wind Damage
This impact is not specific to the coastal region, although the potential wind damage is higher in coastal areas. An increase in extreme wind speed would have considerable consequences, especially in the coastal region. Buildings and other wind-vulnerable constructions would have to be strengthened or additional damage would be sustained. The temporal resolution has no relevance for this impact and the spatial resolution of the information required (percentage increase in the mean or maximum wind speed) is relatively coarse (in the order of 1000 km).

Flooding
One of the most important issues in coastal impacts is the increase or decrease in the risk of flooding. Millions of people and enormous assets are threatened by flooding. The most important issue is sea-level rise although a change in storminess and the height of storm surges might be of equal or even greater importance. A decrease in storminess might counteract the impact of sea-level rise. The major parameters for assessing changes in flooding are sea-level rise and the extreme values of - storm surges, wave heights and wave periods. Safety standards for coastal constructions vary between a 1/20 year event to a 1/100 year event, with the expectation that a disaster occurs once per 20 - 100 years. In the Netherlands, safety standards of up to 1/10000 year events are used. The question of how these extremes change with climate change, are extremely difficult to answer. Only very long climate runs combined with long runs of hydraulic models are of use. A model simulation of comparable length to the return period is desirable. Another issue is changes in the extent of sea ice; expansion of sea ice can influence wind fetch in certain cases, consequently affecting surge and wave heights.

Coastal Erosion and Changing Sediment Transport
At present, more than 60% of the world's beaches suffer from erosion. In most cases, erosion will occur in the absence of climate change, but these problems will intensify with future climate change. Changing patterns of sediment movement can cause problems in harbour entrances and may alter dredging costs

considerably. A rising sea level is one of the main causes of coastal erosion. Other major factors are an increase in the number and severity of storm surges and extreme waves. A change in wind direction can also cause higher (or lower) waves and storm surges and in this way can play an important role in coastal erosion and changing sediment transport. Not only are large extremes important but also exceeding smaller thresholds. Questions asked by impact modellers include: For what percentage of time is a wave height of three metres exceeded? Thus, the entire statistical distribution (pdf - probability density function) is of importance. This includes changes in wave direction or changes in pdf 's differentiated over the different compass directions. A change in the main wave direction, for instance, may have a large impact on the extent of coastal erosion. The only means of examining these statistical properties is to use long climate runs or ensemble runs.

Water Management

In coastal regions, an additional water management problem is the discharge of superfluous water. In low-lying areas, discharge is via sluices or pumping stations, and sea-level rise is the main concern. In areas where no discharge problems currently exist, these problems may arise with higher sea levels and the construction of polders may become necessary. In other cases, the pumping height and/or pump capacity must be increased. The height and duration of storm surges can also be of importance because this can change the discharge capacity of sluices.

Salt Intrusion

Salt intrusion can impact the coastal zone in two ways: first, via the river system when salt water intrudes the river from the seaside at distances of more than 100 km inland. Sea-level rise will increase the extent and saline concentration of the intrusion. During storm surges, temporary saline intrusions can cause substantial damage, so changes in storminess could have considerable impact. The second impact pathway is via the subsoil and saline seepage in the polders for areas below mean sea level. With sea-level rise, saline seepage will increase and some areas not currently experiencing saline seepage will start to experience this phenomenon.

Shipping

Sea-level rise will have a positive effect on shipping because less dredging will be required and dredging costs will decrease. Another positive effect anticipated is a reduction in sea-ice thickness and extent due to higher temperatures. However, some negative effects are likely: harbour quays will become too low, other harbour facilities may have to be altered and passages underneath bridges may become too low. Changes in storminess have an impact on shipping via direct wind damage and waves. Many ports are vulnerable to wind and waves from a particular direction and if those conditions were to become more common in the future, this would reduce the economic viability of the port. Indirectly it may affect sediment transport and alter dredging costs.

'Wet' Environment

Climate change will impact the wet environment through a variety of parameters. The most important ones will be temperature and sea-level rise. Warmer water temperatures will affect the marine ecosystem. Some species will become extinct while other new species will migrate into the area. The rate of sea-level rise is critical in areas were tidal flats occur. Most areas can cope with a sea-level rise of up to 50 cm per century; a higher rate of increase will cause problems. Changes in storm surges, waves, wind and sea-ice extent will also affect the 'wet' environment.

Tourism

Temperature plays an important role in attracting visitors to the beach. In many destinations, higher temperature will extend the length of the tourist season. Other places might become to hot (or to dry) and will become less attractive to tourism. Sea-level rise might significantly reduce the size of beaches.

Minimum Required Spatial and Temporal Resolution

One of the key issues for climate and impact modellers to consider is the trade-off between horizontal resolution, vertical resolution, temporal resolution, and simulation length. Given computer capacity limitations, choices have to be made between these four parameters. For example, a longer run means a coarser resolution in space and/or time. Impact modellers must therefore decide what their minimum requirements are to model the specific item that they are interested in, in a realistic way. For instance, to generate realistic storm depressions and storm fields a minimum grid size is required. The following sections summarises the outcome of the workgroup's discussion.

Minimum Required Spatial and Temporal Resolution of Sea-Level Rise

Since the rate of sea-level rise over the next 50 - 100 years is important, the temporal resolution is therefore of this order. The spatial resolution is also important because sea-level rise involves regional differences. In addition to these regional differences one must consider land subsidence or uplift in order to calculate the regional relative sea-level rise. Regional predictions of sea-level change can be made from transient ocean-atmosphere general climate model (OAGCM) simulations. These suggest that, over the period 2000 to 2100, patterns of sea-level change will not be spatially uniform. Results from the HadCM2 model (Figure 1) indicate that some locations may experience more than twice the global mean value. While some of the available OAGCM simulations show some agreement for the larger-scale features (such as a smaller rise in the southern ocean and a larger rise in parts of the Arctic), there are still many differences between the results, especially on the smaller scale. This will be highlighted in the forthcoming IPCC third assessment report.

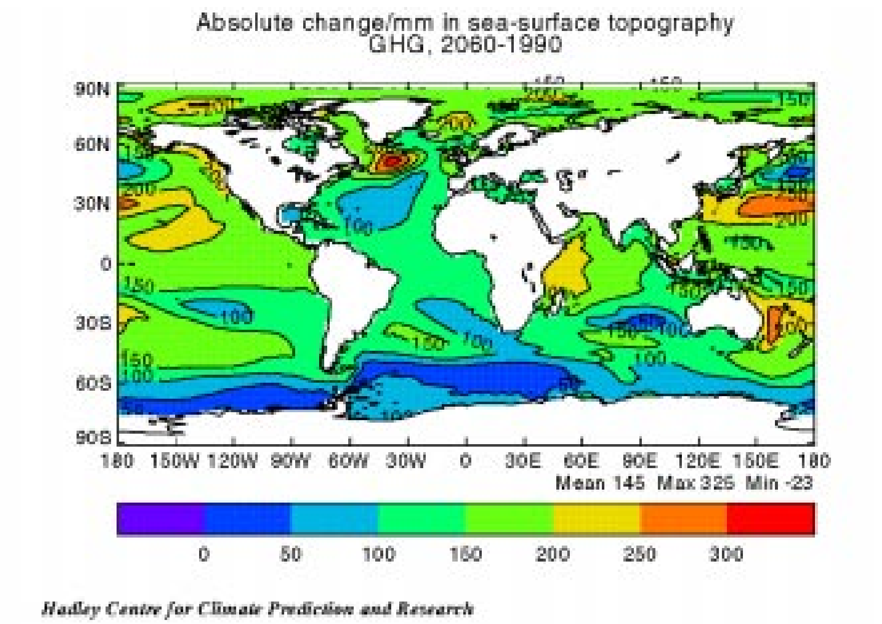

Figure 1. Absolute change (mm) in sea-surface topography for 2060 relative to 1990 (source: Hadley Centre for Climate Prediction and Research).

The pattern of sea-level change is driven by several factors. First, spatially inhomogeneous changes in the density structure of the ocean can occur. This is due to the non-uniform patterns of heat and freshwater input to the ocean, the transport of heat and salinity within the ocean, and the distribution of in situ temperature and salinity (which govern the local coefficients of expansion). Second, changes in patterns of wind forcing can alter the spatial pattern of mean sea-level both directly, through changes to the upper Ekman transport, and indirectly, through changes to the interior heat distribution brought about by altering the Ekman pumping. Furthermore, changes to the oceans' density structure and circulation are linked. The propagation of changes in sea level appears to involve slow-moving Rossby waves and coastally trapped Kelvin waves, so consideration of these phenomena is required in order to understand changes in sea level over time. The required spatial resolution of regional sea-level rise is in the order of hundreds or thousands of kilometres, since this is the scale in which regional sea-level rise is changing.

Minimum Required Spatial and Temporal Resolution of Changes in Storm Surges and Waves
To be able to calculate the change in storm surges and waves one needs the use of storm surge models and wave models. The spatial and temporal resolution of these models depends on the study area, but is at best in the order of tens of meters and minutes, respectively. These models are driven by boundary conditions including wind and pressure fields, which have to be provided by the meteorological models. Fortunately, the resolution needed to drive these models can be coarser. For local models, a spatial resolution of wind and pressure fields of at least 200 km is needed while a resolution of less than 100 km is desirable. The required temporal resolution is at least 6 hourly while 3 hourly or less is desirable. Of even greater importance is the fact that these climate models must generate 'extreme' storms in a realistic way. For this purpose, grid-boxes of less than 50 km might be needed and time steps of less than one hour.

Minimum Required Spatial and Temporal Resolution of Temperature
Regional effects of temperature are important in this impact area therefore spatial scales of thousands of kilometres are relevant. In terms of the required temporal scale, two issues are important. First, seasonal changes are required. Second, information on extremes is needed. For example, a lack of cold winter events has a negative effect on the production of mussels. Hence, statistical distributions (pdf's) including their change in time are needed, and long runs or ensemble runs are necessary.

Minimum Required Spatial and Temporal Resolution of Sea Ice
The items dealt with in this workgroup were reduced wind fetch causing smaller surge and wave heights, effects on shipping and effects on the wet environment. We are therefore dealing with local scales and local modelling, requiring a spatial resolution of up to 50 km and a temporal resolution in the order of weeks or months.

Accuracy and Uncertainty

The required data accuracy is an important issue to address. One must first consider what magnitude of change is needed before an impact is of importance, given the present uncertainty of that impact. When this uncertainty is considerable, a small impact is negligible relative to the situation of low uncertainty. For example, the safety levels considered are relatively high in coastal protection. The return periods used are always longer than the period over which data are available. So in order to calculate design levels, statistical extrapolation is unavoidable. The level of uncertainty depends on the return period used and the availability of data. Uncertainty in the design level is in the order of approximately 10-20%. It is therefore clear that impact modellers should not request scenarios of changes in storm-surge levels with an accuracy of, for instance, 5%. Instead, the uncertainties of present levels should be combined with the uncertainties of the predicted change, and the range that belongs to the present design level should be compared to the range of the future design level with climate change. The uncertainties are considerable for both flood risk and coastal erosion. At present, no morphological models exist that can predict with any certainty, the morphological changes over a period longer than 10 years.

Final Remarks

At the close of the workgroup session, some final issues were discussed.

Different GCM's
Until recently, nearly all impact studies use the outcome of only one GCM. In order to gain a better understanding of the uncertainties involved, the use of more GCM's is strongly advised. However, even when the use of different GCM leads to comparable impacts this does not prove that the uncertainties are small. All GCM's are largely built on the same concepts and may have the same biases and deficiencies.

Long Runs or Ensemble Runs are Needed for Statistics of Extremes
Many of the questions asked by impact modellers cannot be answered by considering only mean values. Changes in the frequency or the distribution of wind direction are of equal importance. Extremes are of even greater importance and require long runs or ensemble runs of up 100 or even 1000 years. Depending on the issue being considered, one has to decide whether long runs or ensemble runs are desired. If changes in time are of importance, statistics have to be computed with long runs. If the interest is in a specific condition or specific statistics at a certain time, a set of ensemble runs is needed. For instance, the 1/100 or 1/1000 year surge height for the year 2100 can be derived with a number of ensemble runs over the period 2090 – 2110. During these 20 years, one may assume that the statistics are stable. The simulation length should then be up to 100 or 1000 years.

