Interpretation of climate models results, downscaling needs and options

Hans von Storch,

GKSS Research Centre, Geesthacht, Germany

Abstract

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, i.e. by time means and time variability on different time scales and its spectrum, by co-variability 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 is variable independently of the presence of changing external factors.

1 Quasi-realistic climate models („surrogate reality")

Models, which 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 (von Storch, 2001).

Such models are complex model – 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 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 down-scaling methods have to be applied (see below; von Storch, 1999).

In the climate system, processes are operating at all time scales. 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 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, a correspondence between the weather at a grid point and the weather at the geographic location formally corresponding to the grid point is hardly possible. 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, the formation of extra-tropical storms. As such, these models strive to be as realistic as possible. Since such models are, on the other hand, nevertheless as significant simplification of the complex real system, we use the term *quasi-realistic* for such models.

The models are considerably less complex than reality, but still *very* complex. They can react in ways which can not be foreseen by simple conceptual models. This is a virtue of such models, as they make them to kind of laboratories to test hypothesis with – they constitute a *virtual* or *substitute reality* (Müller and von Storch, 2004).

2 Free simulations and forced simulations for reconstruction of historical climate

Climate models can be run in different modes. There are “free” simulations and “forced” simulations. The former are useful to generate purely internal variability, whereas the latter allow the analysis of the effect of external factors. An example of a free simulation is shown in Figure 3. The climate model ECHO-G was integrated over 1000 years – with continuously repeated annual cycles of solar insolation and no other external factor. The variables shown are air temperature in different parts of the world. Obviously, the temperature undergoes significant variations, which can not be traced back to “causes”. The reason for this “smoke without fire” effect is the presence of myriads of non-linear chaotic processes. The sum of all these chaotic processes may be conceptualized by the mathematical concept of stochastic noise (von Storch et al., 2001). This noise is integrated by the slow components in the climate system, so that variations on all time scales appear with a to first order approximation red spectrum (Hasselmann, 1976).

When, on the other hand, external time-variable factors are added, characteristic cause-and-effect features may be detected (González-Rouco et al., 2003, Lionello et al., 2004). Figure 4 shows time series of atmospheric forcing by time-variable solar output and the effect of stratospheric volcanic aerosols, and of the 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 19th 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 anti-cyclones will vary from one simulation to the next, but the statistics of the formation of cyclones and anti-cyclones will be similar in any two realizations. In order to get a robust statistic, several simulations with identical forcing are preferable (*ensemble* simulation). To make them different realizations, several measures are possible; a popular method is to use a slightly different initial state.

3 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 images of a possible future; as such they have an impact on the future itself. Thus, scenarios are not only depictions of possible futures, but also active agents forming the future.

The success of the models on larger scales is illustrated in Figure 5. A total on 9 models was analysed with respect to their similarity in the change of precipitation averaged over sub-continental areas (Giorgi et al., 2001a). All nine models have been forced with the same "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. If the models were found to generate conflicting assessments, the symbol "i" was introduced in Figure 5. This exercise was done for a series of sub-continental areas, for both scenari9s A2 and B2 and for the two seasons DJF and JJA. For each of the regions, a square is added with the assessment for the two scenarios and two regions. 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 demonstrates 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. “Large” means here global, continental and sub-continental scales. A rough rule is that contemporary models are skilful 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.

4 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 detail (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; the formation of planetary features needs the presence of the cross 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 non-linear techniques like neural nets are in use. Sometimes the transfer functions relate statistical parameters to each other, such as intra-monthly 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. Also, weather generators are in this group, if their parameters are conditioned on the large-scale state (e.g., Busuioc and von Storch, 2002).

The other group of methods is based on the use of regional climate models. The (in most cases) 12 hourly weather stream generated by a global climate model is used to enforce certain climatic regimes on a regional scale; the dynamical model is constructing a regional 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 somewhat more detail.

One has to keep in mind hat 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 non-trivial 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 a too low resolution.

5 Regional climate modelling

In most cases, regional climate modelling (for a recent overview, refer to Wang et al., 2004) is just regional atmospheric modelling with some rudimentary simulation 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, 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, designed for Baltic Sea catchments studies, is made up of the ocean model BSIOM, the hydrological model and the regional atmospheric model REMO (Jakob; pers. Comm.): the Swedish Rossby Center is working with a system featuring a Baltic Sea model, regional hydrology and a regional atmosphere (Räisänen et al., 2003)

In most cases, the regional models are forced by boundary conditions along the lateral boundaries and, as discussed above, at the surface of water bodies. Mathematically this is not a well-posed problem. The “solution” in the interior is not determined by the lateral boundaries; instead several different states in the interior are consistent with as 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 regions is “flushed”, i.e. how quickly information from the boundaries is advected into the interior so that efficiently a boundary steering is established. In case of mid latitudes, such as Europe, this is very often the case; in ares with little “through-flow”, like the Arctic, this is not the case. Thus, any two extended simulations which are run with the same boundary values but slightly different initial values (which may simply be two observed state 12 hours apart) will generate more or less frequently very different behaviour. For a region like Europe such a “divergence” is rare, while for the Artic is it more frequent (Weisse et al., 2000; 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.

