32: Models of Global and Regional Climate

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The concept of climate simulations with quasi-realistic climate models is discussed and illustrated with examples. The relevant problem of deriving regional and local specifications is considered as well.

When we speak about "climate", we refer to the statistics of weather. The statistics of weather can be described by first and second moments, that is, by time means and time variability on different timescales and its spectrum, by covariability between different variables, characteristic patterns, and the like. The climate is thought to be conditioned by external forcing, such as the presence of greenhouse gases in the atmosphere, changing solar output, and other factors. Thus, external forcings cause changes in the statistics of weather, but weather itself varies independently of the presence of changing external factors.

Key methods to unravel the dynamics of the climate system are the analysis of observed data and experimentation with climate models of varying complexity.

"Observed" data cover a wide range of data sets. Examples are *in situ* readings of precipitation, wind-speed and other variables, stream flow in rivers, conventional oceanographic and atmospheric vertical soundings, and also pixel data derived from satellite retrievals, and sophisticated "analyses". The latter are subjective or empirical (kriging-based) spatial interpolations of point observations, or model simulations into which the observed data have been assimilated using the concept of *state-space* modeling. All weather maps are such analyses. Important data sets of 6-hourly weather maps since 1948 or 1960 have been prepared by National Centers for Environmental Prediction (NCEP) and by European Center for Medium Range Forecast (ECMWF) (e.g. Kalnay *et al.*, 1996; Gibson *et al.*, 1997).

Climate models are process-based dynamical models (for further reading, refer to Müller and von Storch, 2004), which operate on the entire globe or in limited regions of the world. Climate models describe several compartments of the climate system, as for instance, the atmosphere, the oceans, the cryosphere, the surface hydrology, the vegetation, or cycles of matter. Thus, climate models may have different qualities of "complexity" – they may describe fewer components, but describe these components in greater detail. GCM-based models (GCM stands for "General Circulation Model"; such models operate with the "Primitive Equations", which describe the relevant atmospheric dynamics in detail – for further information refer to the references given), which are named quasi-realistic in the following, are of that sort (e.g. Washington, 1999). Another modeling strategy is to consider more components but in less detail – an example is the CLIMBER model (e.g. Ganopolski *et al.*, 1997). The former are often called *complex* and the latter *medium complexity* – these terms are in use but are not really precise semantics in describing the differences between the two classes of models.

In the following, we discuss the utility of "quasi-realistic" models. There are many books and articles on this subject. The books by Washington and Parkinson (1986), McGuffie and Henderson-Sellers (1997) and von Storch *et al.* (1999) describe the challenges of numerical modeling on a technical level, while the monograph by Müller and von Storch (2004) deals more with the philosophical problems related to the usage of such models. Also the collection of papers offered by Trenberth (1993) or von Storch and Flöser (2001), the articles by Bengtsson (1997) and Manabe (1997), and the description of the state-of-the-art in the Intergovernmental Panel on Climate Change (IPCC) reports (Houghton *et al.*, 1996, 2001) may be helpful for the interested reader.

Section "Quasi-realistic climate models (surrogate reality)" discusses the construction and validation of quasi-realistic global models, Section "Free simulations and forced simulations for reconstruction of historical climate"

Encyclopedia of Hydrological Sciences. Edited by M G Anderson.

the performance of such models in reconstructing historical climate, and Section "Climate change simulations" climate change simulations. The problem of how to infer a description of the impact-relevant regional and local climate is dealt with in Section "Downscaling"; the major downscaling tools are regional models; the construction of such models is considered in Section "Regional climate modeling". The success in reconstructing the climate of the past decades of years is demonstrated in Section "Reconstructions", and scenarios of plausible future climate change are discussed in Section "Regional scenarios". The article concludes with the Section "Conclusions".

The examples used throughout the text are chosen subjectively – and with a bias towards work done in the mostly European academic milieu of the author. It would have been equally possible to write this article with a very different set of examples, without compromising the representativity and usefulness of this article.

QUASI-REALISTIC CLIMATE MODELS (SURROGATE REALITY)

Models that can realistically simulate the sequence of weather events are called *quasi-realistic* climate models. They comprise circulation models of the atmosphere and the ocean and other components such as the land surface and sea ice. The components of such a model are sketched in Figure 1 (Hasselmann, 1990).

Such models are complex models – their degree of complexity is a compromise of computation possibilities and the required length of the integration. If the model is supposed to be integrated for 1000 years, then a coarser spatial resolution is chosen and some processes are described in a less detailed manner. For such an integration, a spatial grid size of about 300 km is often used. In order to achieve a higher spatial resolution, so-called downscaling methods have to be applied (see below; von Storch, 1999).

In the climate system, processes are operating at all timescales. On the other hand, the numerical formulation of the dynamical equations requires a cut-off at a certain scale. Figure 2 sketches the situation for atmospheric dynamics – with faster processes on smaller scales, and slower processes on larger scales. The space/time truncation, sketched in Figure 2 by hatching, leads to the disregard of many processes such as cumulus convection. These processes are, however, essential for the formation of the general circulation of the atmosphere – therefore they are included into the numerical equations as "parameterizations". That is, the expected effect of such processes on the resolved processes conditional upon the resolved state is specified. All models, atmospheric and oceanic, global and regional, contain many of these parameterizations, and they are a major cause for the different performance of dynamical models.

The skill of models in describing the real world depends on the spatial scale. Phenomena on larger scales are better described than smaller scales. Grid point values are

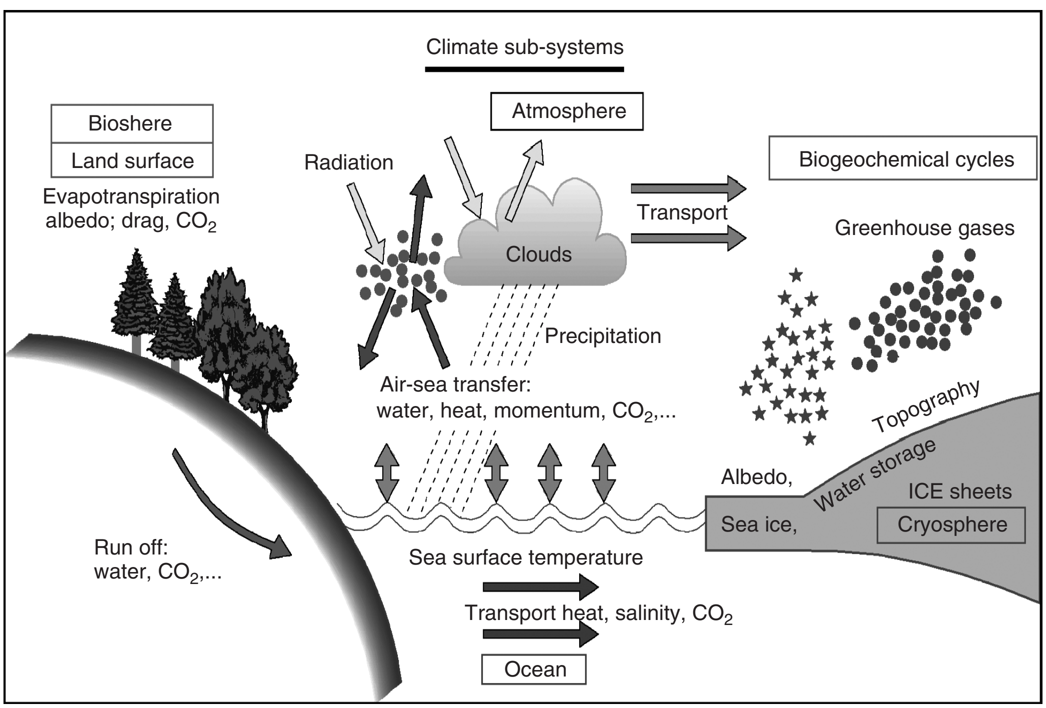


Figure 1 Components of a dynamical climate model (Hasselmann, 1990, © JCB Mohr, Tübingen). A color version of this image is available at http://www.mrw.interscience.wiley.com/ehs