Basic Research on Cause-Effect Relations should not be Neglected
Modelling is not the only way of studying the effects of climate change. A principle understanding of the physics and the mechanisms involved is also of great importance. Models are important tools in helping to understand the complex interaction between the many processes involved, but the basic processes have to be first understood.

Working Group 1C

Climate Needs and Availability of Climate Scenarios at the Interface of Hydrological (Fresh-Water) and Coastal (Salt-Water) Impacts. Do we Need a Bridge?

Participants: Willy Bauwens, Martijn Booij, Ana Cardoso, Pieter Jacobs (chair), ChrisKilsby, Günther Können, Luis-Jose Mata, Hans Middelkoop (rapporteur), Agustín Sanchez-Archilla and Roger Street

Report by: Hans Middelkoop and Pieter Jacobs

INTRODUCTION

It is generally accepted that climate impacts on freshwater systems and coastal areas are of great importance to nature and society, worldwide. For both sectors, a large number of impact studies have been undertaken over the past decennia. To assess climate impacts, various types of climate change scenarios related to the natural water cycle have been developed and applied. New techniques have been developed to specify and incorporate (sub) daily weather extremes in the scenarios, by means of weather generators and dynamical/statistical downscaling techniques, and by addressing the combined effects of changes in sea level and storms on storm surges. In the application of scenarios, there seems to be a remarkable difference between the freshwater hydrology and coastal sectors, geographically and methodologically. For example, weather generators for simulating extreme precipitation and coherent spatial patterns of precipitation have been developed for hydrological impact analyses, while the development of downscaling methods for storm-surge estimates have been applied to coastal areas.

To date, little attention has focused on the interface between the hydrological (freshwater) and the coastal systems. In these areas, the coastal processes interfere with fluvial processes and hence climate impact analyses must be based on scenarios from both sectors simultaneously. This raises the question of whether climate impact analyses at the interface of hydrological (fresh-water) and coastal (salt-water) systems require particular needs and availability of climate scenarios other than ‘adding’ the inputs and impacts from the two sectors separately. From the point of view of scenario development: is anything ‘extra’ needed and, therefore, is the hydrological and coastal impacts interface a separate case in its own right?

The working group addressed these questions, and attempted to identify examples and applications that would clarify whether the interface area is a ‘missing’ gap among the many impact analyses carried out so far, in the sense that it implies additional and new demands from climate change scenarios. The group discussed the general characteristics of the interface by means of examples, identified relevant input parameters from climate change scenarios, and summarised the key issues that might make the interface a special case in the science of scenario development.

THE INTERFACE

The interface between hydrological and coastal systems is where their fluxes of water, salt, sediment, nutrients (e.g., nitrogen and phosphate), pollutants (e.g., heavy metals, organic micropollutants, radionuclides) and temperature come together and interact. These fluxes can vary greatly in magnitude between different regions, and the equilibrium between opposite fluxes from the coast and the fluvial system may shift from place-to-place as well as in time. At the mouths of rivers that discharge large volumes of freshwater, there may be only a limited intrusion of saline water into the river mouth, while the opposite is the case at the mouth of small catchments or urban drainage systems. At the mouths of rivers that carry large amounts of sediments, a delta will be progressively built-up. An extreme example of progressive delta formation can be found at the mouth of the Yellow River. In other estuaries, such as the Scheldt estuary at the Dutch-Belgian border, there is very little contribution from fluvial sediments, and only marine sediments being moved backwards and forwards with the estuarine tides. The channel dimensions and flow dynamics within the lower river reaches determine: the extent to which sediments and sediment-associated pollutants accumulate within the estuary, their distribution, and whether they are transported out to sea. In the Netherlands, for example, large amounts of polluted sediments from the heavily industrialised Rhine and Meuse rivers have accumulated in the lower Rhine-Meuse delta, following the enclosure of one of the estuaries with a barrier dam. When climate changes these fluxes and the factors controlling their interference may also change.

Geographically, the interface between the hydrological and coastal systems includes the lower river reaches, the river mouths and estuaries, coastal wetlands, and may even comprise an entire river delta. Many coastal and delta areas, particularly those regions near a river mouth, are densely populated and form centres of industry and transport, while the remaining space is often intensively used for agriculture. Fresh water is required to prevent salt intrusion, for example, through ground-water seepage in adjacent low-polder areas, for agriculture, for industrial use and for drinking water production. In many of these areas, the interface area is subject to rigorous human control: the river and estuaries are embanked to protect the land from flooding, navigation channels have been dredged, and (as in the Netherlands) barrier dams may control the flow dynamics within the estuary. On the long term (decades or longer), processes of erosion and sedimentation will lead to an equilibrium state between the morphology and the water-flow regime of the estuary. In more natural conditions, the interface may be characterised by a river delta with an estuary, wetlands and coastal barrier. The delta and wetlands may undergo regular flooding. The morphological development of these areas depends on the balance between sediment yield from the upstream river catchment, coastal erosion, and soil subsidence or sea-level rise. Coastal processes may be dominated by waves or tides. Even in apparently natural coastal areas, rivers (both discharge and sediment load) may be heavily managed: in upstream reaches, fresh water may be extracted from the river for irrigation (which is lost by evapotranspiration) and sediment yields may be substantially reduced when it is trapped in upstream reservoirs. In Arctic regions, freshwater flow into the oceans is characterised by a strong seasonality: river water levels are determined by snowmelt, and riverflow is controlled by ice jams in late spring. For each of these geographic units, different climate change impacts can be identified at various spatial and temporal scales and are discussed in the following section.

INTERMEZZO: Rhine-Meuse delta – an example of impact analysis in a regulated estuary

Figures 1 and 2 show the interface between the coastal and hydrological systems in the Netherlands: The Rhine-Meuse estuary and Lake IJsselmeer. The lower reaches of the River Rhine and the Meuse distributaries in the Netherlands are heavily regulated. The rivers have been embanked to prevent the adjacent land from flooding, the main channels have been normalised for navigation and to prevent the formation of ice jams, weirs and sluices have been constructed to control the water distribution over different branches and to allow a sufficient navigation depth during periods of low river flow. Many branches of the estuary have been closed-off from the sea by barrier dams, for example, the northern branch of the Rhine (the "IJssel") which discharges into a lake that has been separated from the sea by a large barrier dam. Discharge of surplus water from the lake occurs at low tide by gravity through a series of sluice gates in the dam. The water system in these areas is mainly driven by sea level, the tidal regime and river discharge. Another example is given by the lower reaches of the Rivers Rhine and Meuse around the city of Rotterdam, where river flow is regulated by the operation of the Haringvliet sluice gates. These gates are always closed during high tides to prevent salt intrusion along the southern branch of the delta. At low river discharge, the gates are also closed during low tides to redirect the river water along the northern branch to minimise salt intrusion there.

Management of the Rhine-Meuse estuaries concerns three main issues; flood protection, freshwater supply and inland navigation. These all depend on the combined effect of sea level, storm surges and river discharge. In addition, the freshwater demand from the adjacent area varies by season and depends on weather conditions. Using a Decision Support System developed at RIZA, the interplay between these factors can be simulated and their effect on the 'user functions' assessed. For climate impact assessments in this area, scenarios are needed that provide simultaneous estimates of changes in sea level, storm duration and intensity, and river discharge.

Figure 1. The interface between the coastal and hydrological systems in the Netherlands: The Rhine-Meuse estuary and Lake Ijsselmeer.

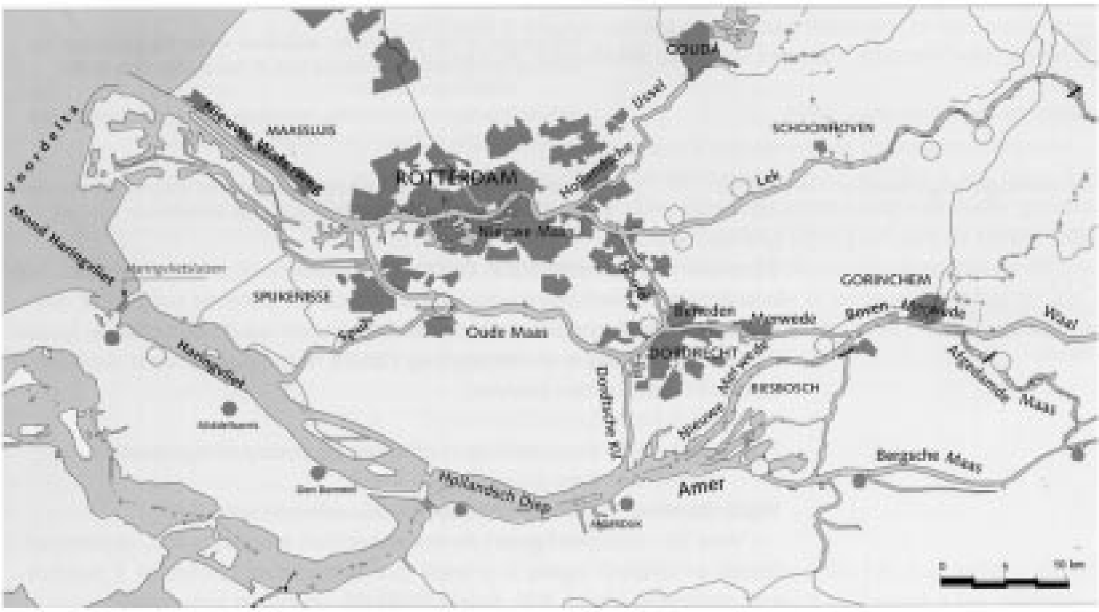

Figure 2. Detailed map of the Rhine-Meuse delta in the Netherlands.

Impacts

Different types of empirical, conceptual and physical models are available to determine the interplay between external forcings at the interface and to assess the effect of climate change on: estuarine water levels, salt intrusion, wetland ecosystems, and morphological development. By definition, the climate-induced factors controlling the processes interacting at the interface come from the coastal and the hydrological sides simultaneously.

The relevant climate parameters for impact analysis will depend on the interface characteristics and on the fields of interest to users in this area. These are summarised in Table 1, which primarily highlights the climate-related parameters that are relevant to the interface, without considering in detail how they are affected by climate. These partly summarise the results of the working groups dealing individually with coastal impacts and hydrological impacts, and are not elaborated here.

A. Coastal systems

	Mean Sea Level	Tide	Waves	Surges	Direct Wind
Flooding	X	X	X	X	x
Salt intrusion	X	X		X	
Water management	X	X			
Navigation	X	X	X	X	x
Pollution	X	X			
Channel morphology	X	X	X	X	
Wetland ecology	X	X	X	X	
Delta morphology	X	X	X	X	x

X = major influence
x = minor influence

B. Hydrological systems

	High discharge	Low discharge	Sediment yield	Ice
Flooding	X			X
Salt intrusion		X		
Water management	X	X		x
Navigation	x	X		X
Pollution	x	X	X	
Channel morphology	x	X	X	
Wetland ecology	X	X		
Delta morphology	x	X	X	

X = major influence
x = minor influence

Table 1. Summary of the main impacts and their dependency on climate-related parameters.

First, the impacts tables were discussed independently. Second, additional parameters that are characteristic of the interface were identified and finally, the combined effects of the coastal and hydrological parameters were considered. Parameters considered relevant to the interface were: swell (mainly relevant for navigation) and negative surges (resulting in extremely low water levels and shallow navigation depth). However, the most important characteristic of the interface area is that the sea-bound and river-bound parameters in Table 1 interact. The combined effect of both systems is more than the (mostly non-linear) addition of the impacts caused by parameters from both systems. Because of this interaction timing is relevant, and hence the impact analysis must be based on the probabilities of the joint occurrences of critical conditions in sea-bound and river-bound parameters.

