Climate scenario development: time series, extremes and probabilities

Work package leader : Dr. ir. W. Hazeleger (KNMI)

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1 Description work package

1.1 Problem definition, aim and central research questions

Climate scenarios represent estimates of possible future climate changes. In 2006 KNMI published 4 discrete scenarios for the Netherlands based on global and regional climate model output and scaling relationships. These scenarios serve as a standard for climate impact research and guide adaptation policies. Since then, stakeholder consultations indicated that there is need for extra information, in particular on local extremes, time series of future weather and on probabilities of changes. To address this, a new generation scenarios will be released in 2012/13 based on newest information available.

With the 5th assessment of IPCC coming up, new climate model output will be generated and new experimental setups have been developed, such as decadal predictions (Smith et al. 2007) and high resolution non-hydrostatic simulations (CORDEX, CMIP5, ENSEMBLES). Also, knowledge on climate change processes has improved (e.g. changes in icecaps; Velicogna 2009) and new probabilistic methods have been constructed (e.g. Tebaldi et al. 2005). The latter led to new probabilistic scenarios for the United Kingdom (UKCP09), obtained from global models combined with statistical downscaling.

A wealth of new climate information is available. The information can be used to describe different sources of uncertainties: model uncertainty, emission scenario uncertainty, initial condition uncertainty, natural climate fluctuations and structural uncertainty. Natural fluctuations dominate climate changes up to decadal time scales and emission scenario uncertainty dominates on longer time scales. Knowledge on the uncertainties can guide the choice of how to construct climate scenarios. By providing weights to an ensemble of climate simulations, probabilistic scenarios can be constructed. When model and structural uncertainty dominates, process knowledge is needed. For instance when estimating icecap contributions to sea level changes.

Within this workpackage we will capitalize on the new information and build upon newly developed scientific approaches to provide a scientific underpinning to a next generation climate scenarios. The specific scientific question we address is:

How can uncertainty of future climate change predictions and projections be represented in time series and scenarios of future climate change?

New ensembles of global and regional climate model data allow us to analyze changes from global to regional scales. This information is required to make probabilistic scenarios. New statistical methodologies will be developed to assess changes in extremes. In order to produce physically consistent time series of change, we will use novel weather prediction techniques in climate models at high resolution to produce time series from models directly. Finally, for the Netherlands scenarios of sea level are extremely relevant. The largest unknowns are associated with disintegration of ice caps.

In the projects we will:

- Make an inventory of uncertainties in new global and regional climate and climate impact projections and predictions (WP 2.1)
- Develop new techniques, using statistics (WP 2.2) and climate models (WP 2.3), for producing time series and scenario’s for extremes in future climate.
- Develop knowledge on key processes of sea level rise, where models do not suffice (WP 2.4)

1.2 Interdisciplinarity and coherence between the projects

Throughout the workpackage uncertainties associated with climate change are addressed in different ways. We will assess uncertainties (2.1), develop process knowledge (2.4) and develop new methodologies on quantifying uncertainties (2.2; 2.3). The acquired knowledge will guide the development of a new generation of scenarios. The approach crosses different disciplines. Within climate research, a wide range of expertise is covered, involving regional and global climate modelers, statisticians and sea level experts. However, the interdisciplinary character is primarily found in the translation to climate impacts.

In WP2.1 we will work actively together with Theme 1 (Water Security, WP 4.1), Theme 7 and 8 (Decision Support).

Within Theme 6, results from regional climate models, studied in WP 1, will be used in WP 2.1 and 2.2. Vice versa, we will deliver data on large-scale climate changes (boundaries from global climate models for regional models generated in WP 2.3) to WP 1. We will work actively with WP 3 and 4 on providing knowledge on uncertainties, in particular when it comes to use of climate scenarios by stakeholders in the hotspots

1.3 Stakeholders

The stakeholders are users in the hotspots of the Knowledge for Climate program, in particular mainport Schiphol, major rivers, shallow waters and peat meadow areas. For Schiphol these are primarily capacity planners of the airport, for river discharge and shallow lakes these are the water boards and water managers. The sea level scenarios are of direct relevance to the water defense managers and water boards. It is expected that the results will feed into the developing national “Deltaprogramma” on spatial planning of the delta of the Netherlands.