A method to overcome this intermittently emerging divergence is to cast the whole regional modelling problem not as a boundary problem but as a state space problem, in which the dynamical model is used to augment existing knowledge about the regional sate of the atmosphere. The latter is knowledge about the large-scale state of the atmosphere above a certain level, where the influence of the regional physiographic details is small. This concept leads to *spectral nudging* (von Storch et al., 2002), 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 forced only with lateral conditions. Also the emergence of intermittent divergence is suppressed (Weisse and Feser, 2003).

6 Regional scenarios

In the European project PRUDENCE (e.g., 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 not all simulations have been executed, and the process of comparing the responses of the various models is not yet completed. But first results emerge, among others that during winter the regional models deviate little from each other.

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 the details of frequency distributions is obtained.

As an example, the precipitation during summer time has been examined (Christensen and Christensen, 2002) as well as wind conditions over the North Sea (Woth, pers. comm.). In both cases a similar result is obtained, namely that the mean conditions are weakened – i.e., 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 6). 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; Woth, pers. comm.).

7 Conclusions

- Global climate modeling allows the representation of global, continental and sub-continental scales. Global models fail on 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.

Acknowledgements

I am thankful to Sebastian Wagner and Katja Woth for helpful comments.

8 References

Busuioc, A., and H. von Storch, 2003: Conditional stochastic model for generating daily precipitation time series, Climate Research 24, 181-195

Christensen, J.H., T. Carter, F. Giorgi, 2002: PRUDENCE employs new methods to assess European climate change, EOS, Vol. 83, p. 147.

Christensen, J.H. and O.B. Christensen, 2003: Severe summertime flooding in Europe. Nature, Vol. 421, p. 805-806, 20 February 2003.

Giorgi, F., P.H. Whetton, R.G. Jones, J.H. Christensen, L.O. Mearns, B. Hewitson, H. von Storch, R. Fransico and C. Jack, 2001a. Emerging patterns of simulated regional climatic changes for the 21st century due to anthropogenic forcings. Geophys. Res. Lett., 28(17): 3317-3320.

Giorgi, F., B. Hewitson, J. Christensen, M. Hulme, H. von Storch, P. Whetton, R. Jones, L. Mearns and C. Fu, 2001b: Regional climate information - evaluation and projections. In J.T. Houghton et al (eds.): *Climate Change 2001. The Scientific Basis*, Cambridge University Press, 583-638

González-Rouco J. F., E. Zorita, U. Cubasch, H. von Storch, I. Fischer-Bruns, F. Valero, J. P. Montavez, U. Schlese and S. Legutke, 2003: Simulating the climate since 1000 A. D. with the AOGCM ECHO-G. *Proc. ISCS 2003 Symposium, 'Solar Variability as an Input to the Earth's Environment'*, Tatranská Lomnica, Slovakia, 23-28 June 2003. ESA SP-535, 329-338.

Hasselmann, K., 1976: Stochastic climate models. Part I. Theory. Tellus 28, 473-485

Hasselmann, K., 1990: How well can we predict the climate crisis? In: H. Siebert (ed) Environmental Scarcity - the International Dimension. JCB Mohr, Tübingen, 165 - 183

P. Lionello, S. de Zolt, J. Luterbacher, and E. Zorita. Variability of the winter European climate and the NAO index during the last 500 years. Submitted to Climate Dynamics

Müller, P., and H. von Storch, 2004: *Computer Modelling in Atmospheric and Oceanic Sciences - On the Generation of Knowlegde.* Springer Verlag Berlin - Heidelberg - New York

Räisänen, J., U. Hansson, A. Ullerstig, R. Döscher, L.P. Graham, C. Jones, H.E.M. Meier, P. Samuelsson, U. and Willén, 2003: European climate in the late 21st century: regional simulations with two driving global models and two forcing scenarios. Climate Dynamics, in press.