Several situations were identified in which the joint occurrence of critical values would impact the interface area (Table 2). First, these are the combinations of parameters in Table 1 that have similar impacts. For example, the combination of high river flow with a storm surge and a rise of sea level will lead to the highest water levels and is therefore important for safety. Storm surges and extreme river flows are not necessarily correlated. As an example, one may consider the Rhine-Meuse estuary. The storm at sea occurs when a strong depression crosses the North Sea. If the same depression were to causing flooding in the Rhine, it would take at least a week or so before the floodwaters reach the river mouth. This is because it takes a day for the depression to reach the entire Rhine basin, and subsequently it takes another few days before the rainwater has collected in the channel system and the flood wave reaches the coast. In this example, the storm surge is not correlated with the river flood. This is not a rule, as examples can easily be found where there is a correlation between the two. One example is the monsoon flood regime of Andhra Pradesh. Other examples, such as small river catchments or urban drainage systems (Ho Chi Minh City was mentioned as an example) often suffer from serious flooding caused by a combination of a storm surge and heavy rainfall, which is positively correlated. During a major storm in October 1998 in the Netherlands, many small rivers flooded their banks, and the water was prevented from draining into the North Sea by strong northwest winds.

High sea-water levels (due to a rise in mean sea level and storm surge) in combination with low river flow will lead to a progressive intrusion of a salt wedge in the lower river reaches. This will limit the intake of water for agriculture, industry and drinking water production. In arctic rivers the interplay of river flow (depending on snowmelt), river ice and seawater level influence both the intrusion of salt water in the river mouth and the water level. Occasionally during high river flows, a storm surge may lead to flooding of the arctic river delta with salt water instead of fresh water, with negative consequences for the natural vegetation.

	Mean Sea Level	Tide	Waves	Surges	Direct Wind
High discharge	Floods Wetland ecology	Floods	Floods	Floods Wetland ecology	
Low discharge	Salt intrusion	Salt intrusion		Salt intrusion (extreme or moderate surges) Navigation (negative surges)	Morphology
Sediment yield	Morphology Wetland ecology	Morphology Wetland ecology	Morphology	Wetland ecology	
Ice				Floods	

Table 2. Relevant combinations between parameters from the coastal and hydrological sectors for impact analyses at the interface.

In addition to the co-occurrence of extremes of sea-bound and river-bound parameters, there may be situations where not only the extremes are relevant, but other parts of the parameter regime also become relevant. A clear example was found for the intrusion of salt into the lower river mouth. During the winter period when river discharge is moderate or high, salt intrusion may occur only during storm surges. This would require statistics of extreme storms in combination with statistics of moderate winter river flow. However, during summer when the river carries little water, salt intrusion may increase during moderate storm surges and in this case, statistics of moderate storm surges are relevant. In this example, it should be noted that the role of storm surges in impact analyses varies according to the interest of the user. Extreme surges are primarily relevant for safety analyses, while moderate surges (coinciding with low river flow) affect salt intrusion.

The interaction between the parameters and the impacts of climate change may be subtler, particularly for morphological processes operating over longer time scales. Both water and sediment transport processes are involved. Within the fluvial system, climate change may increase erosion and sediment delivery to the channel system. Though sediment transport occurs mainly during periods of high river discharge, the transfer of sediment through the river network to the estuary is a highly non-linear process with a large number of additional sediment sources and (temporary) sediment sinks. In addition, land use changes and water management activities may affect both river flow and sediment yield. Sediment delivery to the estuary and stream power will be highest during periods of high river flow. However, the net morphological effect will depend on the role of wave action, tides and storm surges in the erosion of the coastal zones. At the decadal time scale, the balance between sediment yield on the one hand and erosion and sea-level rise on the other hand may determine whether a delta will continue to grow or will submerge below sea level. Morphological processes at the scale of individual river floods or storm surges are determined by extremes, while the long-term development of a delta depends both on long-term statistics of extremes and on changes in mean sea level.

From this preliminary (and incomplete) inventory of the interface system and the relevant processes it was concluded that the interaction between the coastal and hydrological processes leads to situations and impacts that would be less strong or not present without this interaction. The next key issue to address is whether the parameters that control the processes and impacts at the interface can be considered independent from each other or not.

Joint probabilities

Estimates of changes in mean values of sea-bound and river-bound parameters may be considered independently from each other, and may arise from separate downscaling of sea and land/river scenarios. However, in the case of extremes, the joint probabilities of occurrence may be non-trivial. For example, a severe flood may result from a simultaneous storm surge and a high river flow. It is then important to know whether the occurrence of the two events is independent. A similar example can be found for downscaled temperature and precipitation scenarios that are used to estimate snow accumulation and snowmelt. In this situation, it is crucial that the co-occurrences of below-zero temperature and precipitation are correctly predicted by the downscaling procedure.

Figure 3 is a schematic representation of the probability distributions of two variables in separate graphs. If variables X and Y are independent, the joint probability (for example: P(X=c AND Y=c)) is calculated as the product of the two probabilities P(X=c) *P(Y=c). If the variables were not independent, the joint probability would be different (less if the variables are negatively correlated, more if they are positively correlated). For example, this would be the case if the atmospheric circulation influences the impact of both variables in the same way. If the variables X and Y are dependent, conditional probabilities may be used to compute the joint probabilities. The conditional probabilities become extremely useful if they remain unaltered in a changed climate. Note that, when X and Y are downscaled, the downscaling procedure(s) for X and Y should be such as to retain the correct correlation structure between the two variables. However, this is rather unlikely when separate downscaling procedures are used for X and Y. In general, one must ensure that the downscaling procedure does not impair the dependence structure of the variables.

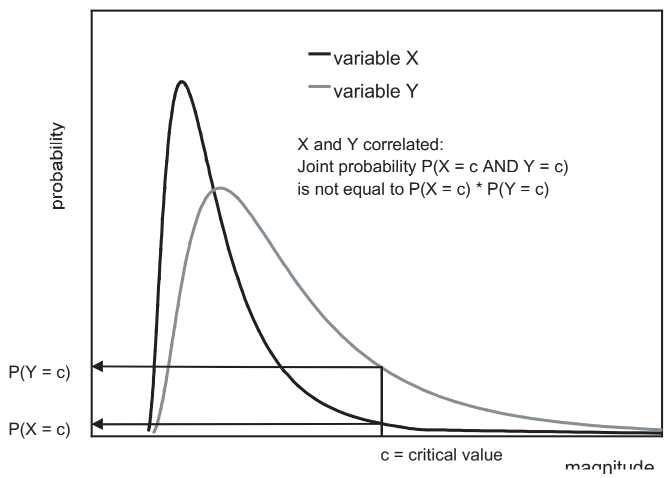

Figure 3. Concept of joint probabilities.

Evaluation

The interface between coastal and hydrological systems is characterised by hydraulic and morphological processes that are of a complex nature, interact and all depend directly or indirectly on climate. Even without climate change, it is a major task to estimate the probability of occurrence of critical events for water management that are the result of events coinciding at sea and river boundaries. This applies to estimates of extreme water levels and flood protection, but also to salt intrusion and deposition of sediments and pollutants. Sensitivity analyses and time series analyses of past events should be carried out to evaluate whether different climate-related parameters are correlated. This should be undertaken before developing and applying a climate-change scenario.

Separate downscaling approaches for fluvial hydrological impacts and coastal impacts may work well for mean situations of the interface, but this is not the case for extremes. The timing and joint occurrences of extremes is of crucial importance in the interface between hydrological and coastal systems. There are many examples where the parameters from both sectors are correlated. This means that for climate impact analyses of extremes in the interface, the joint probabilities of extremes cannot be derived from the individual probability distributions alone. Instead, conditional probabilities are needed to obtain the joint probabilities. Ideally, climate scenarios should provide estimates of joint probabilities for combinations of parameters from both sectors and the downscaling method should not impair the dependence structure of the variables from both sectors.

Climate-change scenarios and their downscaling results should not only consider the spatial and temporal distribution of each parameter, but also the correlations in time and space between different climate parameters acting upon the hydrological and coastal systems. Climate models and downscaling techniques should also be able to indicate whether existing correlations will remain unchanged in the future, or they should provide plausible estimates of how these correlations may change in response to global warming.

Thus, the scenario needs for impact analyses in the interface area, give rise to further evaluation criteria for scenarios. In addition to the mean, variance and probability of extremes, the correct estimation of joint probabilities for different combinations of climate variables should be used as a criterion for evaluating downscaling results. Greater confidence can be placed in the physical consistency of a downscaling technique that provides accurate temporal and spatial dependencies between different variables. In summary, from the perspective of scenario development, the hydrological and coastal impacts interface is a separate case in its own right.

Working Group 2A

Methods – 'Artificial Scenarios'

Participants: Thomas Beckmann, Timothy Carter, João Corte-Real, Joost de Wolff, Kathy McInnes (chair), Hans Middelkoop, Linda Mortsch (rapporteur), Serge Planton, Andreas Schumann

Report by: Linda Mortsch

INTRODUCTION

The working group was directed to discuss a number of questions and the key points are summarized.

- What is the usefulness of 'artificial scenarios', global climate models (GCMs), regional climate models (RCMs), analogues, and 'tailored' downscaling techniques in climate impact assessment? Discuss the potential applications, strengths and weaknesses of these scenario development methods.
- How do we deal with the uncertainty of climate-change scenarios?
- What about the other uncertainties in the cascade of uncertainties in impact assessments?

What is the usefulness of 'artificial scenarios', GCMs, RCMs, analogues and 'tailored' downscaling techniques in climate impact assessment?

Selection of scenarios

The type of climate-change scenario selected is dependent upon the type of study, its objectives and/or motivations, the results required and the users of the study information. Usefulness is determined by the way the scenario helps to meet the purpose and application of the study with a minimum of compromises.

- Methodological studies focus on scenario development techniques and testing of methods for impact assessment rather than assessment of impacts per se. Activities include comparison of GCMs or downscaling techniques. Impact results are not robust.
- Impact assessments are generally undertaken to inform policy. The focus is on addressing a particular question, issue or sensitivity. It is often driven by stakeholder interests or problems. The impact results must be robust and reflect the uncertainties through a range of possible outcomes.
- Science assessments such as the IPCC assessment reports review, evaluate and synthesize current climate change information. Valuable to this effort is consistency of and comparability among the scenarios used to derive impacts.

Types of Scenarios

Artificial Scenarios

Artificial scenarios are developed by systematic changes to observed data, for example, 10% precipitation, 2°C temperature increase, 0.5m sea level change, and river flow. These scenarios should not be developed arbitrarily but with guidance from GCMs (e.g., limits of changes) or stakeholder-specified vulnerabilities in a *'guided sensitivity analysis'*. These scenarios provide an opportunity to reframe the climate change problem by exploring critical thresholds or changes. For example, by choosing a range of systematic changes in temperature, precipitation and evaporation, and assessing the impacts, a researcher can develop a response surface of climate changes and related impacts. GCM-derived scenarios (and/or other scenarios) and their impacts can also be mapped unto this surface. The range of impacts from the climate changes and, thereby, the uncertainties can be displayed. Artificial scenarios also have relevance as an exploratory tool to direct researchers to key sensitivities that warrant more detailed and stringent scenario development and impact assessment methods.

Implementing this technique can be problematic. Do you implement variable by variable; or in combinations of variables; and how is consistency maintained? Caution should be used in the development of extremes from 'artificial scenarios'. It is also dangerous to apply arbitrary changes especially when the phenomena are a result of a combination of effects (e.g., runoff).

The artificial scenario is easier to use in assessments of the impact of sea-level rise than changes in hydrology because there are fewer parameters to modify.