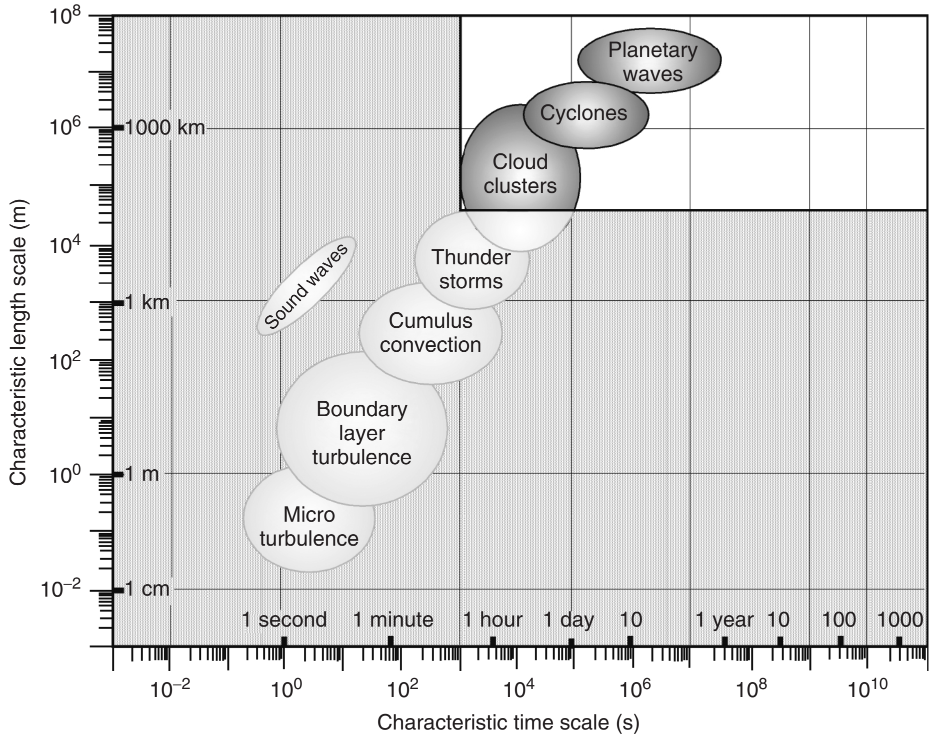


Figure 2 Resolved and unresolved processes and scales in a contemporary atmospheric model (Müller and von Storch, 2004, © Springer Verlag)

usually meaningful only if the variables are smooth so that the grid point value is representing a larger area. However, when the considered variables vary strongly from grid point to grid point, such as rainfall, the sequence of events at a grid point and at the geographic location, formally corresponding to the grid point, likely will not compare well. Grid point values do not represent local values when there is a great amount of spatial variability of scales of the grid size and smaller. For larger areas, represented by many grid boxes, this is no longer a problem.

Such models have been shown to have considerable skill in reproducing many aspects of contemporary climate, such as the annual cycle, the level of stochastic variability, and the formation of extratropical storms. These models strive to be as realistic as possible. Since these models are, nevertheless, significant simplification of the complex real system, we (Müller and von Storch, 2004) use the term *quasi-realistic* for such models.

Figure 3 provides an example of a sophisticated characteristic of atmospheric dynamics, namely, the "storm track" in the North Atlantic. The storm track is conveniently defined by the intensity of the band-pass filtered variance of 500 hPa geopotential height. The variations on timescales between 2.5 and 6 days are shown in the diagrams – variations on these timescales are related to the formation and migration of baroclinic storms. The model generates a pattern and intensity of the storm track (Figure 3, bottom) which is very similar to pattern and intensity derived from ECMWF analyses (Figure 3, top). The intensity in the model output is smaller than in the analyses – but the difference is usually considered acceptable within the range of uncertainties.

Figure 4 provides another example of a validation of GCMs. It compares the performance the analyses of rainfall determined in the ERA-40 data set (prepared by the European Center for Medium Range forecast; ECMWF) with the precipitation simulated in many GCMs (Kharin *et al.*, 2004). Specifically, the spatial distributions of the time-mean precipitation and 20-year return values are studied and compared with their counterparts derived from ERA-40.

The diagram is not easily understood, but it provides a compact description of the skill of a set of models. In the first step, the spatial average of the spatial distributions is subtracted – so that "anomaly fields" are obtained. From these anomaly fields, three characteristic numbers are calculated and displayed in Figure 4 by one symbol for each model. The trick is that in this diagram three characteristic numbers are displayed by one symbol in a two-dimensional diagram.

- The *mean-squared difference* between the anomaly field of the considered model and the ERA-40 reference