2 Project 2.1 Assessment of uncertainties in regional climate change

Project leader: Dr. ir. W. Hazeleger

2.1 Problem definition, aim and central research questions

Problem definition

Uncertainty is inherent to the science of climate change. For adaptation uncertainty can be taken into account in different ways. For instance, when no-regret measures are anticipated, upper bounds of possible climate changes with a long time horizon are most relevant. Flexible adaptation measures require insight in various sources of uncertainty (emissions, model quality, natural variability) in order to respond timely to climate changes. In some (hydrological) applications, this uncertainty range is expressed as probability density functions of climate variables (e.g. Tebaldi et al 2008; New et al 2007). This probabilistic approach is the key component of the recently published UKCP09 climate change scenarios. Alternatively a limited number of discrete scenarios can be used (such as the KNMI’06 scenarios, based on scaling relationships expressing global change variables from models to the local

scale). These have been used in a study for estimating future flood risks and effectiveness of flood management levels in the Netherlands (AVV project, e.g. Brouwer et al 2007). The optimal way to take uncertainties of future climate into account depends, amongst many other issues, on the chosen adaptation strategy, the available tools, the spatial scales and the considered time horizon.
In this project we will quantify uncertainties in future climate projections and predictions for different time and spatial scales and for different variables, in order to guide the development of adequate climate change scenarios. We will span the entire range of uncertainties between global emissions to ultimately the local climate impact assessment. We will use newest model results and refine existing methods of weighting and combining projections (e.g. Giorgi and Mearns 2002, Tebaldi et al 2005), tailored to the use of the information by the hotspots. Two case studies related to the hotspots in the overall Knowledge for Climate program, one on river discharge and one on winds, will be included as an illustration of the use of the constructed scenarios.

The general research question is:

What are the uncertainties in predictions and projections of future climate change and its impacts? How can this uncertainty optimally be represented in scenarios to be used by decision makers in 'hotspots' of climate change?

This leads to the following specific objectives that will be addressed in this project:

- To obtain insight in the uncertainties in existing and new global and regional climate simulations at a range of spatial and temporal scales, with an emphasis on meteorological parameters needed by hotspots
- To obtain insight in the uncertainties in a limited number of climate impact parameters
- To provide guidance in developing climate change scenarios of hotspot-relevant climate change variables (water management; 'Major Rivers hotspot' and airport capacity management; 'Schiphol hotspot')

2.2 Approach and methodology

Current state-of-the-art

Various techniques exist to quantify uncertainties of different origin. Model uncertainty is handled by analyzing multimodel ensembles (e.g. Meehl et al. 2007), perturbed parameter experiments (Murphy et al. 2004) or stochastic parameterizations. Natural variability, due to the chaotic nature of the atmosphere and low-frequency variability in climate, is handled by analyzing large ensembles of one model (e.g. Sterl et al. 2008). Emission uncertainty is dealt with by analysing a range of emission scenarios of GHGs and aerosols. Initial condition uncertainty is of interest when addressing near-future (decadal) predictions, starting from observed initial states currently being developed (e.g. Smith et al. 2008; CMIP5 WCRP). Regional and local downscaling uncertainty involves the use of a range of regional climate modelling archives (PRUDENCE, ENSEMBLES) and high resolution (several km) non-hydrostatic models such as HARMONIE (developed in tranch 1 of the Knowledge for Climate program and used in WP 1).Finally, the translation of climate change into local impacts involves the use of a range of impact assessment model versions and statistical techniques (New et al 2007; Tebaldi and Lobell 2008; Hingray et al 2009). There is *large confidence* in global and continental warming due to human emissions of greenhouse gases, there is *some confidence* in continental scale projections of precipitation, but there is only *indicative* climate change information at the local scales (see Hawkins and Sutton 2009). It is the goal of this study to quantify this uncertainty range across scales, resulting in climate change information that is useful for application in local 'hotspot' studies.

Methodology

The PhD project is subdivided into 3 steps.