- Positive aspects of artificial scenarios:
- The scenario is simple to construct.
- Data are often readily available; data requirements are less stringent.
- The scenario can be applied at a large and small scale.
- Artificial scenarios can be used to identify sensitivity and vulnerability of regions, sectors, and activities.
- It is easily communicated to stakeholders.
- The method offers scope for synthesis and comparability among/across many climate impact assessment studies.
- Negative aspects of artificial scenarios:
- The simplistic changes may not reflect the complexity of the problem or the changed conditions may not be physically possible.
- These scenarios do not have the internal consistency and complexity of GCM and RCM scenarios.
- It may be difficult to find 'actual climate' realizations of the 'artificial climate' conditions.
- Probabilities of occurrence cannot be determined; how certain is this change; is it a 'realistic' change?
- Since the scenario is not tied to socio-economic and development scenarios or changes in greenhouse gas concentrations, there is no relationship to climate policy.

Global climate models (GCMs)
Current GCM climate change runs provide information on a 'no climate policy' or 'business-as-usual'. Most of the recent GCM experiments used a greenhouse gas forcing based on a continued increase in equivalent greenhouse gas concentration of 1% per year from 1990 onward (IS92a) although five other scenarios were presented by the IPCC. New greenhouse gas emissions scenarios are being developed for the IPCC through the Special Report on Emissions Scenarios (SRES). The four 'families' of emissions scenarios are based on different 'story lines' or assumptions of how global population growth, economic development, technology development, and governance may unfold. Future GCM experiments and climate impact assessments, should explore the implications of the four families of scenarios to address a wider range of climate change impacts that result from these different greenhouse gas forcings. While the forcing factor, greenhouse gas emissions, is the same in these scenarios, the paths and the end-point, and hence the climate impacts of the scenarios are different because of alternative visions on changes in demographics, socio-economics, and technology.

A GCM climate change scenario should not be presented as the 'best-guess scenario' or 'worst-case scenario'. Using only one GCM scenario for a climate impact assessment misrepresents the uncertainty in the projection of future climate change and the range of potential impacts resulting from increasing greenhouse gases. Impact assessments based on scenarios developed from the ensemble runs from one GCM can be used to illustrate and assess the variability in that model. Individual ensemble runs or ensemble means from a suite of GCMs can be used to demonstrate the range of impact outcomes from various models and thereby illustrate the range of uncertainty. Lack of time and funding are often cited as the reasons for not using a range (at minimum two) of scenarios from GCMs or other methods in impact assessments.

Climate impact assessors need expert guidance on the best GCM model runs to choose for their applications. They need assessment and intercomparison of performance and applicability of the GCMs globally, in various regions, for selected parameters etc., so that they can use the scenarios appropriately with an awareness of the strengths and weaknesses and/or the relative degree of change in climate elements (e.g., a 'wet' model, a large temperature increase).

While there is a large amount of information on the strengths and weaknesses of this scenario generating method, some key points from the discussion are presented.

Strengths:

- Internal consistency of parameters and based on sound scientific principles.
- Complex method that acknowledges the complexity of the climate system and the problem.
- Related to socioeconomic scenarios that tie into future greenhouse gas emissions.

Weaknesses:

- Large spatial scale.
- Short time steps are often difficult to obtain (and the quality is questionable).
- Difficult to develop extremes.
- Systematic errors.

- GCM modelling and climate change scenario generating method not easily communicated from atmospheric scientists to impact assessors and finally to stakeholders.
- There is a large investment in developing and using the scenarios appropriately.
- So far, most scenarios have presented 'business as usual' conditions and do not explore a climate policy.

Regional climate models (RCMs)
RCMs (a form of dynamic downscaling) are not necessarily better at projecting climate changes since they are constrained by the boundary conditions of the GCMs in which they are nested. The systematic errors in the GCMs can be transferred to the RCMs. However, the enhanced topography in the RCMs leads to better representation of orographic effects and wind fields. Projected changes in precipitation and ice are also improved. RCMs are useful for impact assessment applications (e.g., storm surge) where GCM elements, such as winds, are suspect but critical to the analysis. In a recent application, a RCM was used to develop the 'current, present climate' in a data sparse region. To test the uncertainty in the RCMs, it may be useful to 'nest' a RCM in two or more GCMs to determine the response of the RCM and the implications of different boundary conditions.

Analogues (spatial and temporal)
In the development of spatial analogues, climatic information (e.g., temperature and precipitation) and adaptation strategies from another region are applied to the study area. Often GCM climate changes are used to define the new climatic conditions and then the researcher uses information from regions that may be representative of these new conditions. Spatial analogues are less useful for hydrological applications than for agricultural applications. The crops, pests and growing conditions occurring elsewhere may become representative of future conditions in the study region because of climate change, and one can learn from the functional relationships.

Temporal analogues often focus on extreme events, such as droughts, floods and ice storms that have occurred in the study area in the past, to investigate the resulting impacts and adaptations. Another modification of the analogue method is to develop an ensemble of observed cold and/or warm years or wet and/or dry years to assess the sensitivity of hydrology, for example, to a series of climatic conditions. However, the conditions developed by this method are not outside the realm of natural variability, which may be exceeded by climate change conditions.

Analogues can be presented as a metaphor rather than as a quantitative depiction of future reality. Since they are based on an actual climate event or a region's climate, they are more easily communicated to stakeholders.

Strengths:

- Events have occurred in the past.
- Data are available.
- Stakeholders can relate to the events.
- It is easier to relate adaptations to impacts since they occurred, and were observed and implemented.

Weaknesses:

- Boundary conditions vary between regions. For example, if a spatial analogue is being used, the topography, day length and storm-track conditions, can be very different between regions. For a temporal analogue, the socio-economic and political conditions from another time period can be very different and not applicable to present or future events.

- Data quality can be poor if the period of interest occurred a long time ago (observing instruments and/or methods have changed).

- Probabilities of occurrence cannot be assigned.

Downscaling
In the discussion, not much attention was devoted to downscaling methods since Working Group 2B, 'Downscaling – Methods and Suitability for Producing Hydrological Impact Scenarios', has addressed this topic. However, one important observation from the discussion was that the choice of probability distribution can be critical in downscaling, adding another dimension of uncertainty.

How do we deal with uncertainty of climate change scenarios?

A wide range of climate-change outcomes has not been addressed because GCM experiments have focused on 'business-as-usual' socio-economic scenarios from the IPCC – IS92b. Only a few climate-modelling centres have incorporated other greenhouse gas emissions scenarios for the future (most use a 1% per year increase, although a 0.5% per year increase has been developed for the Hadley HadCM2 experiments).

Responses to or considerations of uncertainty in impact assessments include:

- Monte Carlo techniques. This method allows for a range of uncertainty to be addressed and presented in the climate impact assessment since several solutions (of climate change) are assessed. One application in Germany generated 25,000 scenarios.

- Expert judgment was used in earlier impact assessments to identify potential climate changes and to fit probability distributions. Qualitative, expert judgment was used as a first approximation of the climate sensitivities and impacts because there was a lack of quantitative, modelling studies. The method was criticized because of its subjectivity.

- Ensemble runs of one GCM or the mean of ensemble runs of more than one GCM can be used to illustrate the range of possible outcomes and uncertainties.

- 'Climate surprises' such as short-term cooling in Europe, resulting from changes to the thermohaline circulation, should be considered.

- A fixed time period should be used as the baseline climate for impact assessments. Researchers should consider non-stationarity in the time series. The implication for impacts assessment of a moving baseline climate (based on periods such as 1951-1980; 1961-90, 1971-2000) needs to be determined. What is the effect of the warming signal in the baseline climate?

- Consecutive extremes need to be considered because they can cause serious damage. They often occur in clusters and are not independent. For example, tropical cyclones in Australia are linked to El Niño conditions. What is the probability of consecutive events occurring? Weather generators need to be conditioned for these events.

- Mitigation and/or adaptation alter the vulnerability to climate change, and the interplay and balance between the two leads to uncertainty.

What about other uncertainties in the cascade of uncertainties in impact assessments?

Cascade of uncertainty

A simple representation of the cascade of uncertainty is depicted in Figure 1. The level of uncertainty in impact assessment information increases as one moves from socio-economic development, technology, and population growth, which are some of the drivers of greenhouse gas emissions to adaptation and mitigation strategies. One way to deal with the uncertainty is to engage researchers, impact assessors, the public, and managers and decision-makers in on-going communication on climate change.

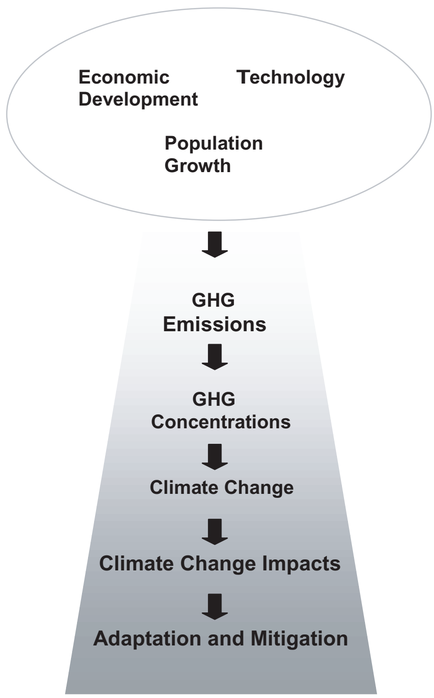

Figure 1. Simplified cascade of uncertainty.

Some of the issues discussed:

- The uncertainties in an impact assessment should be made explicit and the degree to which the uncertainties are addressed or not addressed should be presented.

- Stakeholder priorities add salience to climate change assessments.

- Maintaining credibility with stakeholders is important especially when differing information is available from climate-change impact assessments.

- Climate sensitivity analysis explores how well a system or region can respond to and cope with changing climatic conditions.

- Adaptation scenarios affect vulnerability. There are different types of adaptations that have to be considered (e.g., technology and policy). However, adaptation to extreme events may make a region more or less vulnerable to a reoccurrence of an event and may change the severity of the impacts (e.g., the 1993 and 1995 floods in Germany).

- Water resource management must be 'robust' and adaptable to a range of future conditions.

- Climate change is only one of the many uncertainties that water managers need to consider; how much attention should be given to it?

- Management methods are critical to the assessment of impacts, and development of adaptation and mitigation strategies. Are resource managers reactive to climate change or are they anticipating impacts and planning to respond/adapt to the impacts? How do managers deal with or manage uncertainty?

Working Group 2B

Downscaling - methods and suitability for producing hydrological impact scenarios

Participants: András Bárdossy (chair), Elaine Barrow, Björn Beckmann, Martijn Booij, Henk van den Brink, Iain Brown, Adri Buishand, Martin Dubrovsky, Eigil Kaas, Chris Kilsby (rapporteur), Miroslaw Mietus, Robert Wilby

Report by: Chris Kilsby

AGENDA

The working group was tasked with surveying the requirements for downscaled variables for use in hydrologic impact assessments, together with an evaluation of the strengths and weaknesses of different methods of downscaling. It was hoped that this would allow the matching of requirements and methods. The reader with an interest in the details of downscaling methods is referred to the review papers in the bibliography, which contain descriptions and references to a large number of methods.

Some specific issues had also been identified in advance, including:

- value of the downscaling procedure;
- extra information available from using different GCMs; and
- how to deal with poor GCM control performance.

REQUIREMENTS

Impact assessments vary widely in their data and scenario requirements. The range of possible scenario requirements was therefore charted by separately considering the variables and their characteristics.

Variables
A large range of derived variables may be needed for hydrological impact assessments. These assessments are typically performed at catchment scale, ranging from 1 to 1000 km^2 area, but may be required at large basin scales of up to 10,000 km^2 which is still only 20% of the area of an average GCM grid-box. Variables often take the form of time series at a number of points, or sometimes areal averages. They include:

- soil moisture, saturated area, evaporation;
- river flows/depths, local runoff and lake/reservoir inflows/depths;
- snow melt, glacier melt, snow depth/cover;
- groundwater recharge, groundwater levels.

These variables cannot be estimated reliably (if at all) by GCMs, even at GCM grid scales, and so in general are derived using hydrological models with fundamental or primary variables as inputs (Table 1). The primary variables are available from GCMs, but in general must be downscaled to produce realistic values for use at local or catchment scales.