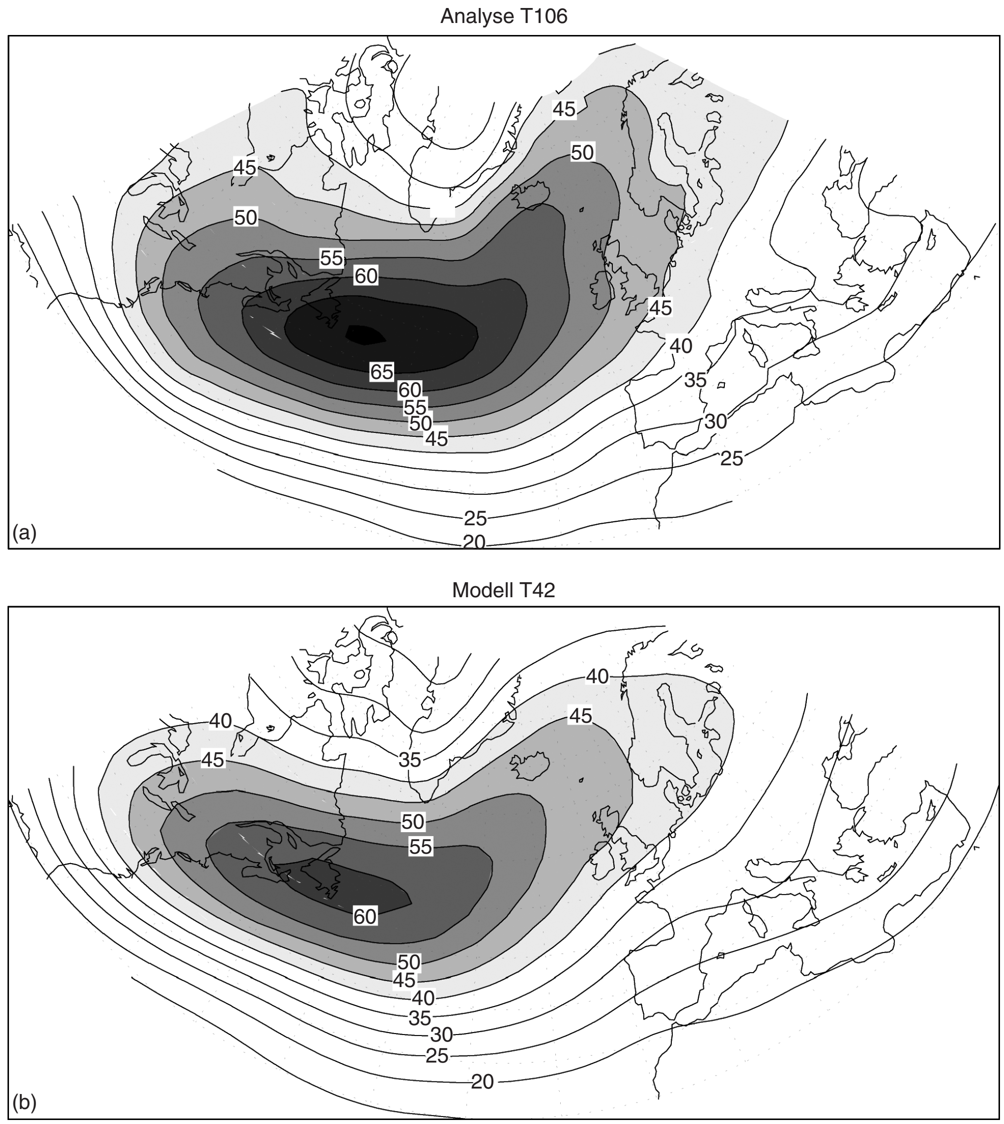


Figure 3 North Atlantic storm track as given by the band – passed filtered variance of 500 hPa geopotential height (band – pass: 2–5 to 6 day variability is retained) in ECMWF analyses (a) and in an extended simulation with the T42 ECHAM3 model (b) (von Storch *et al.*, 1999, © Springer Verlag)

anomaly. To facilitate easier comparison, the mean-squared difference is normalized by the variance of the reference anomaly. This characteristic number is given by the light blue circles emanating from the horizontal axis, where the units are given.

- The *ratio of variances* of model anomaly and of the reference anomaly (given by green dashed circles emanating from right vertical axis).
- The *correlation* indicated of the model and reference anomalies. This is given by the by pink straight lines emanating from left vertical axis.

The ERA-40-reference itself has a ratio of variances of one, a mean-squared difference of zero and a pattern correlation of one – its dot is placed on the lower margin of the diagram.

Usually the spatial variance of the simulated *time means* is underestimated (dashed circles, 50–80%), while the normalized mean-squared difference is moderate (light blue circles, 20–40%). The pattern correlation is high (typically 80%). The spread for the *20-year return values* is much larger (circles in Figure 4). Some of the models are doing similarly well as the mean precipitation, while other models produce a much too small variability (less than 20%) but a large high mean-square difference (100%). The pattern correlation is less than 80%, in some cases, as little as 50 and less percent. Interestingly, the comparison of the ERA-40 analysis with other analyses by NCEP

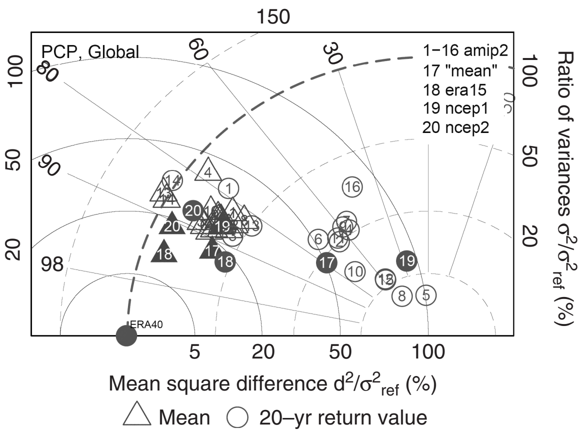


Figure 4 Comparison of the simulation of the time mean (triangles) and 20 year return values (circles) of precipitation in a series of 16 GCMs with the ERA-40 analysis (Kharin *et al.*, 2004). Also shown are the comparison with two NCEP-reanalyses, an earlier, shorter ERA reanalysis and the average of all 16 considered GCMs. Three characteristic measures are shown – the mean-squared difference, the ratio of spatial variances and the anomaly correlation. The mean-squared difference of the ERA-40 anomaly field and the model anomaly field is indicated by the light blue circles emanating from the units given on the horizontal axis. This parameter is normalized by the spatial variance of the reference anomaly field. The ratio of spatial variances of the reference and model anomaly fields is given by the green dashed circles emanating from the vertical axis. A color version of this image is available at http://www.mrw.interscience.wiley.com/ehs

(numbers 18 and 19) indicates substantial difference among reanalyzes. Obviously, the estimation of precipitation in reanalyzes provides further improvements, if space/time details are needed.

Figure 5 displays the outcome of a survey among 104 climate modelers, who have been asked to subjectively assess the skill of contemporary climate models in the end of the 1990s in describing a number of processes (Bray and von Storch, 1999). They were requested to respond to a seven-graded scale, varying between “very good” and “very bad”. For obvious reasons, the response “very good” is almost never heard. Hydrodynamics, that is, the implementation of the laws of conservation of mass and momentum, is considered to be well reproduced. However, thermodynamic processes, related to convection or clouds, are assessed by many experts as being insufficiently represented. Of course, this assessment is partly reflecting the wish of modelers to continue their work in improving their models, but the outcome of the survey is also strong evidence that models really need to be improved.

Quasi-realistic models are considerably less complex than reality, but nevertheless, *very* complex. They can react in ways that cannot be foreseen by simple conceptual

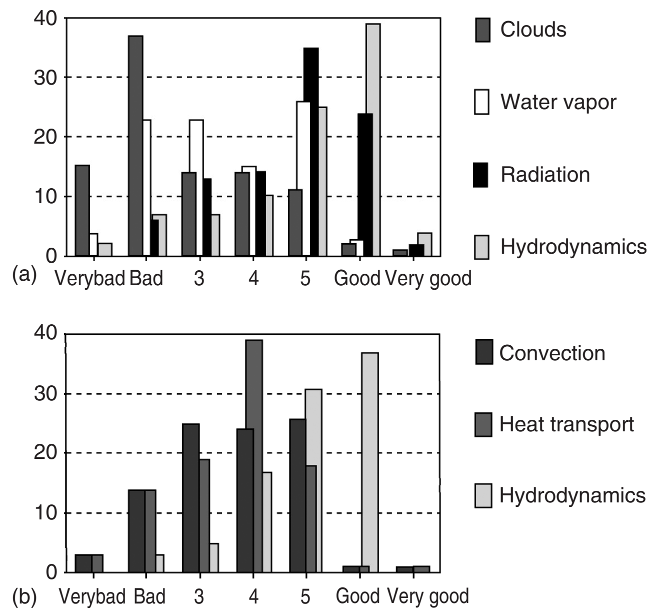


Figure 5 Result of a survey among climate modelers on the confidence into the description of processes in atmospheric (a) and oceanic (b) models. Answers were requested on a scale varying between ‘‘very bad’’ and ‘‘very good’’. The units on the vertical axis are in percent. (Bray and von Storch, 1999, © 1999 AMS)

models. This is a virtue of such models, as they make them to laboratories to test hypothesis with – they constitute a *virtual* or *substitute reality* (Müller and von Storch, 2004).