1. *Evaluation of uncertainties in global and regional climate model simulations,* by:
    a. Analysis of variance (ANOVA) in ensembles of climate runs (see below), for time scales of a year to a century and from global to regional scales for a variety of meteorological variables.
    b. Fitting simple statistical models (e.g. regression models, extreme value distributions) to the data to evaluate the origin of the spread.
    c. Determining the biases of the simulated mean climate, the trend and the variability. The observational record of 20th and early 21st century climate is long enough to allow for this (novel) evaluation of trend and variability.
2. *Evaluation of uncertainties in local climate impacts (for a limited set of cases)*, by:
    a. Assessing uncertainties in meteorological parameters relevant to hotspots (rainfall sums for river discharge, local wind extremes etc).
    b. Using resampling techniques to create long time series of derived parameters.
    c. Using a relatively simple impact model (such as the river routing model TRIP) forced by a range of model outputs and run with a range of model parameter setting
3. *Guided comparison of various forms of future climate information*, by:
    a. Creating a probabilistic (model output weighted) climate change framework, using insight in the various sources of uncertainty, from the global scale to the local climate impact level.
    b. Creating a limited number of discrete scenarios, that samples the spread in relevant, often multivariate, climate impact parameters.
    c. Evaluate the usefulness of options (a) and (b) for a range of climate adaptation strategies.

Available climate model simulations for different sources of uncertainty

- **Global model and climate response and emission scenarios**: CMIP3 (Meehl et al 2007) and upcoming CMIP5 ensemble.
- **Natural variability**: 17 member ensemble of the global ECHAM5/OM model from the ESSENCE project (Sterl et al, 2008)
- **Initial conditions**: decadal prediction ensembles from CMIP5, EU-ENSEMBLES, EU-THOR, EU COMBINE projects and obtained with EC-Earth

- **Regional downscaling**: PRUDENCE and ENSEMBLES output (available regional climate simulations: http://ensemblesrt3.dmi.dk) and upcoming CORDEX
- **Local downscaling**: Case studies with non-hydrostatic regional climate models (HARMONIE)

2.3 Scientific deliverables and results

Paper 1: Assessment uncertainties from global to regional scales
Paper 2: Assessment uncertainties climate impact
Paper 3 & 4: Confronting methods for representing uncertainties: Bayesian and scenario methods
The 4 scientific papers form the basis for the PhD thesis.

2.4 Integration of general research questions with hotspot-specific questions

The choice of the analyzed parameters is driven by needs of hotspots of the Knowledge for Climate program. We focus on needs for Schiphol airport (primarily meteorological variables) and Major Rivers (variables needed for discharge models). In earlier stakeholders-meetings together with the "Climate Knowledge Facility" (see www.kennisvoorklimaat.nl), the needs were articulated by the hotspots. Hydrological case studies will be conducted in WP 3 (slow track) and will benefit from the knowledge generated here. We will collaborate with Theme 1 (Water Security, WP 4.1) and within Theme 6 in WP 3 and 4 where the use of climate information in hotspots is studied.

2.5 Societal deliverables and results

Insight in uncertainties in recognizable parameters for decision makers associated with hotspots (in particular relevant to water management and airport capacity management). We work with WP 3 and 4 in order to deliver information on uncertainties. Regular project meetings will be used for that. Furthermore, we work with the case studies in WP 3 in to-the-point hotspot relevant case studies.

KNMI already provides practical information services on climate. The knowledge generated in this project will lead to improved regional scenarios. Knowledge of changes climate extremes is essential to manage climate-related risks to humans, ecosystems and infrastructure, and develop resilience through adaptation strategies.The results will support, through services in WP 4, climate policy at local, national and regional scales. It is information on the longer time scale (several decades ahead) that is needed for governments to minimize to the societal and environmental impacts of climate variability and change.

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3 Project 2.2 Analysis of extremal behavior under non-stationary climate conditions

Project leader: Dr. A.M.G. Klein Tank and Dr. T.A. Buishand (KNMI) Prof. dr. ir. G. Jongbloed (TUD/EURANDOM)

3.1 Problem definition, aim and central research questions

Changes in extreme weather events have significant impacts and are among the most serious challenges to society in coping with a changing climate. According to the IPCC (2007), ‘confidence has increased that some extremes will become more frequent, more widespread and/or more intense during the 21st century’.

Many practical problems require knowledge of the behaviour of extreme values. In particular, the infrastructures we depend upon for food, water, energy, shelter and transportation are sensitive to high or low values of meteorological variables. For example, high precipitation amounts and resulting stream flows affect sewerage systems, dams, reservoirs and bridges.