Rinke, A., and K. Dethloff, 2000: On the sensitivity of a regional Arctic climate model to initial and boundary conditions. Clim. Res. 14, 101-113.

von Storch, H., 1999: The global and regional climate system. In: H. von Storch and G. Flöser: Anthropogenic Climate Change, Springer Verlag, ISBN 3-540-65033-4, 3-36

von Storch, H., 2001: Models. In: H. von Storch and G. Flöser (Eds): *Models in Environmental Research.* Springer Verlag, 17-33 von Storch, H., H. Langenberg and F. Feser, 2000: A spectral nudging technique for dynamical downscaling purposes. Mon. Wea. Rev. 128: 3664-3673

von Storch, H., J.-S. von Storch, and P. Müller, 2001: Noise in the Climate System - Ubiquitous, Constitutive and Concealing. In B. Engquist and W. Schmid (eds.) *Mathematics Unlimited - 2001 and Beyond*. Part II. Springer Verlag, 1179-1194

Wang, Y., L. R. Leung, J.L. McGregor, D.-L. Lee, W.-C. Wang, Y. Ding and F. Kimura, 2004: Regional climate modelling: progress, challenges and prospects. J. Meteor. Soc. Japan (submitted)

Weisse, R., H. Heyen and H. von Storch, 2000: Sensitivity of a regional atmospheric model to a sea state dependent roughness and the need of ensemble calculations. Mon. Wea. Rev. 128: 3631-3642

Weisse, R. and F. Feser, 203: Evaluation of a method to reduce uncertainty in wind hincasts performed with regional atmosphere models. Coastal Eng. 48, 211- 255

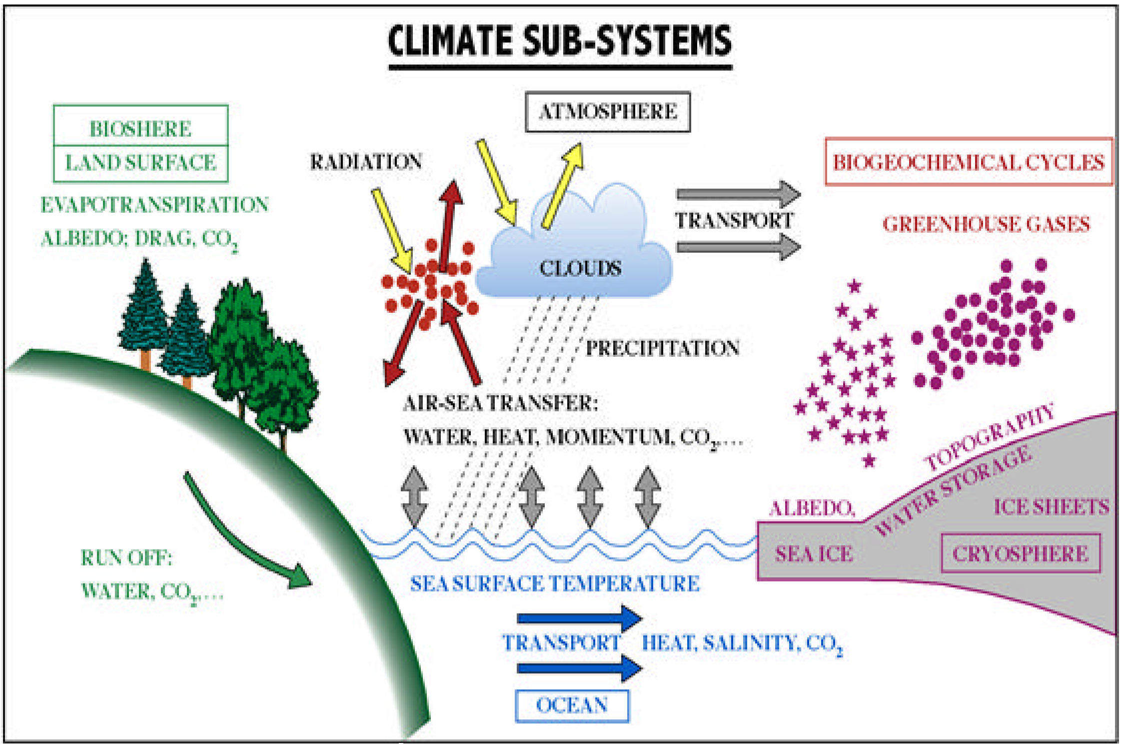

Figure 1: Components of a dynamical climate model. (Hasselmann, 1990)