Primary variables	Time resolution	Requirement
Precipitation	5min,1hour,1day, 1month	Calculating runoff and soil moisture
Temperature	Daily maximum, minimum or 6hr	Snow/rain, snowmelt, frozen ground/rivers and calculating evaporation
Radiation, Wind speed, Humidity, Sea-Level Pressure	6 hr or daily mean	Calculating evaporation

Table 1. Requirements for primary variables.

Characteristics of downscaled variables

Some assessments demand specific characteristics of the downscaled variables, summarised in Table 2.

Characteristic	Reason for requirement
High resolution in time/space	Accounting for spatial/temporal variability in rainfall/runoff processes
Physical consistency between two or more variables	To allow credible applications to future regimes which may be outside observed range
Reproduction of statistics:	
• Mean, variance	Basic reproduction of rainfall regime
• Persistence	Dry spell length, droughts
• Low frequency variability	Inter-annual variability, multi-year droughts
• Spatial correlation	Large river basin rainfall patterns, large scale flooding
• Extreme properties	Flood modelling and drought risk analysis
Large ensembles, long series	Statistical analysis - risk and return period

Table 2. Characteristics of the downscaled version.

Survey of methods

Downscaling methods were considered in two broad categories, dynamical (modelling) and empirical (statistical), following the keynote paper of Bárdossy. Reviews and comparisons between empirical and dynamical methods have been performed, (Mearns *et al.*, 1999 and Murphy, 2000) and of empirical methods (Wilks and Wilby, 1999; Xu, 1999, and papers referenced therein).

Dynamical Methods

Dynamical methods use atmospheric models with smaller grid squares than GCMs to perform the downscaling. Examples of methods and their typical characteristics are shown in Table 3. Note that although most models run on 15 minute or 1-hour time steps, the archived output is typically available only at 1-day or even 1-month resolution.

Method	Space Resolution (km)	Integration length (yr)	Time Resolution (hr)
Global Time Slice	100	30	6
Regional Climate Models	15-50	10-30	6
Stretched models	15-50	10-30	6

Table 3. Characteristics of downscaling methods.

Dynamical methods are often preferred because they are designed to have good physical consistency between variables and in response to climate forcing. Some models have been shown to exhibit realistic low frequency variability. Experiments for unobservable scenarios can also be run in principle for changes in land use, for example. The models can in general preserve spatial correlations (e.g., between rainfall in separate weather systems). To some extent, and on their own scale, they can also produce extremes, although these are limited to 'low-return period' events.

The main drawbacks for dynamical methods are that they are limited by their computational demands in areal extent, spatial resolution, length of simulation and availability/access to output. Further, the usual strategy of nested application within GCM boundary conditions leads to the inheritance of GCM errors. Since there is no feedback to the driving conditions, there is little opportunity for the avoidance of bias and correction of GCM errors. Dynamical methods also introduce another layer of uncertainty, which may not be easy to assess in straightforward statistical terms.

Empirical methods

Many empirical methods and combinations of methods and stochastic models have been developed, including in a rough order of complexity:

- a factor of the observed series, with the factor derived from GCM predictions: the simplest method available and often used for 'first-look' regional assessments, but seriously deficient in physical consistency and ability to produce changes in seasonal and temporal regime;

- statistical regression methods, generally using local variables with regional circulation patterns as predictors for example, canonical correlation analysis, singular value decomposition, redundancy analysis;

- classification methods for example, weather types/circulation patterns, with the advantage of including a climatological basis;

- re-sampling methods using observed data for example, nearest-neighbour, analogues, which have the advantage of directly retaining spatial and temporal correlations;

- conditional models for example, mixture models/hierarchical models, Markov models, Non-homogeneous Hidden Markov Models (NHMM), weather generators, stochastic rainfall models, with possibilities for downscaling multiple variables. These can combine long-term variability associated with deterministic weather 'states' with short-term behaviour produced by a stochastic element.

Some further hybrid methods have been developed, including:

- Regional Climate Model (RCM) - run only for a single weather type.

- Atmospheric model with disaggregation of rainfall/soil moisture feedback.

Additionally, a number of different applications of empirical methods have been used, including:

- direct conditioning by GCM output (at the daily or monthly scale);
- classification from GCM output;
- parameterisation of statistics from GCM output.

Table 4 was constructed to show the general strengths and weaknesses of the different approaches, using a scale of 1-5 to describe the performance of the different methods, where 5 is good, 1 is poor. In the table, physical consistency is taken to mean the preservation of relationships between variables, and the ability to correctly produce changes in downscaled variables dependent on changes in predictor variables. Long series capability is taken to mean the ability to generate long or ensemble series for statistical analysis (e.g., high-return periods). Low-frequency variability is taken to mean the realistic reproduction of decadal scale variations. Spatial capability refers to the ability in producing multi-site scenarios, and the performance in reproducing spatial correlation between sites.

Capability	Physical consistency	Space resolution	Time resolution	Long series capability	Low frequency variability	Spatial capability
Method						
Factor	1-2	5+	5+	1	NA	5+
Regression	1-4*	5	3&	2-4#	2-4*	1-5@
Classification	1-4*	5	4	3-4#	3-4*	3-5
Conditioning	1-4*	5	5&	3-5#	4	3-4
Re-sampling	1-4*	5+	5+	3-4	3-4	5

* depends on choice of predictors – increasingly a wide range of thermodynamic variables (e.g., humidity) allow more confidence in model performance under climate change;
\+ needs suitable observed series;
& may need inflation of variance to produce realistic record;
\# dependent on driving variables/GCM record;
@ depends on technique and training variables.

Table 4. Strengths and weaknesses of empirical downscaling methods.

All the techniques clearly provide higher spatial and temporal resolution, but this may be at the expense of physical consistency or low frequency behaviour. Whilst recent inter-comparisons tend to confirm that dynamical and empirical methods can perform equally well (e.g., Murphy, 2000), the convenience and flexibility of empirical methods ensures their popularity. However, the pitfalls of physical inconsistency remain, and a major task facing empirical methods is the inclusion of more physical basis.

Dealing with poor GCM controls

The value of all downscaling methods is determined by the reliability of the GCM scenarios that they use as their starting point. Experience in the working group suggested that this was the single largest problem currently faced in impact assessments.

A series of issues was discussed, and only a limited consensus was reached:

- If a GCM is to be assessed on the performance of its control or historic integration, which variables should be used for validation? Suggestions included SLP (sea-level pressure) fields and upper air patterns/climatology.

- In cases where there are compensating errors, can you trust a model with some poor validations? For example, a GCM may perform well over Europe, but not elsewhere in the world, casting doubt on its physical and internal consistency.

- Should we use multiple GCM output, and weight according to some measure? The use of a variety of scenarios derived from different GCMs is often promoted as beneficial, supposing that the differences derive from genuine variability/uncertainty in process or knowledge. However, this is only true if the variation is not due to simple model error or inadequacy, otherwise the model should be excluded entirely.

- Validation of GCMs is usually done on the averaged quantities in a control/historic integration - what about using the consistency of changes in key variables?

Some suggested courses of action were:

- to agree standards for validation of GCM predictor variables;

- to provide metadata on archived variables – the CLIVAR project CMIP, (Coupled Model Intercomparison Project) provides a basis for this;

- to check the internal consistency of a GCM by testing observed downscaling relations using GCM internal variables; and

- to investigate the use of internal consistency of changes in key variables, perhaps contrasting extreme wet or dry periods in the available record.

Value of downscaling

Strategies for assessing downscaling methods, their necessity, and the value added by downscaling were discussed. A necessary preliminary question is: Can we accept coarse-scale information in the impact model? If so, we don't need downscaling. A second check is to establish what time scale (or space scale) is required, or should be reproduced. In general, hydrologic assessments require that monthly or annual means/variance are reproduced, and it is often necessary to reproduce frequency distributions of the variables (e.g., rainfall) at daily/hourly scales.

The most common method of assessment is to calculate the explained variance, or goodness of fit to the observation, r^2. However, this is often inappropriate, because of the non-uniqueness of the methods (i.e., a method may produce many solutions or daily series given one set of GCM variables). We should consider other diagnostics instead, which may include:

- Frequency distributions, extremes, return periods etc;

- Distribution of spell lengths;

- Performance at different time or space aggregation levels; and
- Multiple diagnostics can use joint probabilities of related, relevant variables.

Summary and priorities for research

A number of deficits of current knowledge and methodology were identified:

- Poor reliability of GCMs was still the greatest obstacle, affecting both empirical and dynamical downscaling methods.
- There is a lack of observed data consistent with available GCM output for development and validation of scenarios and methodology.
- More modelling centres should adopt the LINK model of data accessibility.
- Poor availability of predictor variables reduces physical consistency achievable by empirical methods. Reanalysis data sets have been a major step forward, and efforts must continue to increase the physical basis of such methods.
- Multivariate reanalysis data sets are only of value to statistical downscaling if the equivalent variables have been archived for GCM future climate experiments.
- Discussions about the role/value of atmospheric moisture variables to statistical downscaling are still ongoing, and to date, the inclusion of such information has not become standard practice.

It was generally recognised that there are complementary strengths in both empirical and dynamical downscaling methods. Whilst the future promise of modelling approaches to scenario production was acknowledged, it was felt that the current practical necessity of empirical methods had been established. How long this would be the case is something of an open question. In closing the working group session, a very approximate estimate was agreed of some 25-30 years before RCMs will be able to supply satisfactory rainfall fields for basic catchment hydrological impact assessments as discussed here, leaving plenty of scope for downscaling to develop.

REFERENCES

Mearns, L.O., Bogardi, I., Giorgi, F., Matyasovszky, I. and Palecki, M. (1999) Comparison of climate change scenarios generated from regional climate model experiments and statistical downscaling, **Journal of Geophysical Research-Atmospheres** 104(D6), 6603-6621.

Murphy, J. (2000) Predictions of climate change over Europe using statistical and dynamical downscaling techniques, **International Journal of Climatolog**y 20(5), 489-501.

Wilks, D.S. and Wilby, R.L. (1999) The weather generation game: a review of stochastic weather models, **Progress in Physical Geography** 23(3), 329-357.

Xu, C.Y. (1999) From GCMs to river flow: a review of downscaling methods and hydrologic modelling approaches, **Progress in Physical Geography** 23(2), 229-249.

Working Group 2C

Variability and Extremes

Participants: Willy Bauwens, Ana Cardoso, Richenda Connell, Roger Flather, Pieter Jacobs, Jason Lowe, Luis Jose Mata, Mark New (rapporteur), John de Ronde, Agustín Sanchez-Archilla, Roger Street, Uwe Ulbrich, David Viner (chair)

Report by: Mark New

INTRODUCTION

The remit of working group 2C was to explore approaches for the incorporation of 'variability' and 'extremes' in climate-change scenarios for the water-related impact studies. While recognising the importance of many facets of variability for climate change science – for example, detection of a climate change impact signal against natural variability in the impact system – the discussions of the working group centred around the subject of extremes. Several characteristics of extreme events of relevance to impacts studies were identified.

Extreme events need to be stakeholder-defined. Different stakeholders in different (or the same) systems will have different perceptions and definitions of an extreme event. Normally this will be an event that has a high negative impact. Such an event will usually be a low probability event (stakeholders tend to have adapted to higher frequency, thereby reducing their impact) but need not necessarily be so. Stakeholder-defined extreme events may not be associated with extreme climate events per se, but may occur because of a combination of factors that are not extreme when considered in isolation. Focusing on stakeholder-defined extreme impacts rather than extreme climate events may permit many aspects of climate variability that are not relevant to the impact in question to be ignored, simplifying the scenario problem.

Extreme events are observationally (or experimentally) constrained. Our ability to quantify and identify extreme events are conditioned by observations. Here observations are defined in the broader sense, as measurements or information about past events, and as information we can obtain from model simulations of past or future conditions. 'Imagining' extreme impacts beyond the limits of observational data is possible, but is more speculative in nature.