Most existing systems for water management and other infrastructure have been designed under the assumption that climate is stationary. This basic concept from which engineers work assumes that weather variations occur, but with properties which are constant with time, and which fluctuate around an unchanging mean state. This assumption of stationarity is still common practice for the design criteria for (the safety of) new infrastructure, even though the notion that climate change may alter the mean, variability and extremes of relevant weather variables is now widely accepted (e.g. Milly et al., 2008).

For precipitation events that occur relatively often, there is evidence of change already over the past decades. The majority of station observations in the Netherlands and surrounding areas show an increase in the number of days per year with at least 20 mm precipitation between 1946 and 2008. Since 1950, the precipitation thresholds which are exceeded on average once per year in the Dutch records have increased by about 10% (Klein Tank and Lenderink, 2009).

It is possible to account for non-stationary conditions (climate change) in extreme value analysis (Coles, 2001), but the best way to do this is still under debate amongst scientists. Nevertheless, adaptation strategies to climate change should now begin to account for the decadal scale changes in extremes observed in the past century, as well as projections of future changes in extremes such as those obtained from climate models (Klein Tank et al., 2009). The observed and/or projected changes (although highly uncertain) may be so large that simply relying on traditional methods of extremes estimation for design of infrastructure would no longer appear to be prudent.

The central research question addressed in this project is: “how should we account for a changing climate when assessing and estimating extremes?” The extremes may be changing in such a way as to cause changes that are larger than would simply result from a shift of the entire probability distribution to a higher range (Hegerl et al., 2004; IPCC, 2007). Pertinent research questions include: how should the observed changes in extremes in the past be assessed and included in the analysis; what is the best way to deal with the available future climate model projections; how is extremal behaviour influenced by the natural variations in large scale climate variables, what is the benefit of data pooling, how should spatial dependence of extremes (multivariate) be included?

3.2 Approach and methodology

Extreme value theory is used to evaluate the intensity and frequency of rare events that lie far in the tails of the probability distribution of weather variables. Such analysis often requires probability estimation of events that are unprecedented in the available record, say events that occur once in a hundred or thousand years (large quantiles of the distribution), while the observation series may be only about 50 years long. For an introduction to extreme value theory one can read, amongst many publications, Coles (2001) or Beirlant et al. (2004).

There are two common approaches to estimating the probability of extreme events: the “peaks over threshold” or POT method, and the “block maximum” method. The POT method is based on the result that conditional on the fact that an observation exceeds a preset high level, its distribution can be approximated by a Generalized Pareto Distribution (GPD). The block maximum method is based on the result that the distribution of block maxima (e.g. maxima over a year or season) can be approximated by a Generalized Extreme Value (GEV) distribution.

Nonstationarity can be incorporated by allowing the GEV (or GPD) parameters to depend on time-varying covariates. Apart from full parametric models, nonparametric smoothing using local likelihood models (Hall and Tajvidi, 2000) and semiparametric techniques based on a penalized likelihood (Chavez-Demoulin and Davison, 2005) have been considered. For POT modeling of nonstationary data time-varying thresholds (Coelho et al., 2008) and preprocessing methods (Eastoe and Tawn, 2009) have been suggested.

The domain of this study will be Western Europe, focusing in particular on the Netherlands, Belgium, Luxemburg, Northern France and part of Germany. Both observational data and climate model simulations will be analysed. The steering variables which have been used to construct the KNMI’06 climate change scenarios for the Netherlands will be considered as covariates. Another candidate is the so-called North Atlantic Oscillation signal.

Changes in rare extreme events may be difficult to detect locally. Therefore certain assumptions will be made (and tested) regarding the spatial variation of distributional parameters from one location to another. For example, given that large-scale climatic influences may be more or less homogeneous in a given area, it may be appropriate to assume that the shape parameter in the GEV distribution has the same value at all locations in that area. Such an assumption would enable “data pooling” in which records from multiple stations are combined to form a larger data sample (see e.g. Hanel et al., 2009). Other approaches could include more sophisticated spatial modelling, perhaps using Kriging of the extreme value distribution parameter estimates . We will investigate whether the spatial pattern of certain covariates (e.g. seasonal mean values) can be used to restrict the number of parameters in the model.