FREE SIMULATIONS AND FORCED SIMULATIONS FOR RECONSTRUCTION OF HISTORICAL CLIMATE

Climate models are run in different modes. There are “free” simulations and “forced” simulations.(The wording “free” and “forced” is somewhat misleading. All climate simulations are, in a sense, forced, as they are exposed to a series of prescribed factors external to the model. In case of “free” simulations, these external factors do not vary, except for a fixed annual cycle. Variations in “free” simulations are therefore entirely due to the internal dynamics of the model and cannot relate to specific external factors. In contrast, “forced” simulations respond to a forcing, which varies irregularly. Thus, such model simulations exhibit a mix of externally induced variability and internally generated variability.) The former are useful to generate purely internal variability, whereas the latter allow the analysis of the effect of external factors. Figure 6 shows an example of a free simulation. The climate model ECHO-G was integrated over 1000 years – with continuously repeated annual cycles of solar insolation and no other external factor

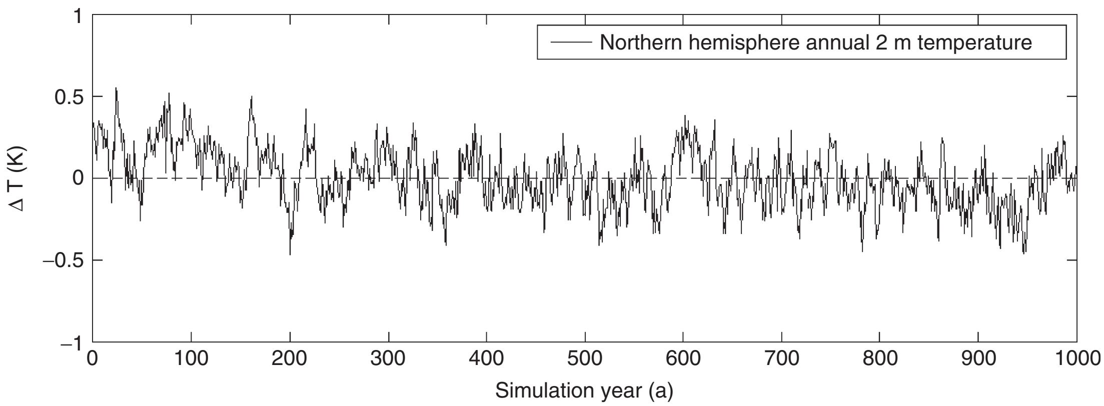


Figure 6 Air temperature anomalies (deviation form the long-term mean) simulated in a 1000-year ''free'' simulation (Wagner *et al.*, 2005, © Springer Verlag)

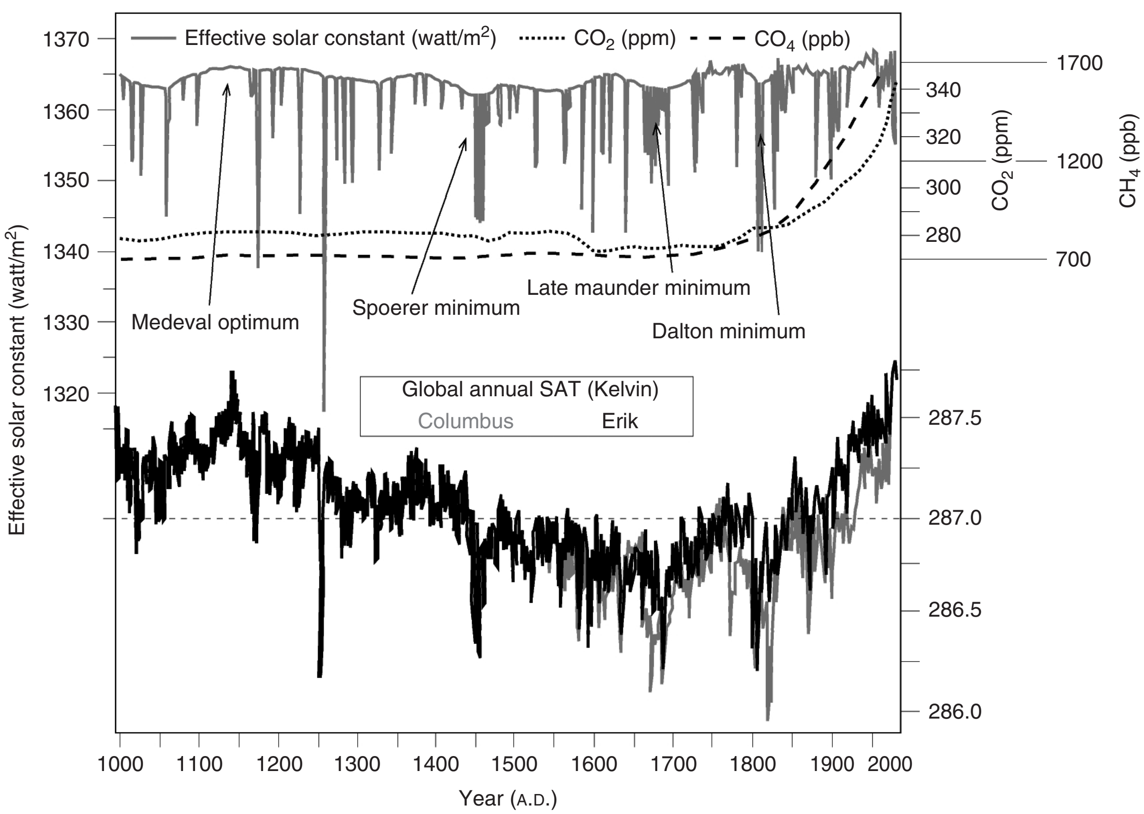


Figure 7 Time variable forcing (a) and temperature (b) in a 1000-year simulation and in a 500-year ''forced'' simulation

(Wagner *et al.*, 2005). The variable shown is air temperature averaged across the Northern Hemisphere. Obviously, the temperature undergoes significant variations, which cannot be traced back to "causes". The reason for this "smoke without fire" effect is the presence of myriads of nonlinear chaotic processes. The sum of all these chaotic processes may be conceptualized by the mathematical concept of stochastic noise (e.g. von Storch *et al.*, 2001). This noise is integrated by the slow components in the climate system, so that variations on all timescales appear with a first-order approximation red spectrum (Hasselmann, 1976).

On the other hand, characteristic cause-and-effect features emerge when external time-variable factors are added (González-Rouco *et al.*, 2003; Lionello *et al.*, 2004). Figure 7 shows time series of atmospheric forcing by time-variable solar output and the effect of stratospheric volcanic aerosols, and by variable atmospheric concentration of the two greenhouse gases carbon dioxide and methane. Here, the radiative effect of the volcanic aerosols is accounted for by reducing the solar insolation for a short time. The time series of global mean air temperature is also displayed. This series is composed of variations unrelated to the forcing, like in the free simulation, and to variations excited by the forcing. A close inspection reveals that the variable output of the sun (including the volcanic effect) is the dominant factor until the middle of the nineteenth century. Since then, the effect of the ever-increasing greenhouse gas concentration is becoming dominant.