How can observed data be used?

Having noted that extreme-impact events are observationally constrained, discussion then focussed on how observed data might be used to enhance understanding of probabilities and processes of such events, and to help in construction of scenarios for extreme events under climate change.

Remotely sensed data. The increasing availability of remotely sensed data provides new opportunities for incorporating a spatial component in scenarios. For example, one valuable source of observed data that has not been widely exploited in scenario construction is radar (both network and single site) data. These data are of high temporal and spatial resolution and are gridded, and would provide a useful tool for the investigation of extreme rainfall events. However, at present these data are not routinely archived or made available to the research community.

Traditional methods. The water sector has well-established and proven techniques for defining the statistical properties of extreme phenomena - be they climatic, hydrological or oceanographic – and using them for design purposes. However, these techniques are predicated on stationary causative conditions. There is a need to investigate their robustness under transient conditions.

Use of indirect data. In some instances, direct measurements of a phenomenon may not be available or may be of poor quality, or of inadequate length to enable the identification of extreme events, or determination of return periods. Proxy data or measurements of related phenomena that are of superior quality and length have potential to identify extreme phenomena if the two are correlated. An example might be the use of pressure data to identify extreme wind events, or the identification of synoptic weather-type indices that are related to particular climate-induced extreme-impact events. However, the use of indirect data carries the risk of misclassification, and hence a greater onus on the validation of the effectiveness of such an approach.

Use of observed extreme impacts. Once extreme impact phenomena have been identified in the historical record, they can be used (as temporal analogues) to 'track back' through the chain of events and precursor conditions that led to the extreme impact. This approach enables the identification of sets of conditions and their joint probabilities that, while not necessarily exceptional themselves, combine to produce an extreme impact. The information gained from back tracking can then be used to define the information that needs to be included in future climate scenarios.

Potential observed extreme impacts. 'Potential' extreme impacts are defined as lower-impact events that under slightly different antecedent conditions would have been extreme. Backtracking through such 'near misses' would provide useful information, additional to that gleaned from analysis of events that did have large impacts. Moreover, near misses may be the only source of information for systems where large impact events have not occurred in the historical record.

Spatial analogues. Extreme impact events in nearby systems can potentially be used in the same way as the temporal analogues described above to provide information on the combinations of events that might produce an impact of similar magnitude in the system of interest.

Changing vulnerability. The vulnerability of an impact system will alter over time due to changing land-use and socio-economic conditions. When analysing historical or spatial analogues it is important to be aware of this changing vulnerability as phenomena that may not have had an excessive impact in the past may do so under current or future system conditions.

Scenarios for extreme events – some avenues to explore?

The working group noted that there has been little attention paid to the development of scenarios for extreme events. This is despite the fact that it is the changes in extreme events that are likely to have the greatest impact. It was suggested that the reason for this paucity arises from the belief that GCMs (and downscaling methods) are incapable of providing meaningful information about changes in extremes at appropriate temporal and spatial scales. To some extent, this belief may have acted as a barrier to an exploration of the potential of GCMs to provide information, either directly or through downscaling approaches. A number of ways to advance the development of scenarios for extremes were suggested.

Explore the potential of GCMs. While recognising the potential limitations of GCMs, it was felt that there was much to be gained from GCM output, particularly in the light of a stakeholder-defined or bottom-up approach to scenario development. Some examples:

- Ask new questions relating to extremes - GCMs may actually be able to provide directly useful information on climatic phenomena that lead to extreme impacts, for example, the change in the bv probability of consecutive dry years.

- Make use of daily data that are now available from several modelling centres - such data provide new opportunities for an examination of changes in the probabilities and joint probabilities of daily climate phenomena.

- Focus on specific conditions producing extreme events - identify the mechanisms producing extreme events in GCMs, evaluate whether they are realistic, and examine how the frequency and/or intensity of these mechanisms alter under transient climate change.

- Make use of multiple GCM simulations - in all the above approaches, multiple GCM simulations can be used to evaluate whether different models are simulating similar changes and whether the mechanisms driving these changes are similar. Broad agreement between models will increase confidence in scenarios for changes in extremes.

Downscaling. As with other climate information, downscaling is required to overcome the mismatch in spatial and temporal scales between GCMs and most impact systems. There is likely to be greater uncertainty attached to scenarios for extreme events that arise through downscaling. Additional research is therefore required for the validation of the ability of existing downscaling methodologies to represent extremes and changes in their probability. Existing techniques may have to be modified, or new ones developed (perhaps focusing on specific conditions producing extremes), to enable the development of believable scenarios for extreme events. The bottom-up identification of conditions leading to extreme impacts may be useful for constraining the downscaling problem to only those climatic phenomena that are of relevance to the impact system being studied.

Descriptive scenarios. Where quantitative scenarios for extreme events are difficult to develop, an alternative approach is to develop descriptive scenarios that make use of what data are available, and expert judgement on expected changes in extremes. Such descriptive scenarios should be developed in partnership with stakeholders so that climate scientists are able to provide judgement that is understandable and of relevance to the stakeholders.

Guidelines for climate impacts assessors

Recognising that many researchers and impact assessors are not climate experts, but nonetheless may need to generate climate change scenarios (that may or may not include scenarios for extreme events), the working group came up with the following (non-exhaustive) list of issues that scenario generators should address:

- Where possible employ a bottom-up, stakeholder-defined definition of impacts that are of concern; this is equally the case for extreme events (impacts) and for changes in average conditions. The key point is to first identify thresholds that are dangerous for the stakeholder or system of interest, and then explore the climate information that is required to evaluate the threat of climate change to these thresholds.

- Read the relevant literature on climate change scenarios and the GCM simulations used to generate scenarios so that scenarios can be constructed with full knowledge of any limitations in the approach used and the GCM data employed. This is particularly the case for scenarios of changes in extremes, which are almost invariably subject to enhanced uncertainty.

- There is a need to be transparent about the techniques used to generate scenarios. This should include unambiguous reference to any GCM model version and integration that is used and a full description of any downscaling that is employed.

- Make use of meta-data from GCM centres. Before using GCM output, it is essential to understand what the model variables actually describe. In many cases, the physical phenomenon that the model variable describes may be different to the user's understanding of the term used to describe the variable.

- Make use of multiple GCMs. As noted earlier, use of output from several GCM integrations provides critical information on the robustness of a climate change signal: the greater the agreement between different GCMs, the more confident one can be that the derived scenario is a real climate change signal.

- In constructing scenarios for extreme events impact assessors have a heightened responsibility to evaluate their methodology in terms of (1) the realism of any GCM data used, (2) the ability of any downscaling technique that is used to represent extreme events realistically and (3) the appropriateness of any Extreme Value techniques for application to non-stationary phenomena.

Impediments to progress

The working group concluded with a discussion on existing impediments to progress in development climate change impacts science and scenario construction. Two major data-related 'bottlenecks' were identified.

Observed data. Identification and quantification of extreme events in the historical record requires good quality, long-term data. The same is so for downscaling techniques that make use of observed data for calibration or training. Therefore, there is a need to augment existing digital meteorological data with retrieval and digitisation of archived records from the first half of the twentieth century. While there have been some notable efforts to do this, much 'data rescue' remains to be done. In addition, there is a large amount of data already digitised, archived in various institutions across Europe, but not widely available outside the host organisation. There is a pressing need for these data sets to be more freely available, as required under the EC directive on 'free availability of data'. A strong recommendation emanating from this working group is that serious consideration should be given to the establishment of a European Climate Data Centre, along the lines of data centres managed by NOAA in the USA. The initial cost of such a data centre would be more than offset by the additional research stimulated, and by reducing the individual data retrieval costs of many climate-related research programmes and projects funded by the EC.

GCM data. Development of scenarios for extremes is particularly hampered by the type of data available from GCM centres. There was a general call for provision of daily and sub-daily data, both for surface climate variables, and for upper-level variables that are critical for many downscaling techniques. In addition, it was felt that there was a need for longer control runs, climate-change integrations that extended beyond 2100, and more ensemble integrations. The full potential of GCMs can only be explored by scenario scientists once detailed output is made available. The IPCC Data Distribution Centre, the UK Climate Impacts LINK project, and the Canadian Climate Modelling Centre were cited as examples of what could be achieved if effort and financial backing were put into GCM data provision.

Climate Scenarios for Water-Related and Coastal Impacts: Workshop Summary and Recommendations

Royal Netherlands Meteorological Institute (KNMI), P.O. Box 201,
3730 AE De Bilt, the Netherlands (Jules.Beersma@knmi.nl)

Jules Beersma

SUMMARY OF THE WORKSHOP

The goal of this workshop: 'Climate Scenarios for Water-Related and Coastal Impacts', was to review the construction and application of climate scenarios for impact studies with an emphasis on water-related areas. Three main impact areas were considered: hydrological impacts, coastal impacts and impacts at the interface between the two (e.g., river deltas). The workshop investigated the requirements for climate scenarios in each of these three areas. The question of whether impacts at the interface require more than a simple combination of the climate scenarios that are typical for hydrologic and coastal impacts was also addressed. In addition, the workshop explored which climate scenario generation methodologies, such as downscaling techniques and weather generators, are most suitable for each impacts area.

It was recognised during the workshop that for most water-related and coastal impacts it is changes in the (daily) variability of weather variables (including extreme events) rather than changes in the mean that are most important. The potential of general climate models (GCMs) to reproduce current climatic variability and to simulate changes in variability (and hence in weather extremes) is limited. For most water-related impacts some kind of post-processing or downscaling of GCM output is required in order to obtain sensible results. Two downscaling methodologies - dynamical downscaling (making use of regional climate models, i.e., RCMs, or of high-resolution time-slice experiments with GCMs) and statistical (or empirical) downscaling - were considered at the workshop.

For hydrological impact assessments, statistical downscaling seems the most suitable methodology to apply until RCMs are able to supply realistic daily variability in rainfall patterns at the catchment scale.

For coastal impacts, where the spatial coherence and temporal development of low pressure systems (and of the associated extreme wind fields) are crucial, dynamical downscaling is presently the most suitable methodology, partly because statistical downscaling is less developed in this impacts area. However, there is still a large amount of uncertainty about future changes in extra-tropical storm activity. Recently performed high-resolution time-slice GCM simulations confirm that there is a relationship between extra-tropical storminess and the North Atlantic Oscillation (NAO), but climate models disagree about future changes in the intensity of the NAO. Consequently, there is also a large degree of uncertainty about changes in storm surges.

It was concluded that the 'interface' is a field in its own right. A key issue here concerns the establishment of joint probabilities of 'hydrological' and 'coastal' parameters. These joint probabilities are likely to change as climate changes, but it is not known how they will change. It is important that the dependence structure of the variables of interest is preserved in any downscaling procedure adopted, which argues for the use of a single downscaling method that accounts for all variables.

Regardless of the impact area, a first step to determine the requirements for a climate scenario should be a sensitivity study using 'artificial scenarios'. Such a study helps to determine the minimum requirements regarding relevant meteorological variables, the desired spatial and temporal resolution of scenario information, and the types of changes in variability and extremes to which an impact area are especially sensitive. These requirements can be used to decide if 'downscaling' is needed and what kind of downscaling is most appropriate. They can also provide guidelines for tailoring existing techniques or developing new ones. Furthermore, in order to obtain a proper baseline or reference condition against which to compare the impacts of anthropogenic climate change, an assessment of the impacts of natural (decadal) climate variability should also be incorporated at this stage.

Workshop recommendations

- *Assessing downscaling techniques*

A desire was expressed for a systematic assessment of statistical and dynamical downscaling techniques. There is a need for comparison of results of different downscaling techniques but also for intercomparison with the results of the GCMs on which downscaling is based. A proper assessment of the performance of RCMs requires simulations with one RCM bounded by different GCMs as well as with different RCMs nested in one GCM. It was recognised that a fundamental comparison of downscaling techniques is not so easily performed. Although the IPCC Third Assessment Report (of Working Group I) will devote a chapter to the comparison of different scenario generation techniques, an assessment of the performance of those techniques is still required.