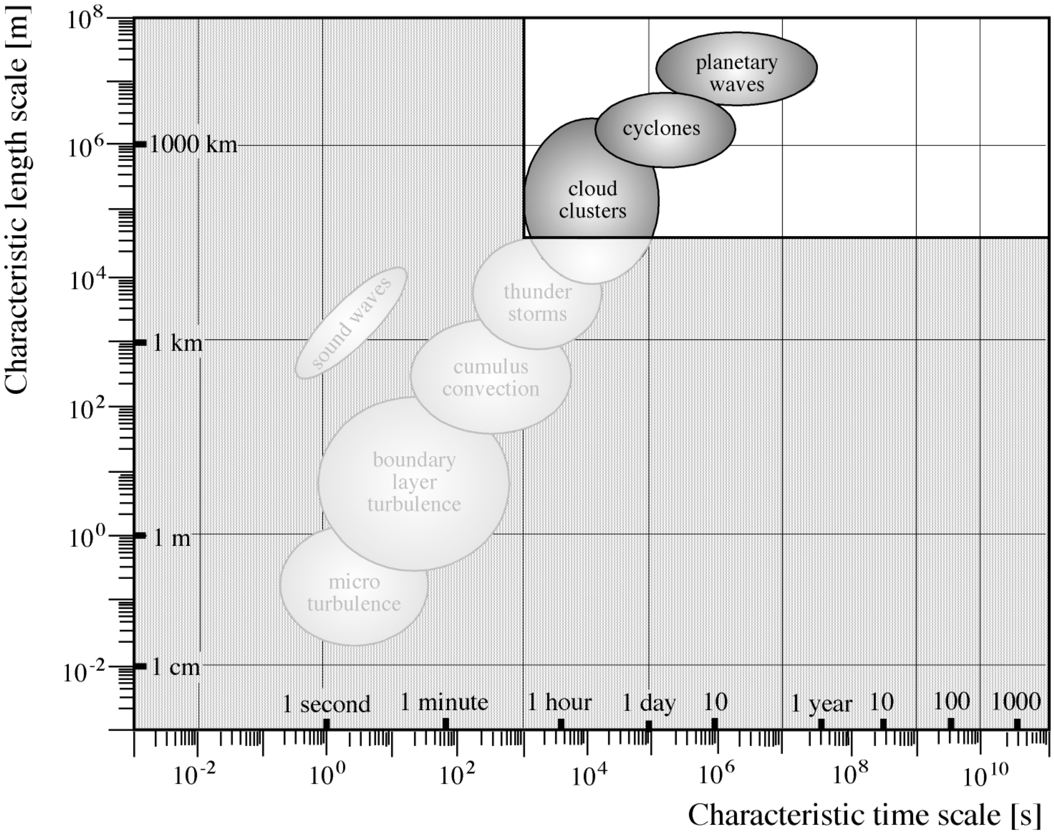

Figure 2: Resolved and unresolved processes and scales in a contemporary

atmospheric model. (Müller and von Storch, 2004)

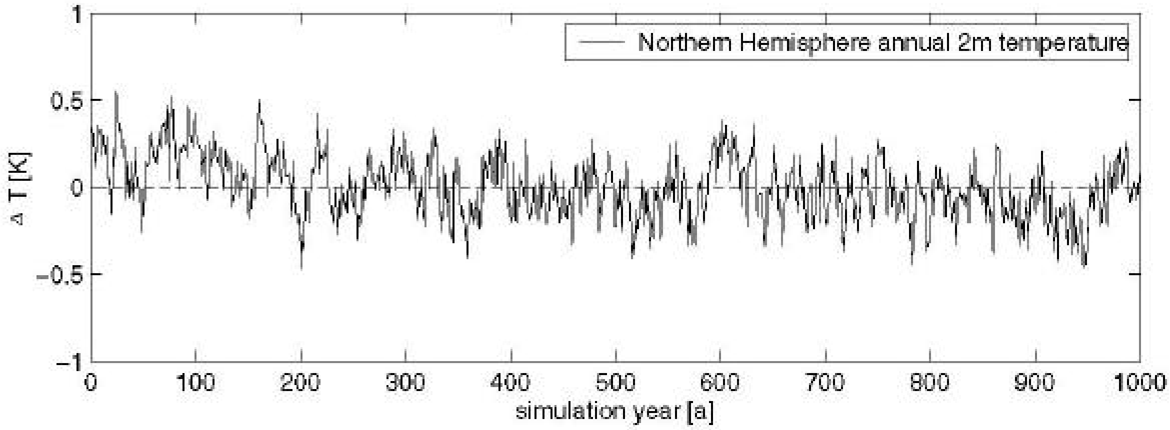

Figure 3: Air temperature simulated in a 1000 year free simulation (Wagner, pers. comm.