It is also interesting to investigate the dynamics of extremal behavior under a gradual change of climate. Based on observational data and output of climate models, this dynamics will be studied using regression models with the large scale climatological parameters as explanatory variables and measures of extremity as response. Qualitative and quantitative assumptions on the behavior of the regression function (monotonicity, smoothness, convexity; Robertson et al., 1988; Wand and Jones, 1995) can be incorporated to obtain nonparametric estimators for the regression function that can be used for extrapolation purposes, e.g. to obtain short term (decadal) predictions.

3.3 Scientific deliverables and results

Starting point of this project will be the preliminary work by Hanel and Buishand (2009), who analyzed the 1-day summer and 5-day winter precipitation extremes over the Rhine basin in 15 RCM simulations. They fitted a dynamic GEV model, allowing the parameters to vary with time. Related approaches will be developed and other types of precipitation extremes and temperature extremes will be considered. Nonparametric and semiparametric models in which the GEV parameters vary smoothly over time will be considered. As an alternative for the block maximum method (using the GEV distribution), the feasibility of the POT method will be explored. In addition, various informative covariates will be incorporated in the statistical models.

The results contribute to the objectives of the work package. Estimates of changes in extremes and their uncertainties will be based on sound statistical theory.

At least 4 papers will be delivered, of which one paper in a high-profile international statistical journal, explaining the methodologies developed. Furthermore, at least one presentation will be given at an international scientific conference. In addition, user-friendly software written in the statistical package R and in a low-level programming language, if needed for reasons of speed or massive data handling.

3.4 Integration of general research questions with hotspot-specific questions

The results of this project have direct relevance for the hotspots. However, there is no one-to-one link with specific questions posed by the hotspots. The emphasis is on advancing the science with respect to extremes estimation under nonstationary conditions. Many applications require this type of knowledge on extremes. The types of extremes studied in this project relate to the questions posed by the hotspots.

For practical applications, a key question of interest concerns the interpretation of estimated return values. In the case of a stationary climate, return values have a clear interpretation as the value that is expected to be exceeded once every return period, or with probability 1/(return period) in any given year. In a changing climate, return values can have several different interpretations. These different interpretations will be addressed in the project.

3.5 Societal deliverables and results

KNMI already provides practical information services on weather and climate extremes, such as frequency tables for the occurrence of extremes and maps of return periods of extremes. The knowledge generated in this project will lead to improved information services on extremes under climate change conditions. Knowledge of changes in weather and climate extremes is essential to manage climate-related risks to humans, ecosystems and infrastructure, and develop resilience through adaptation strategies.

The results will also contribute to the next generation of KNMI climate scenarios for the Netherlands, which are planned for 2013.

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4 Project 2.3 Generating dynamically consistent future climate scenarios under persistently anomalous atmospheric circulation

Project leader: Dr. Gerard van der Schrier

4.1 Problem definition, aim and central research questions

Regional climate change is a superposition of the global change, changes in the atmospheric circulation and local feedbacks. For instance, an increased frequency of easterly winds during summer will warm western Europe more than the increase of the global-mean temperature will explain. While the increase of global-mean temperature is relatively well predictable, climate models disagree on changes in the large-scale circulation, making regional climate predictions less reliable. One of the consequences is that often statistical techniques are used to derive local climate information. This implies that physical consistency between different meteorological variables may be violated.

This is the motivation to address explicitly possible changes in atmospheric circulation in climate change scenarios. In its 2006 climate change scenarios, KNMI has therefore added the effects of possible feedbacks between different climate phenomena. We here propose to use a state-of-the-art climate model to investigate weather characteristics of a possible climate in 2050, taking into account circulation changes by forcing the model to reproduce, in a dynamically consistent way, the desired circulation change.

Using KNMI's state-of-the-art climate model, simulations of future weather are made under conditions that prevail in 2050. In these simulations, a new technique for introducing optimal tendency perturbations, recently developed at ECMWF, is used. The model is adjusted to produce an atmospheric circulation over the North Atlantic sector which is characterized by a more persistent west circulation in winter and a more persistent east circulation in summer. This will then be consistent with the KNMI '06 G+ and W+ scenarios. The benefit of using this technique is that the average atmospheric circulation is modified while ate the same time synoptic scale variability is able to adjust to these large-scale circulation adjustments. Next to a dynamically consistent response on the synoptic scale, these simulations will also see dynamically consistent changes in the boundary conditions to the atmospheric model, like soil moisture, sea surface temperatures, snow cover and the Atlantic Meridional Overturning Circulation.