- *Availability of climate data*

The workshop recommended the establishment of a centrally co-ordinated 'European Climate Data Centre (ECDC)' by the European Commission. An ECDC should provide free and easy access to high temporal resolution (i.e., at least daily) data and meta-data from the beginning of the 20th century onwards. Detailed baseline climatologies, including extreme events, are essential for calibrating impact models as well as for the development and training of statistical (empirical) downscaling models. Efficient archiving and distribution of observed data allows researchers to spend more time on impact assessment and less time on data processing. It was recognised that there is still some friction between the EC directive on 'free availability of environmental data' and the data policy of most European national meteorological agencies.

- *Availability of model data*

In addition to the need for observed data, there is also a need for easy access to climate model data from both GCMs and RCMs. There was a general call for provision of daily and even sub-daily data, and for surface and upper level variables. To obtain some feeling for the performance of models, there is a need for meta-data (provided with the data) and for references to model validation or model comparison studies such as the Coupled Model Intercomparison Project (CMIP). Although the usefulness of the IPCC Data Distribution Centre (DDC) was acknowledged it does not fulfil the need for (sub-) daily data and meta-data. It was also felt that it would be useful to have guidelines on the use of scenario data like those available at the DDC (IPCC-TGCIA, 1999).

- *Selecting GCM outputs*

Although there have been calls from members of the impacts community to have a limited number of standard GCM outputs made available for use in impacts assessments, in practice this desire is difficult to fulfil. Many different criteria can be used to select model outputs. These vary according to the specific requirements of the user, and unless there are good scientific reasons for doing so (e.g., well-established errors in a model), it would be unduly restrictive for a data provider to prescribe the use of some GCM outputs and exclude others. Rather, impact researchers are encouraged to apply the criteria outlined in the IPCC guidelines on the selection and use of scenario data (IPCC-TGCIA, 1999) on a case-by-case basis.

• *Incorporating uncertainty*
Different types of uncertainty surround impact assessments. It was acknowledged that uncertainty should be adequately addressed in impact studies, acknowledging which uncertainties have been considered and which have been ignored. In order to quantify at least a part of the uncertainty in future projections, the use of ensembles (from ensemble runs and/or different GCM simulations) was promoted. Ensembles can be used to determine ranges of change or to adopt a more probabilistic framework for impact assessments.

• *Methodology versus policy-driven impact studies*
It was recognised that one can distinguish two types of impact studies, methodology-driven ones and policy-driven ones. Methodological impact studies are often undertaken to evaluate impact models or scenario methods (e.g., examining a new downscaling technique). Although they may also provide useful information on the sensitivity or response of a system to climate change, this is not their primary purpose. In contrast, policy driven studies are conducted with a specific policy-relevant question in mind (e.g., assessing the potential implications of climate change for dam safety).

Quite often impact studies of the first type have been used inappropriately to serve policy and stakeholders. It was regarded beneficial to focus more on the second type and to produce more policy-relevant information by inverting the conventional approach to analysis, i.e., by starting with the stakeholders who are in a position to determine critical impacts in their own sector of concern based on assessments of risk, safety and loss of money. Such an approach would demand a better dialogue between scientists and stakeholders to ensure that relevant information is passed on to the stakeholder.

• *Communication of knowledge*
The network of climate modellers, impact researchers, scenario developers and stakeholders that has been established during the two ECLAT projects should be maintained and extended. It is recommended that this network continue to be used to communicate new techniques and promising developments, serving both current and future needs for climate information in Europe and beyond.

REFERENCE

IPCC-TGCIA (1999) **Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment.** Version 1. Prepared by Carter, T.R., M. Hulme, and M. Lal, Intergovernmental Panel on Climate Change, Task Group on Scenarios for Climate Impact Assessment, 69pp. (Web address: http://ipcc-ddc.cru.uea.ac.uk/cru_data/support/guidelines.html)

Appendices

Page numbers

Appendix 1: Workshop Agenda

Wednesday 10 May 2000

12:30	**Lunch**
14:00	Opening/Welcome Günther Können (the Netherlands)
14:10	Goals of ECLAT-2 David Viner (UK)
14:20	Summary of ECLAT-2 EW-1 Representing uncertainties in climate and related scenarios for impact assessment Tim Carter (Finland)
15:00	**Keynote paper:** Stochastic downscaling methods to assess the hydrological impacts of Climate Change on river basin hydrology András Bárdossy (Germany)
15:40	**Coffee/tea break**
16:00	**Keynote paper:** Climatological changes in storm surges and river discharges: the impact on flood protection and salt intrusion in the Rhine-Meuse delta Pieter Jacobs (the Netherlands)
16:40	1st Working Group Assignments (Jules Beersma)
17:00	**Presentation:** Development of daily precipitation scenarios at KNMI Adri Buishand (the Netherlands)
17:40	Close
19:00	**Dinner**

Thursday 11 May 2000

09:00 **Keynote paper:** Scenarios for extra-tropical storm and wave activity: methodologies and results
Eigil Kaas (Denmark)

09:40 **Keynote paper:** Climate change effects on storm surges: methodologies and results
Roger Flather (UK)

10:20 1st meeting of Working Groups (2h:40 min)

13:00 **Lunch**

14:00 **Plenary - Working Group reports:**

14:00 Report of WG 1A: Hydrology
Rob Wilby (UK)

14:20 Report of WG 1B: Coastal impacts
John de Ronde (the Netherlands)

14:40 Report of WG 1C: Interface
Hans Middelkoop (the Netherlands)

15:00 **Coffee/tea break**

15:30 2nd Working Group Assignments

15:40 2nd meeting of Working Groups (2h:20 min)

18:00 Close

19:00 **Dinner**

Friday 12 May 2000

09:00	**Plenary - Working Group reports:**
09:00	Report of WG 2A: Artificial scenarios Linda Mortsch (Canada)
09:20	Report of WG 2B: Downscaling Chris Kilsby (UK)
09:40	Report of WG 2C: Variability and extremes Mark New (UK)
10:00	Discussion
10:30	**Coffee/tea break**
11:00	**Presentation:** Sustainable management and quality of water. An overview of related EU RTD activities with emphasis on the implications of climate change on hydrological regimes and water resources Panagiotis Balabanis (EU officer European water resources)
11:40	Summing up and recommendations Günther Können and Jules Beersma (the Netherlands)
11:50	Final discussion on the Workshop findings and recommendations
12:20	Workshop output and future ECLAT-2 activities David Viner (UK)
12:30	Closing remarks/Adjourn
13:00	**Lunch**

Appendix 2: List of Participants

Panagiotis Balabanis
European Commission
Research Directorate General
Directorate D.I - Preserving the Ecosystem I
Water Management and Quality
SDME 7/34
200 rue de la Loi
B-1049 Brussels
BELGIUM
Tel: +32-22953630
Fax: +32-22963024
E-mail: panagiotis.balabanis@cec.eu.int

András Bárdossy
Institut für Wasserbau
Universitätsbereich Vaihingen
Pfaffenwaldring 61
D-70550 Stuttgart
GERMANY
Tel: +49-711-685-4663
Fax: +49-711-685-4746
E-mail: bardossy@iws.uni-stuttgart.de

Elaine Barrow
Canadian Climate Impacts Scenarios (CCIS) Group
c/o Environment Canada - Prairie and Northern Region
Atmospheric and Hydrologic Science Division
2365 Albert Street, Room 300
Regina
Saskatchewan S4P 4K1
CANADA
Tel: +1-306-780-6049
Fax: +1-306-780-5311
E-mail: elaine.barrow@ec.gc.ca

Willy Bauwens
University of Brussels (Vrije Universiteit Brussel)
Laboratory of Hydrology
Pleinlaan 2
B-1050 Brussel
BELGIUM
Tel: +32-2629-3038
Fax: +32-2629-3022
E-mail: wbauwens@vub.ac.be

Björn Beckmann
Royal Netherlands Meteorological Institute (KNMI)
P.O. Box 201
3730 AE De Bilt
THE NETHERLANDS
Tel: +31-30-2206-402
Fax: +31-30-2210-407
E-mail: beckmann@knmi.nl

Thomas Beckmann
Potsdam Institute for Climate Impact Research (PIK)
Postfach 60 12 03
D-14412 Potsdam
GERMANY
Tel: +49-331-288-2650
Fax: +49-331-288-2600
E-mail: beckmann@pik-potsdam.de

Jules Beersma
Royal Netherlands Meteorological Institute (KNMI)
P.O. Box 201
3730 AE De Bilt
THE NETHERLANDS
Tel. +31-30-2206-475
Fax: +31-30-2210-407
E-mail: beersma@knmi.nl

Martijn Booij
University of Twente
Faculty of Technology & Management
Department of Civil Engineering
Discipline Group of Water resources Management
P.O. Box 217
7500 AE Enschede
THE NETHERLANDS
Tel: +31-53-489-2449
Fax: +31-53-489-4040
E-mail: m.j.booij@smj.utwente.nl

Henk van den Brink
Royal Netherlands Meteorological Institute (KNMI)
P.O. Box 201
3730 AE De Bilt
THE NETHERLANDS
Fax: +31-30-2210-407
Tel: +31-30-2206-705
E-mail: brinkvdh@knmi.nl

Iain Brown
UK Climate Impacts Programme
DETR/University of Oxford
12 St. Michael's St.
Oxford OX1 2 DU
UK
Tel: +44-1865-432074
Fax: +44-1865-432077
E-mail: iain.brown@ukcip.org.uk

Adri Buishand
Royal Netherlands Meteorological Institute (KNMI)
P.O. Box 201
3730 AE De Bilt
THE NETHERLANDS
Tel: +31-30-2206-450
Fax: +31-30-2210-407
E-mail: buishand@knmi.nl

Ana Cardoso
Portuguese National Council on Environment and Sustainable Development
Rua de S. Domingos a Lapa 26
200-835 LISBOA
PORTUGAL
Tel: +351-21-3929926
Fax: +351-21-3929929
E-mail: cnads.acardoso@ipamb.pt

Timothy Carter
Finnish Environment Institute
Box 140, Kesäkatu 6
FIN-00251 Helsinki
FINLAND
Tel: +358-40-740-5403
Fax: +358-9-40300-390
E-mail: tim.carter@vyh.fi

Richenda Connell
UK Climate Impacts Programme / DETR
University of Oxford
12 St. Michael's St.
Oxford OX1 2 DU
UK
Tel: +44-1865-432073
Fax: +44-1865-432077
E-mail: richenda.connell@ukcip.org.uk

João Corte-Real
Instituto de Ciencias Aplicada e 25 Tecnologia
Department da Fisica
Universidade de Lisboa Campo Grande EDF C1Piso 1
Lisboa
PORTUGAL
Tel: +351-1-757-3634
Fax: +351-1-757-36
E-mail: jcr@fc.ul.pt

Dennis Doortmont
Royal Netherlands Meteorological Institute (KNMI)
P.O. Box 201
3730 AE De Bilt
THE NETHERLANDS
Tel: +31-30-2206-885
Fax: +31-30-2210-407
E-mail: doortmon@knmi.nl

Martin Dubrovsky
Institute of Atmospheric Physics
Husova 456
50008 Hradec Kralove
CZECHIA
Tel: +420-49-526-3759
Fax: +420-49-526-3759
E-mail: dub@ufa.cas.cz

Roger Flather
CCMS - Proudman Oceanographic Laboratory
Bidston Observatory
Bidston Hill
Prenton CH43 7RA
UK
Tel: +44-151-653-8633
Fax: +44-151-653-6269
E-mail: raf@pol.ac.uk

Pieter Jacobs
RIZA, WST
Van Leeuwenhoekweg 20
3316 AV Dordrecht
THE NETHERLANDS
Tel: +31-78-6322612
Fax: +31-78-6315003
E-mail: p.jacobs@riza.rws.minvenw.nl