The overall development of the simulated temperature during the last millennium is consistent with the historical account, but the range of the variations is larger than what has been reconstructed from proxy-data, like tree rings.

The emergence of variability unrelated to external forcing factors makes also a forced simulation to a random experiment – the resulting weather stream is not determined by the forcing, but *conditioned*. For instance, the details of cyclones and anticyclones will vary from one simulation to the next, but the statistics of the formation of cyclones and anticyclones will be similar in any two realizations. In order to get a robust statistic, several simulations with identical forcing are preferable (*ensemble* simulations). To make them different realizations, several measures are possible; a popular method is to use a slightly different initial state.

CLIMATE CHANGE SIMULATIONS

In climate change simulations, assumed changes of the forcing are administered to the model. These changes are "scenarios" of possible and plausible changes. In most cases they refer to the emission of greenhouse gases, sometimes to the emission of anthropogenic aerosols. These emissions themselves are based on scenarios of economic and social development. The output of the climate models is then named a "climate change scenario" of a possible and plausible future climate.

The scenarios are not predictions; they do not describe the most probable development; instead usually several different scenarios are presented, which differ significantly from each other. Scenarios are plausible and consistent images of a possible future; have an impact on the future itself. (The movie "The day after tomorrow" provides a story of future climate change; it is, however, not the scenario as it describes a climate which is impossible to emerge as it is not consistent with the physical laws of climate.) Thus, scenarios are not only depictions of possible futures, but also active agents forming the future. (In the context of global warming, various scenarios of possible future development are prepared to emphasize the severity of the threat of global warming. As such, they help the formation of a climate policy mitigating the envisaged anthropogenic climate change.)

The consensus of the models given a specific emission scenario on larger scales is illustrated in Figure 8. A total

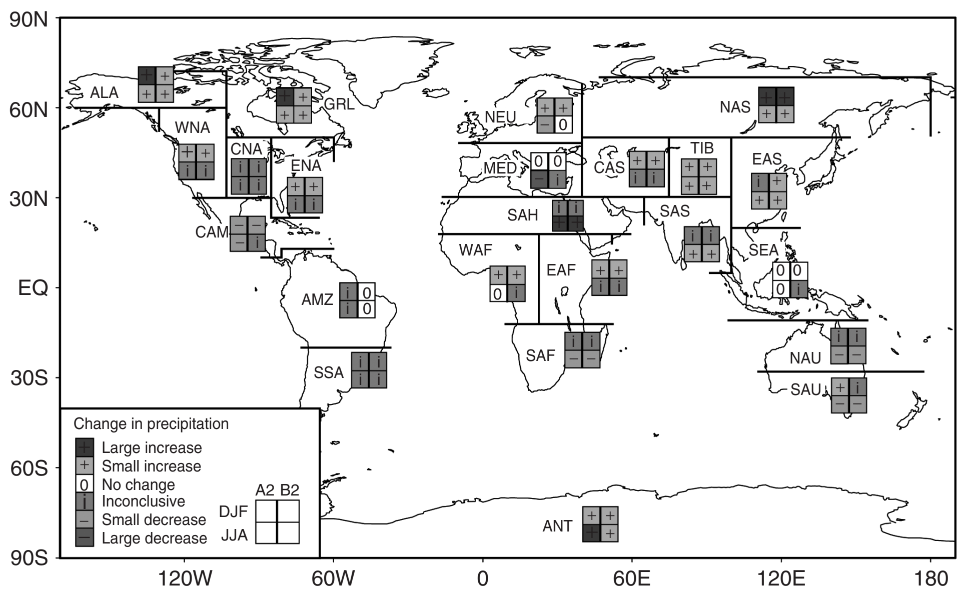


Figure 8 Convergence of climate models in simulating the same regional change in precipitation according to the greenhouse gas emission emissions scenarios A2 (left two boxes) and B2 (right two boxes) at the end of the twenty-first century. The top two boxes refer to northern winter (DJF), the bottom to the northern summer (JJA). For further details, refer to the text (Reproduced from Giorgi *et al.*, 2001a by permission of American Geophysical Union). A color version of this image is available at http://www.mrw.interscience.wiley.com/ehs

of 9 models was analyzed with respect to their similarity in the change of precipitation averaged over subcontinental areas (Giorgi *et al.*, 2001a). All nine models have been forced with the same Special Report on Emissions Scenarios (SRES) scenarios provided by the IPCC for its Third Assessment Report. Whenever 7 out of the 9 models produced similar responses, the models were considered agreeing in envisaging a small or large increase or small or large decrease of precipitation, or no change in precipitation. The symbol "i" was introduced in Figure 8 if the models were found to generate conflicting assessments. This exercise was done for a series of subcontinental areas, for both scenarios A2 and B2 and for the two seasons December-January-February (DJF) and June-July-August (JJA) (A2 is a scenario, which describes a rather steep increase in the usage of fossil fuels and emissions into the atmosphere. B2, on the other hand, assumes more efficient measures to curb emissions.). For each of the regions, a square provides the assessment for the two scenarios and two seasons. Obviously, the models agree in most cases – and indeed the pattern of responses is the same, also if a number of earlier climate change experiments exploiting somewhat different scenarios are checked (not shown; Giorgi *et al.*, 2001a).

The argument seems to indicate that the similarity among models would be a proof for the reality of the response. This is certainly not so; the arguments certainly demonstrate the stability of the response across models – but since the models are not developed independently of each other, they may all suffer from the same limitations.

The climate change simulations provide useful information on large scales. Here "large" means global, continental, and subcontinental scales. A rough rule is that contemporary models are skillful on scales of $10^7\,km^2$. On smaller scales, the model output will often depend on the specifics of the considered model.

This is insofar a severe limitation as the effect of changing climate is felt on a regional scale; assessing the impact of climate change requires scenarios on the regional and even local scale. Thus, extra efforts are required to derive the required impact-relevant regional scenarios. Tools for that purpose are discussed next.

DOWNSCALING

The idea of downscaling is that the smaller scale climate may be understood as the outcome of an interaction of larger-scale dynamics and smaller-scale physiographic details (e.g. von Storch, 1999). The concept is based on the observation that the global scale circulation is already formed on an aqua planet without any physiographic features (a planet entirely covered by the ocean, without any land and topography); the formation of stationary planetary features needs the presence of the gross land–sea contrast and the largest mountain ranges.

There are several downscaling methods in use (Giorgi *et al.*, 2001b).

One main group is utilizing empirically determined transfer functions, which relate variables of regional or local interest to well-simulated large-scale variables (for an overview, refer to Giorgi *et al.*, 2001). Such transfer functions are often regression equations, but also nonlinear techniques like neural nets are in use. Sometimes the transfer functions relate statistical parameters to each other, such as intramonthly percentiles of an impact variable and monthly mean air pressure fields. Another approach is to directly relate meteorological state variables like free tropospheric temperature and humidity to relevant surface variables (Wilby and Wigley, 1997). Weather generators are also used for downscaling, with their parameters conditioned on the large-scale state (e.g. Busuioc and von Storch, 2003).