The scientific questions of this proposal relate to identifying and quantifying feedback processes between atmospheric dynamics and its boundary conditions under climate of the year 2050 in which the large-scale atmospheric circulation has a more persistent westerly character in winter and a more persistent easterly character in summer over the North Atlantic sector. This will provide a dynamically picture of future weather under 2050 conditions. Furthermore these studies will lead to a better underpinning of the uncertainty imposed by the large scale circulation on regional climate changes.

Specifically, the feedbacks of interest include the interaction between decreased levels of soil moisture, either due to enhanced potential evapotranspiration or decreased summer precipitation, and rising temperatures. The combination of dry soils and a continued high level of potential evapotranspiration lead to a consistent shift in the radiation balance where reduced levels of the latent heat flux are compensated by an increase in the sensible heat flux, leading to increased temperatures. Another feedback targeted by these studies is the rise in surface temperatures of the North Sea, leading to intensified precipitation extremes, due to increased evaporation. A third feedback involves large-scale changes in snow cover over the European continent and how these relate to a 2050 climate with more persistent west circulation. Snow cover is closely coupled to Earth's radiation balance and strongly influences both daily maximum and minimum temperatures. The proposed studies will look into reduced snow cover in eastern and northern Europe and its feedback on length or severity of cold spells in western Europe. Finally, the studies will investigate a response of the Atlantic Meridional Overturning Circulation. Previous studies have identified a link between atmospheric circulation over the North Atlantic sector and the formation of deep water in the North Atlantic ocean. This proposal will identify and quantify this feedback.

4.2 Approach and methodology

The climate model used here is the EC-Earth model. Its atmospheric part consists of IFS, the ECMWF Numerical Weather Prediction model. This model is modified in order to meet the requirements of climate research. It is very well suited to the type of research proposed here since it outperforms competing climate models in the simulation of essentials of the atmospheric circulation over the North Atlantic sector.

To reproduce the KNMI'06 W+/G+ scenarios, the model has to be forced to produce a large-scale circulation that favours eastern (western) winds over Europe during summer (winter). This forcing is an additional forcing perturbation to the model tendencies and is computed using a Forcing Sensitivity (FS) calculation. Such a FS determines tendency perturbations, which, when applied in the climate model, will enhance the projection onto a specified target after a forecast of several days. The modification, or bias-correction, of the atmospheric circulation change which characterizes the climate scenario is captured in this target pattern. A climate simulation will consist of a sequence of many of these forecasts. The specified circulation will be recovered at the end of each forecast, which will draw the mean climate state towards the specified circulation. Each forecast will involve the calculation of a new set of FS fields.

In order to keep the methodology as lucid as possible, and to be able to make simulations of at least 30 years length, we intent to do the FS calculations using a dressed-down version of the EC-Earth model. In this latter version, the resolution will be reduced to T95 and the assumption is made that over the timespan of each forecast, boundary conditions like SSTs, soil moisture or snow cover will not drastically change; a valid assumption if the length of the forecasts remains limited to a few days.

The Forced Sensitivity calculations require the use of a tangent model and its adjoint of the atmospheric component of EC-Earth. Both are available. Moreover, these type of experiments have been performed with a much simpler model, focusing on past climates rather than future climates, and the ECMWF IFS model, using the same Forced Sensitivity calculations, is currently used in climate analysis simulations.

After an initial phase in which the model is set-up to make the FS calculations, we will demonstrate the validity of the model set-up, including the validity of the simplifications. Parallel to this, the PhD student will have to become familiar with the EC-Earth model and the details of the Forced Sensitivity calculations. After completion of these initial phases, the actual simulations and control simulations of 2050 climate without a forced persistent change in the atmospheric circulation are made and subsequently analyzed.

4.3 Scientific deliverables and results

1. A platform on the basis of a state-of-the-art GCM in which sensitivity experiments to changes in large-scale atmospheric circulation can be tested.
2. Dynamically consistent time series of multivariate climate parameters. These results can be off-set to a purely statistical approach in generating time series of climatic parameters under future weather conditions.
3. Identification and quantification of feedbacks within the climate system under 2050 climatic conditions, with atmospheric circulation changes as envisaged under the KNMI'06 scenarios.
4. The simulations will provide dynamically consistent input data for downscaling studies using Regional Climate Models. This constitutes a major link between this initiative and the regional approach of WP1 which will use boundary conditions for regional models obtained from this project.