Eigil Kaas
Danish Meteorological Institute (DMI)
Lyngbyvej 100
DK-2100 Copenhagen Ø
DENMARK
Tel: +45 39 15 74 24
Fax: +45 39 15 74 60
E-mail: ek@dmi.dk

Chris Kilsby
Water Resource Systems Research Laboratory
Dept. of Civil Engineering
University of Newcastle
Newcastle upon Tyne
NE1 7RU
UK
Tel: +44-191-222-5614
Fax: +44-191-222-6669
E-mail: c.g.kilsby@ncl.ac.uk

Günther Können
Royal Netherlands Meteorological Institute (KNMI)
P.O. Box 201
3730 AE De Bilt
THE NETHERLANDS
Tel: +31-30-2206-451
Fax: +31-30-2210-407
E-mail: konnen@knmi.nl

Jason Lowe
Hadley Centre for Climate Prediction and Research
UK Meteorological Office
UK
Tel: +44-1344-856-883
Fax: +44-1344-854-898
E-mail: jalowe@meto.gov.uk

Luis Jose Mata
Center for Development Research
Ecology and Resource Management
Walter-Flex-Str. 3
D-53113 Bonn
GERMANY
Tel: +49-228-346879
E-mail: l.mata@uni-bonn.de

Kathy McInnes
CSIRO Atmospheric Research
Climate Impacts and Coastal Modelling
PMB#1 Aspendale, 3195
AUSTRALIA
Tel: +61-3923-94569
Fax: +61-3923-94444
E-mail: kathy.mcinnes@dar.csiro.au

Hans Middelkoop
Dept. of Physical Geography
Faculty of Geographical Sciences
Utrecht University
P.O. box 80.115
3508 TC Utrecht
THE NETHERLANDS
Tel: +31-30-2532-167
Fax: +31-30-2531-145,
E-mail: h.middelkoop@geog.uu.nl

Miroslaw Mietus
Institute of Meteorology and Water Management
Maritime Branch
Waszyngtona 42
PL-81-342 Gdynia
POLAND
Tel: +48-58-620-3532
Fax: +48-58-620-7101
E-mail: mietus@stratus.imgw.gdynia.pl

Linda Mortsch
Adaptation and Impacts Research Group
Environment Canada
c/o Faculty of Environmental Studies
University of Waterloo
Waterloo
Ontario N2T 2H3
CANADA
Tel: +1-519-888-4567 ext. 5495
Fax: +1-519-746-2031
E-mail: linda.mortsch@ec.gc.ca

Mark New
School of Geography
Mansfield Road
Oxford OX1 3TB
UK
Tel: +44-1865-271919
E-mail: mark.new@geography.oxford.ac.uk

Serge Planton
Meteo-France
CNRM
42 avenue Gaspard Coriolis
31057 Toulouse Cedex 1
FRANCE
Tel: +33-5-6107-9376
Fax: +33-5-6107-9610
E-mail: serge.planton@meteo.fr

John de Ronde
RIKZ
P.O. Box 20907
2500 EX Den Haag
THE NETHERLANDS
Tel: +31-70-3114-208
Fax: +31-70-3114-321
E-mail: j.g.dronde@rikz.rws.minvenw.nl

Agustín Sanchez-Arcilla
International Centre for Coastal Resources
Research (CIIRC)
Jordi Girona, 1-3, Edif. D-1
Barcelona E-08034
SPAIN
Tel: +34-93-401-6472
Fax: +34-93-401-1861
E-mail: agustin.arcilla@upc.es

Andreas Schumann
Ruhr-University Bochum
Institute for Hydrology and Water Management
IA 01/34
44799 Bochum
GERMANY
Tel: +49-234-32-22688
Fax: +49-234-32-14153
E-mail: andreas.schumann@ruhr-uni-bochum.de

Roger Street
Adaptation and Impacts Research Group
Atmospheric Environment Service
4905 Dufferin Street
Downsview
Ontario M3H 5T4
CANADA
Tel: +1-416 739-4271
Fax: +1-416 739-4297
E-mail: roger.street@ec.gc.ca

Uwe Ulbrich
Institut für Geophysik und Meteorologie
Kerpener Str. 13
D-50923 Köln
GERMANY
Tel: +49-221-470-3688
Fax: +49-221-470-5161
E-mail: ulbrich@meteo.uni-koeln.de

David Viner
Climate Impacts LINK Project
Climatic Research Unit
University of East Anglia
Norwich NR4 7TJ
UK
Tel: +44-1603-592089
Fax: +44-1603-507784
E-mail: d.viner@uea.ac.uk

Robert Wilby
Division of Geography
University of Derby
Kedleston Road
Derby DE22 1GB
UK
Tel: +44-1332-591726
Fax: +44-1332-622747
E-mail: kgac513@unix1.derby.ac.uk

Rafal Wójcik
Royal Netherlands Meteorological Institute
(KNMI)
P.O. Box 201
3730 AE De Bilt
THE NETHERLANDS
Tel: +31-30-2206-429
Fax: +31-30-2210-407
E-mail: wojcik@knmi.nl

Joost de Wolff
KEMA Sustainable
KST/ENR
P.O. Box 9035
6800 ET Arnhem
THE NETHERLANDS
Tel: +31-26-3563556
Fax: +31-26-4458279
E-mail: j.j.dewolff@kema.nl

Appendix 3: Relevant web sites

The Adaptation and Impacts Research Group (AIRG)
W ,orks within the Atmospheric and Science Climate Directorate - a branch of the Atmospheric Environment Service (AES) of Environment Canada
http://www.msc-smc.ec.gc.ca/airg/airg.htm

CIIRC
Centre for interdisciplinary applied coastal resources research
http://www.upc.es/ciirc/

Climatic Research Unit (CRU)
Research into natural and anthropogenic climate change.
http://www.cru.uea.ac.uk/

Climate Impacts LINK Project
Provision of the results from the Hadley Centre's climate change experiments (e.g. HadCM2 and HadCM3) and accompanying observational datasets.
http://www.cru.uea.ac.uk/link/

CSIRO: Regional Climate and Ocean Modelling
Develops and runs high-resolution atmospheric models for studies of climate and extreme weather, and develops ocean models that are coupled to global climate models.
http://www.dar.csiro.au/res/regmod/Default.htm

Deutsches Klimarechenzentrum (DKRZ)
Service centre for climate researchers in Germany, responsible for the installation and operation of a high-performance computer centre for basic and applied research into climatology and related areas.
http://www.dkrz.de

DMI (Danish Meteorological Institute): Climate Research
The Climate Research Division at DMI is associated with the Danish Centre for Climate Research. DMI participates in a large number of national and international research projects. The main emphasis is on global and regional climate modelling and seasonal prediction.
http://www.dmi.dk/f+u/klima/english/contents.html

ECLAT-2
Improving the understanding of the application of results from climate model simulations to studies of climate change impacts.
/www.cru.uea.ac.uk/eclat

Environmental Change Institute (Environmental Change Unit), University of Oxford, UK
Centre for teaching and interdisciplinary research on the environment and sustainability
http://www.eci.ox.ac.uk/

Environmental and Societal Impacts Group, National Centre for Atmospheric Research, Colorado, USA
Environmental change and responses to such change
http://www.esig.ucar.edu/esig.html

Environment Canada
Climate change and water.
http://www.ec.gc.ca/water/en/nature/clim/e_clim.htm

European Commission Directorate General XII (DGXII)
Development and implementation of European Union Policy on Research and Technological Development, promotion of public knowledge of science and technology.
http://europa.eu.int/comm/dg12/

The Hadley Centre for Climate Prediction and Research
Jointly funded by the United Kingdom Department of the Environment and the United Kingdom Meteorological Office – assesses both natural and man-made climate change.
http://www.meto.govt.uk/sec5/sec5pg1.html

Hadley Centre
Provision of an authoritative assessment of natural and anthropogenic climate change for the United Kingdom government.
http://www.meto.govt.uk/sec5/sec5pg1.html

Inter-governmental Panel on Climate Change - Data Distribution Centre (IPCC-DDC)
Distribution of consistent and up-to-date scenarios of changes in climate and related environmental and socio-economic factors for use in climate impacts assessments.
http://ipcc-ddc.cru.uea.ac.uk/

Institute for Hydrology, Water Management and Environmental Engineering
Research includes: Hydrology, Water Management, Remote sensing in hydrology and water management, Integrated investigation according to environmental tasks and the use of sustainable development.
http://www.hydrology.ruhr-uni-bochum.de/Allgemeines/lehrstuhl.info_eng.html

IPCC-Geneva
Established by WMO and UNEP to assess the scientific, technical and socio-economic information relevant for the understanding of the risk of human-induced climate change.
http://www.ipcc.ch/

IPCC Special Report on Emissions Scenarios (SRES)
Development of emissions scenarios and scenario database.
http://www.sres.ciesin.org

KNMI: Climate Research
Climate Research consists of 5 divisions: Oceanography, Atmospheric Research, Predictability, Atmospheric Composition, and Climate Analysis.
http://www.knmi.nl/onderzk/

Koninklijk Nederlands Meteorologisch Instituut (KNMI)
Netherlands national research and information centre for climate, climate change and seismology; operational centre for weather and climate observation, weather forecasting and monitoring of seismic activity.
http://www.knmi.nl

Laboratoire de Météorologie Dynamique (LMD)
Mechanisms, evolution and prediction of meteorological and climatic phenomena
http://www.lmd.jussieu.fr/

METEO-France
Research and services related to weather and climate.
http://www.meteo.fr/

PEW Centre for Global Climate Change: relevant reports
http://www.pewclimate.org/projects/env_science.cfm
The Science of Global Climate Change: Global and US Perspectives
http://www.pewclimate.org/projects/clim_change.cfm
Water and Global Climate Change: Potential Impacts on US Water Resources
http://www.pewclimate.org/projects/env_sealevel.cfm
Sea-Level Rise and Global Climate Change: A Review of Impacts to US Coasts

Potsdam Institute for Climate Impact Research (PIK)
Research into the dynamics of global change, bringing together natural and socio-economic processes.
http://www.pik-potsdam.de/

Proudman Oceanographic Laboratory
Research in physical oceanography with a special focus on shelf seas processes, global sea levels and tides.
http://www.pol.ac.uk/

RIZA
Institute for Inland Water Management and Waste Water Treatment. RIZA has four main departments: Wetland Development and Restoration, Water Systems, Water Pollution Control, and Information and Measurement Technology.
http://www.minvenw.nl/rws/riza/home/index_uk.html

STOEC
Storm-track upper Ocean interactions and impact on European Climate (STOEC); EEC Framework IV project funded from December 1997 until July 2000
http://www.met.reading.ac.uk/cag/STOEC/index.html

STORMINESS
Project examining storminess along the Atlantic coastline of the European Union. The broad approach is to identify trends, determine impacts, and develop models that reflect the coastal response to storminess and relate storminess to climate change.
http://crc.ucc.ie/pages/research/storminess.htm
http://www.nes.coventry.ac.uk/geography/storms/default.htm

STOWASUS-2100
Regional STOrm, WAve and Surge Scenarios for the 2100 century
http://www.dmi.dk/pub/STOWASUS-2100/

The UK Climate Impacts Programme
Established by the Government's Department of the Environment, Transport and the Regions (DETR) to provide a stakeholder-led assessment of climate change impacts on the UK.
http://www.ecu.ox.ac.uk/ukcip.html

WASA
The European project set up for verifying, or falsifying hypotheses of a worsening storm and wave climate in the Northeast Atlantic and its adjacent seas in the present century.
http://w3g.gkss.de/G/Mitarbeiter/storch/wasa.html

Water Resource Systems Research Laboratory
Numerical modelling of hydrology, water resources and groundwater, including climate and land use change impact assessment, integrated surface and groundwater pollution control, decision support and related hydroinformatic systems.
http://www.ncl.ac.uk/wrgi/wrsrl/

WRINCLE
Water Resources: the Influence of Climate Change
http://www.ncl.ac.uk/wrgi/wrsrl/projects/wrincle/wrincle.html