The other group of methods is based on the use of regional climate models (Giorgi and Mearns, 1991). In most cases, the 6-hourly large-scale weather stream generated by a global climate model is enforced on the regional domain; the dynamical model is constructing a regional-scale weather stream, which is consistent with both the global weather stream and the physiographic details of the considered region. In the following, we will deal with this approach in more detail.

One has to keep in mind that downscaling operates with the assumption that the large scales are properly represented by the global simulation or the global analysis. This is usually not a problem in case of analyses, but for (free or forced) global simulations this is a nontrivial assumption. For instance, the formation of blocking situations, which may be considered large scale in certain downscaling applications, is not sufficiently simulated if the global model has too low a resolution.

REGIONAL CLIMATE MODELING

Regional climate modeling (for a recent overview, refer to Wang *et al.*, 2004) is in most cases just regional atmospheric modeling with some basic parameterization of the thermodynamics of the upper soil layer. The other climatically relevant state at the surface of the earth, in particular, the sea surface temperature, sea ice and lake ice conditions, the state of the vegetation – are in these cases prescribed. Since a few years, significant efforts are made to construct coupled regional models, which feature regional oceans and lakes, run-off or vegetation explicitly together with the regional atmosphere. For instance, the model system BALTIMOS (Jacob; personal communication), designed for Baltic Sea catchments studies, is made up of the Baltic Sea ocean model, a hydrological model and the regional atmospheric model REMO (Jacob *et al.*, 1995). The Swedish Rossby Center is working with a system featuring a Baltic Sea model, regional hydrology, and a regional atmosphere (Räisänen *et al.*, 2004)

Commonly, the regional models are forced by boundary conditions along the lateral boundaries and, as discussed above, at the surface of water bodies. The lateral conditions are enforced with the help of a "sponge" zone (Davies, 1976) of a few grid points. In the sponge zone, the simulated state is nudged to the externally given state, with stronger nudging coefficients near the model's margin, and weaker ones in the interior. That this concept is practically working fine has been demonstrated convincingly by the "Big Brother Experiment" by Denis *et al.* (2002). In that experiment, a 50-km grid, regional model covering a large area ("big brother") was run over an extended time; then a smaller domain within the larger domain was chosen. The meteorological variables simulated in the large domain along the margin of the small area were selected. The same regional model, with a 50-km grid, was then run on the smaller domain ("little brother"), forced with the boundary values provided by the large-area model after "coarsening", that is, the data was not given every 50 km along the margin, but every 100, 200 or even 500 km. The research question was whether the fine scale features simulated in the smaller domain in the big brother setup would be recovered by the little brother setup. The answer was positive; after a few days, differences between the large-area simulation and the small-area simulation were small. The area considered was the well-flushed Eastern North America and Western North Atlantic. (A region is "well flushed" if the information is quickly advected from the boundaries into and through the interior.)

Mathematically, the problem of inferring the dynamical state of a fluid by providing lateral boundary conditions is not a well-posed problem. The lateral boundaries do not determine a unique "solution" in the interior; instead, several different states in the interior are consistent with a given set of lateral boundary conditions. The tendency to form very different solutions in the interior as a response to the same boundary conditions depends on how well the region is flushed, that is, how efficiently a boundary steering is established. In midlatitudes, such as Europe or in Denis *et al.*, (2002) case, the regions are mostly well flushed; in areas with little "through-flow", like the Arctic, this is not so. Thus, any two extended simulations that are run with the same boundary values but slightly different initial states (which may simply be two observed states 12 hours apart) will generate more or less frequently very different behavior. For a region like Europe, such a "divergence" is rare (Weisse *et al.*, 2000), but Caya and Biner (2004) report a dramatic case in eastern North America. For the Artic, such divergence is more frequent (Rinke and Dethloff, 2000). This phenomenon of intermittent divergence is reflecting the conflicting influences of control by inflow boundary conditions and of regional chaotic dynamics.

Figure 9 shows an example of this intermittent divergence. The observed zonal wind at a location in the German Bight is shown together with grid-box-simulated zonal winds. (There is a problem of comparing local wind affected by local particularities with grid box averages. Deviations between simulated numbers and observed numbers may be due to local effects not described by the model's resolution.) In this case, six simulated time series are shown. They are generated by the same regional model, forced with the same lateral boundary conditions but with slightly different initial values. The reason for these different developments is not that the initial conditions would be very different, leading to different forecasts; instead miniscule differences in the initial conditions excite the chaotic divergence of the dynamical system "regional atmosphere". After a few days, after January 8, the divergence has ceased and the development is the same in all six simulations. This convergence following an episode of divergence reflects the fact that the system moves into a configuration with a more westerly weather regime, so that the information provided with lateral boundary conditions is efficiently "flushed". After several months, a similar divergence episode emerges (not shown).

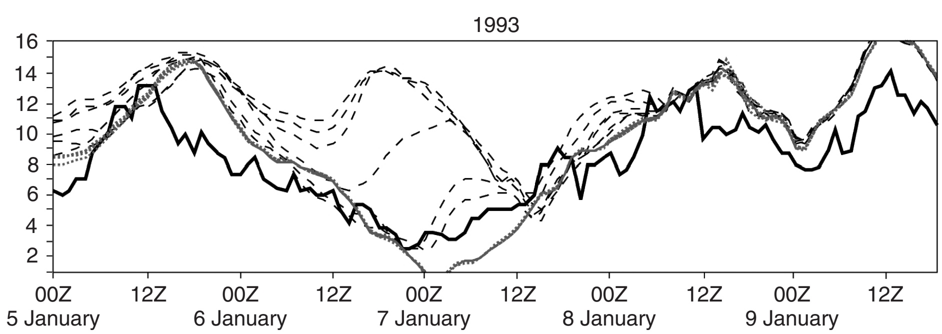


Figure 9 Intermittent divergence in a regional atmospheric model. Shown is the zonal wind at a location in the German Bight, as observed (solid) and as simulated in six simulations with a regional model with conventional lateral boundary forcing (dashed) and with spectral nudging (grey) (Reproduced from Weisse and Feser, 2003, by permission of Elsevier)

A method to overcome this intermittently emerging divergence is to cast the whole regional modeling problem not as a boundary problem but as a state space problem (e.g. Müller and von Storch, 2004), in which the dynamical model is used to augment existing knowledge about the regional state of the atmosphere. The latter is knowledge about the large-scale state of the atmosphere above a certain vertical level, where the influence of the regional physiographic details is small. This concept leads to *spectral nudging* (von Storch *et al.*, 2000; Miguez-Macho *et al.*, 2004), which consists of the addition of penalty terms in the equations of motion. These terms are getting large if the simulated large-scale state deviates from the prescribed large-scale state, but vanish if the model remains close to the prescribed large-scale state. The method has been tested, and it is found that this approach is better in capturing regional details than when the model is forced only with lateral conditions (a case demonstrating this claim is provided by von Storch *et al.*, 2000). In addition, the emergence of intermittent divergence is suppressed (Weisse and Feser, 2003). This is demonstrated by the other set of curves in Figure 9, displaying the development in the six simulations, starting with the same set of initial conditions as in the conventional lateral boundary forcing cases – the curves differ so little that they appear as a somewhat broader grey line.