4.4 Integration of general research questions with hotspot-specific questions

The climate simulations for future weather of this proposal will generate dynamically consistent time series of multivariate parameters under conditions prevalent in 2050, which is one of the main points of interest of the hotspots. It allows for an analysis of future weather conditions in which any incoherency between climate parameters is avoided.

The intended climate simulations will offer new insights how climate change affects aspects of daily airport management. These aspects include cloudiness, extreme precipitation, the frequency and severity of storms and wind direction. Moreover, the number of days with snowfall or frost under 2050, which are likely to decrease, will be quantified in this proposal. Heavy precipitation events, which can have large impact on the local water management, and their dependence on circulation regimes can be modeled, making it possible to advise local water managers on the necessary future dimension of their water handling capacity.

4.5 Societal deliverables and results

Two important contributions to society will be made by this study. The uncertainty in future climate change will be curtailed by identifying and quantifying climate feedback processes. Additionally, this study offers the platform, using the exact same model and methodology, to simulate so-called `show case' years under 2050 conditions. Three examples are the 2050 equivalent of the extremely hot summer of 2003, the heavy rainfalls in the Netherlands in the summer of 2006, and the extremely wet winter of 1996. In the first example, a persistent high pressure system over Europe produced a long and intense heat wave. Dramatically increased mortality rates and reduced crop yields are associated with this event. In 2006 persistent easterly flow led to an extremely warm beginning of the summer, and a related rise in North Sea temperatures. The easterly flow regime was followed by persistent west circulation, causing very heavy showers and local flooding. The winter of 1996 (third example) was extremely wet, up to the point where river dikes were about the collapse.

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5 Project 2.4 Uncertainties related to a rapid disintegration of the Greenland ice sheet and its consequences for sea level scenarios

Project leader: Dr. R.S.W. van de Wal

5.1 Problem definition, aim and central research questions

Recent observations show that the mass loss of the Greenland ice sheet is accelerating (e.g. Velicogna 2009, Van den Broeke et al. 2009). Part of this increased mass loss can be attributed to changes in the surface mass balance and parts can be attributed to changes in the ice dynamics. Regional atmospheric models do show increased ablation in combination with a decrease in precipitation over Greenland. On the other hand observations also indicated that several outlet glaciers underwent rapid thinning particular in the South-East (Howat et al, 2007, Joughin et al. 2008), leading to a further shrinking of the ice sheet. For the last year the mass loss is estimated to be more than 250 Gt/yr or approximately 0.75 mm of global sea level rise per year. As this was much lower 10 years ago it implies that the relative contribution of Greenland to global sea level rise is increasing rapidly at the moment. Though we start to understand the changes in the mass budget it has to be said that the current generation of ice sheet models is not capable to reproduce the observed acceleration and thinning of outlet glaciers. This is probably partly a scale issue as solving outlet glaciers requires a very high spatial resolution, but most likely also partly due to a lack of physical processes captured. The ice ocean interaction is not solved, basal melt rates are only poorly included as well as detailed physics of the calving process. In this proposal we will focus on the uncertainties caused by the ice dynamical processes, which might lead to a faster diminishing of the Greenland ice sheet. It will be attempted to quantify these effects for the next century.

5.2 Approach and methodology

For a better prediction of the future ice sheet changes, there is a clear need to develop ways of incorporating dynamics of the narrow, fast flowing outlet glaciers into the larger scale ice sheet models. For this reason we will further develop a numerical ice flow model (Nick et al. 2009) that is suitable for all Greenland outlet glaciers. This model will be coupled to the existing 3D ice sheet model for Greenland (Van de Wal et al. 1999). The outlet glacier modelling will be validated with recently installed GPS instruments at target glaciers. The data set will be used to distinguish which glaciers show a pronounced annual cycle and which do not have a yearly cycle. This distinction is needed to determine whether the critical processes are the ocean-ice interaction or increased flow resulting from the surface melting itself. The coupled ice sheet-outlet glacier model will be forced either by mass balance data derived from a regional atmospheric model (Ettema et al. 2009) or by a coupling to the EC-earth model. At present attempts are ongoing to couple the existing ice sheet model to EC-Earth based on the mapping and coupling methodology developed by Reerink et al. (2009). Whether the forcing from this newly developed atmosphere-ocean-land-sea ice model is sufficiently accurate for coupling to the ice sheet model remains to be seen, but it is important to test as the EC-Earth model will be an important tool used for the new IPCC scenario calculations.