RECONSTRUCTIONS

One important application of regional models is the high-resolution reconstruction of the weather stream of the past 40 or 50 years (Feser *et al.*, 2001 – "Feser reconstruction"). Using the spectral nudging technique, using the European weather stream on spatial scales of 1500 km and more, reliably analyzed by NCEP since 1948 (Kalnay *et al.*, 1996) as constraint, regional details of the atmospheric state were reconstructed continuously with the regional atmospheric model REMO for 40 and more years on a 50-km grid. The data was stored once an hour.

The added value of this exercise is an increased resolution in space and time; thus it is expected that the tails of the distributions (i.e. of climate) are better described. Figure 10 demonstrates that this improvement has indeed been achieved, at least for wind over the sea (Sotillo, 2003). Quantiles are derived for wind-speed-time series recorded at two buoys. They are compared with quantiles derived from the NCEP reanalysis and from the Feser-reconstruction. In one case, both model quantiles are very similar to the observed quantiles; in the other, only the Feser-reconstruction exhibits the right level of strong windiness. In the former case, the buoy data have entered the NCEP reanalysis, but in the latter the buoy data have not. Thus, it may be concluded that the reconstruction using a regional atmospheric reconstruction together with a spectral nudging approach, is recovering relevant detail to regional climate statistics. However, further analysis of the added value, in particular, in terms of precipitation and wind over land, needs to be done.

This added value is used in assessment studies, for instance, about ocean wave conditions (EU project HIPOCAS; Soares *et al.*, 2002). An example of successfully reproducing local wave conditions at an island in the North Sea is shown in Figure 11. The high wave results, obtained as response to the Feser-winds, are in very good agreement with the local observations, recorded either by a local buoy or by a local radar system. In fact, the wind data set is being increasingly used by regional decision makers.

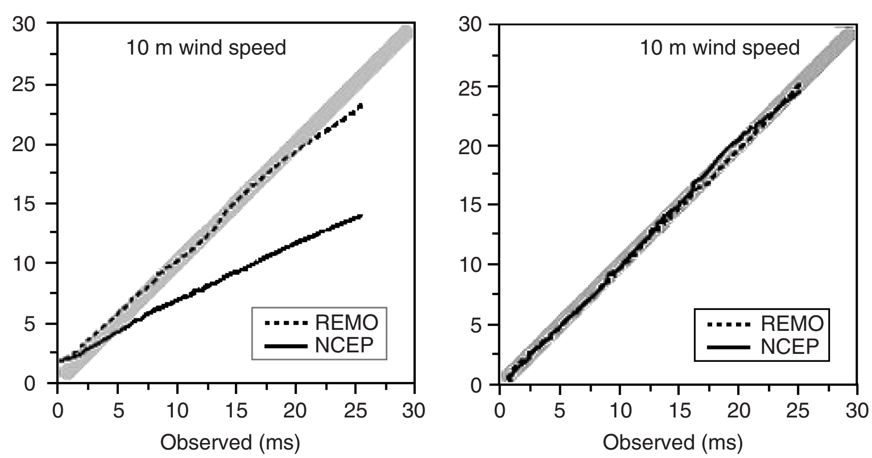


Figure 10 Quantile–quantile plot of 10 m-wind speed at two buoy locations in the east Atlantic (a) and in the Ionian Sea (b). The vertical axis represents the quantiles from the buoy data, the vertical the quantiles derived either from NCEP reanalyses (solid) or from the regional model reconstruction (dashed). Note that the data from the Atlantic buoy has been assimilated into the NCEP reanalysis, while the data from the Ionian Sea buoy are independent (Sotillo, 2003)

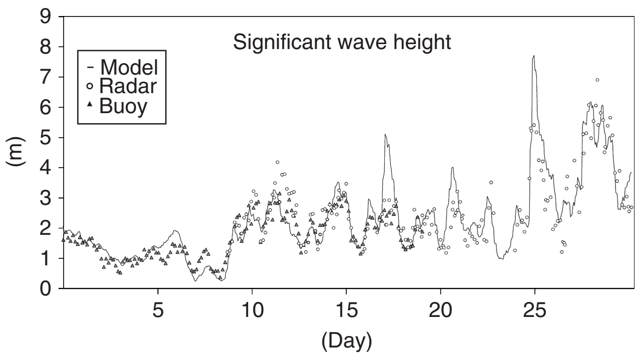


Figure 11 Simulated significant wave height off the island of Heligoland in the German Bight during one month. The line is the significant wave height obtained by running a wave model with the Feser-reconstructed winds in the North Sea domain; the triangles are wave height recorded by a local buoy and the open dots estimates derived from a local radar system (By courtesy of Gaslikova)

The data set has so far not been systematically studied with respect to the reconstruction of precipitation. However, it is already clear that a one-to-one association of grid box precipitation in the model to 50 km by 50 km real averages derived from observations is not possible. Only averages over several grid boxes are meaningful. Figure 12 shows an example for the catchment of the river Odra (Messal, personal communication). The similarity is not perfect but encouraging, considering the uncertainty in the "observed" rainfall. Other aspects which have been examined are related to cloud cover and cloud amounts (Meinke *et al.*, 2004)

REGIONAL SCENARIOS

In the European project PRUDENCE (Christensen *et al.*, 2002), the same set of global climate change scenarios are processed with a large number of regional climate models. Most of the models are purely atmospheric models, but some have added oceanic and hydrological components.

The global scenarios were prepared by the model HadAM3 of the Hadley Center, using A2 and B2 emission scenarios. The boundary values as well as the sea surface temperature and the sea ice conditions from the global run during a 1961–1990 control and during the interval 2071–2100 were used to force the regional models, which were integrated over 30 years. Additionally, in the 2071–2100 runs, the radiative conditions in the regional models were changed according to the emission scenario.

So far, the process of comparing the responses of the various models is not yet completed. First results indicate that during winter the regional models deviate little from each other. The simulated expected changes due to global warming coincide across most models in terms of strong winterly windiness and heavy summer rainfall events (Beniston *et al.*, 2005).

The added value produced by the regional models is expected to consist in a better simulation of the spatially and temporarily smaller scales. In fact, a better description of