The outlet glacier model itself will be a model based on the work by Nick et al. (2009), but improved schemes for calving will be included along the lines presented by Benn et al. (2007), but including the possibility that calving occurs when surface crevasses reach the depth to which basal crevasses penetrate upward into the ice. The depth of crevasses from the surface is based on the early work by Nye (1955, 1957), who proposed that the penetration depth is determined by the depth where the net longitudinal stress becomes zero. In the absence of water in the crevasses at this depth, the longitudinal tensile stress equals the compressive ice overburden pressure. The normal stress responsible for crevasse opening is the resistive stress, Rxx, defined as the full stress minus the weight-induced lithostatic stress and related to the longitudinal stretching rate through Glen's flow law (Van der Veen, 1999)

$$R_{xx} = 2B\dot{\varepsilon}_{xx}^{1/n} \quad (1)$$

Where B represents the temperature-dependent rate factor, n = 3 the flow parameter, and the contribution of other strain rates (ÝΣ) to the effective strain rate has been neglected. The simplifying assumption is made that this stress is constant with depth (Rist et al., 1996; Van der Veen, 1998a). Allowance can be made for depth variations resulting from non-uniform temperatures throughout an ice column if, for example, the stretching rate is considered independent of depth (Van der Veen, 1998b), but such refinement will not significantly alter the behavior of the model glacier.
In addition specific test will be developed for the importance of a complete drainage of the Jakobshavn Isbrae due to basal melting at the ice ocean interface, which is potential a source of roughly 30-40 cm sea level rise which might be mobilized relatively rapidly. As well as the magnitude there is further need for quantification of the time scale of drainage of this basin.

Another category of experiments will be dedicated to the role of melt water production and the speed up of marginal ice sheet areas. Van de Wal et al. (2008) showed that GPS data show a very high seasonal variability of the ice velocity, but also argued that in their specific area the long-term effect of these accelerations is limited. The importance of these observations has not yet been tested in ice flow models. Here, we incorporate based on their velocity data different parameterization schemes for the entire ice sheet in order to quantify the importance for the entire ice sheet. The parameterization is based on schematic routing of the melt water produced at the surface, which varies in space and time. The water follows a steepest descent approach through the grid and some of the water is retained within the ice and released slowly over time to simulate the observation that water is temporarily stored in large lakes and englacially. The outcome of these calculations will show whether the feedback between ice flow and surface melt in the ablation zone is important for the ice sheet as a whole.

5.3 Scientific deliverables and results

1. Collecting data on the interaction between surface melt, water level in crevasses, fjord temperature variation, sea ice coverage, speedup and calving for a few primary target glaciers in Greenland.
2. Constructing a theoretical/empirical calving model, which can be implemented into a time-evolving numerical ice sheet model. Testing the model on the target glaciers.
3. Estimating future mass loss from the major calving outlet glaciers of the Greenland ice sheet as a result of atmospheric and oceanic warming.
4. Implementing the ice flow model for outlet glaciers into the 3-D ice sheet model.
5. Improved estimates of the contribution of the Greenland ice sheet to global sea level during the 21st century and thereafter.

5.4 Integration of general research questions with hotspot-specific questions

In this project it will be attempted to quantify the uncertainty due to climate projections and the uncertainty related to ice sheet model separately. This information will be provided for global sea level as well as for the local sea level, which is not necessarily identical. In this way we can improve adaptation strategies related to local sea level scenarios, obviously with an emphasis on the contribution from the Greenland Ice Sheet.

5.5 Societal deliverables and results

The Antarctic and Greenland ice sheets are important for global sea level (e.g. IPCC AR4). Moreover the key uncertainty in sea level predictions is at present the dynamical imbalance of the ice sheets. Ice sheets can rapidly loose mass via several mechanisms, but they are poorly understood and not captured by the current generation of models. Key uncertainties are the lubrication, grounding line migration and the associated role of outlet glaciers and ice streams. In this proposal we aim to contribute to study of the rapid processes, which might lead to an unforeseen rapid disintegration of the Greenland ice sheet.

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