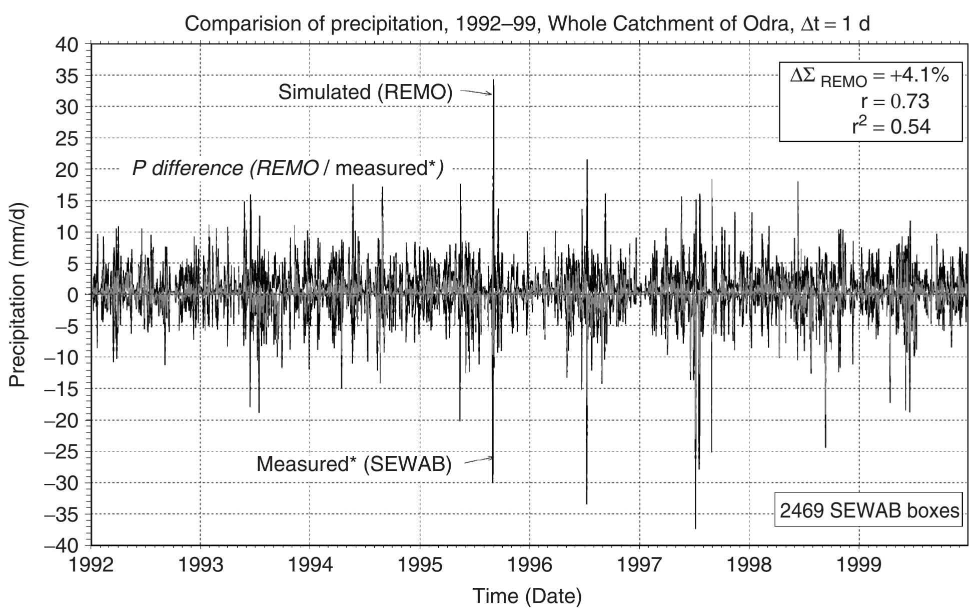


Figure 12 Simulated (upward; black) and analyzed (downward; black) daily precipitation in the catchment of the Odra River in 1997. The correlation is 0.73, the amount of variance described 54%. The grey curve shows the difference. The bias is 4%, which is within the limit of uncertainty (By courtesy of Hillmar Messal)

the details of frequency distributions is obtained (Beniston *et al.*, 2005).

As an example, the precipitation during summer time has been examined, (Christensen and Christensen, 2003) as well as wind conditions over the North Sea (Woth, personal communication). In both cases, a similar result is obtained, namely, the mean conditions are weakened – that is, the total amount of precipitation was found to be decreased, but the intensity of rare events was found to be increased by up to 40% (Figure 13). Similarly, the mean wind speed over the North Sea is envisaged to become slightly weaker on average, while strong westerly winds may increase by a few percent (not shown).

The PRUDENCE experience seems to indicate that the differences resulting from the use of the same global climate change scenario but different regional models are moderate. On the other hand, experiences at the Rossby–Center (e.g. Bergström *et al.*, 2001) indicate that the use of different global climate change scenarios and the same regional model induces much larger uncertainties. Figure 14 shows simulated regional annual precipitation changes in Europe derived by postprocessing (downscaling) two global climate change scenarios (prepared by the Hadley Center and the Max–Planck–Institute of Meteorology) with the Rossby–Center regional model. While broad features are similar, like more rainfall in the northern part and less in the southern, regional details contradict each other, for example, for the terrain of Poland.

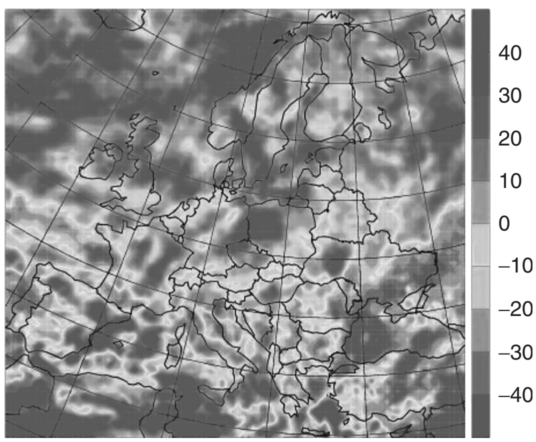


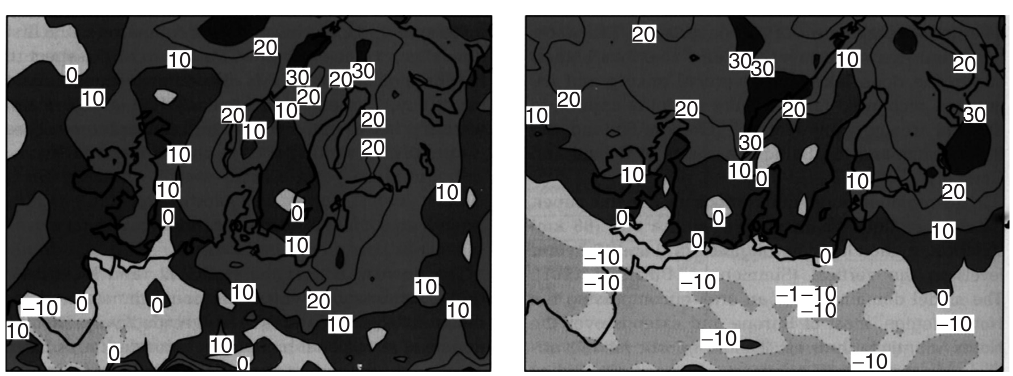
Figure 13 Change in precipitation intensity or the rare summer events as envisaged by a regional climate model for the end of the twenty-first century. The quantity shown is the change in five-day mean exceeding the 99th percentile (Christensen and Christensen, 2003). A color version of this image is available at http://www.mrw.interscience.wiley.com/ehs

CONCLUSIONS

Climate modeling is a standard exercise, which has matured in the past years after its introduction into the 1960s by pioneers like Manabe and Bryan (1969). Climate modeling is commonly understood as the space-time detailed modeling of at least the atmosphere, the ocean, and the sea ice. In such "quasi-realistic" models, the considered components are described in as much detail as is consistent with the anticipated application of the model (in particular the length of the integration time), and is feasible, given the computational platform. The atmospheric components describes baroclinic instability and the associated macroscale vortices (extratropical storms), while the dynamically relevant role of eddies in the ocean is parameterized by a certain type of diffusion (one could say, a climate model's ocean is not filled with water but with mustard).

Nowadays, such models are extended to contain more components of the earth system, in particular, surface hydrology, pathways and cycles of matter, vegetation and ice shelves and sheets.

Global models are meant to simulate phenomena of several grid length sizes; phenomena on scales of a few



(a) (b)

Figure 14 Simulated changes (%) in annual precipitation in Europe in two similar greenhouse gas emission scenario runs with different global climate models (Reproduced from Bergström *et al.*, 2001 by permission of Inter-Research). A color version of this image is available at http://www.mrw.interscience.wiley.com/ehs

100 km or less are usually not simulated reliably. Thus, global model output is of limited utility for areas such as the North Sea, Colorado, or Taiwan. A thumb of rule gives 10^7 km^2 as threshold for skillful presentations for global models at this time. (This length scale is certainly a moving target. With increasing computer power, global models will be run with higher spatial resolution, and the skillful spatial scales will further decrease.) If smaller scaled descriptions and scenarios are needed, then one has to resort to a downscaling method, in particular, to the regional climate modeling. Such regional models are also readily available nowadays, and are presently extended – as their global siblings – to take into account more and more other components of the earth system.

For scientists not working with such climate models, the following items may be useful to remember:

- Global climate modeling allows the representation of global, continental, and subcontinental scales. Global models are not designed for, and thus not well suited for the regional and local scale.
- Global climate is varying because of both internal dynamics as well as external forcing.
- Scenarios of future climate change hinge on the validity of economic scenarios.
- Simulation of regional climate is a downscaling problem and not a boundary value problem.

Acknowledgments

I am thankful to Nikolaus Groll, Brigit Hüncke, Viacheslav Kharin, Hillmar Messal, Sebastian Wagner, and Katja Woth for their helpful comments. Many thanks to Beate Gardeike, who adapted many diagrams for this article. Two reviewers provided useful advice.

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