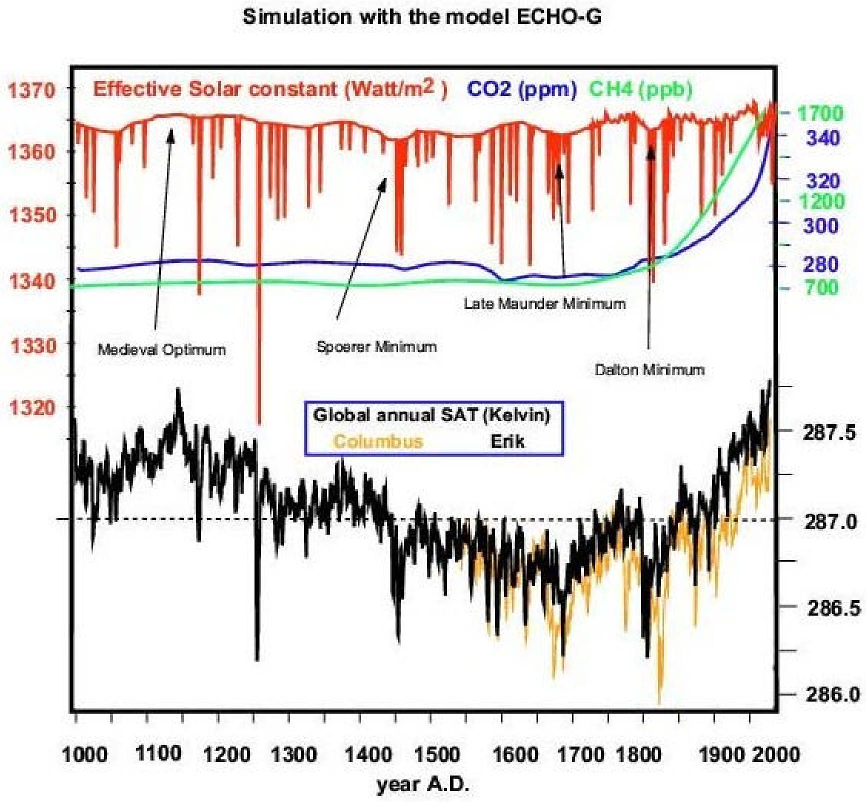

Figure 4: Time variable forcing (top) and temperature (bottom) in a 1000 year simulation and in a 500 year simulation.

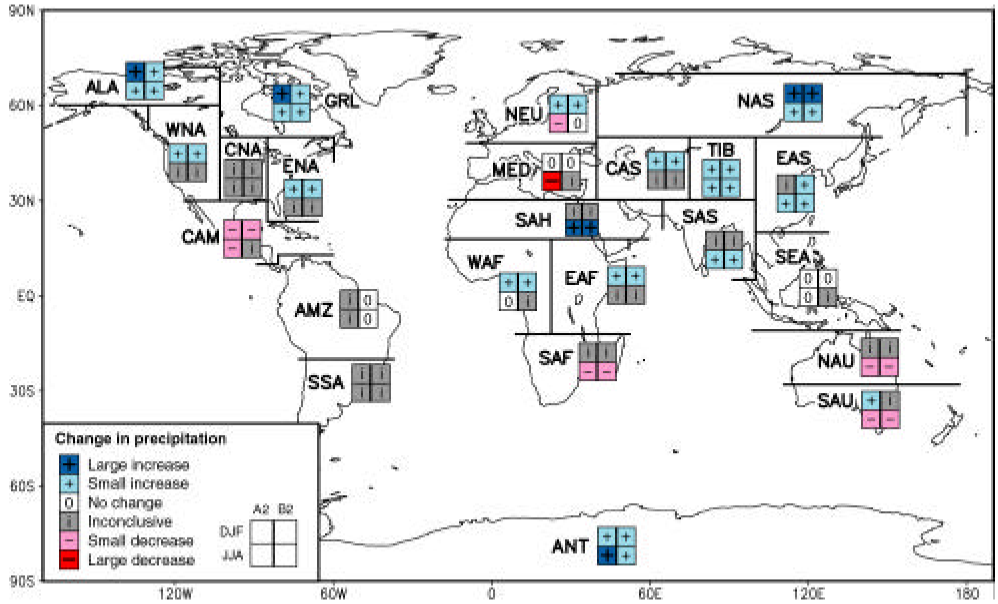

Figure 5: Convergence of climate models in simulating the same regional change in precipitation according to the greenhouse gas emission emissions scenarios A2 (left two boxes) and B2 (right two boxes) at the end of the 21st century. The top two boxes refer to northern winter (DJF), the bottom to the northern summer (JJA). (Giorgi et al., 2001a)

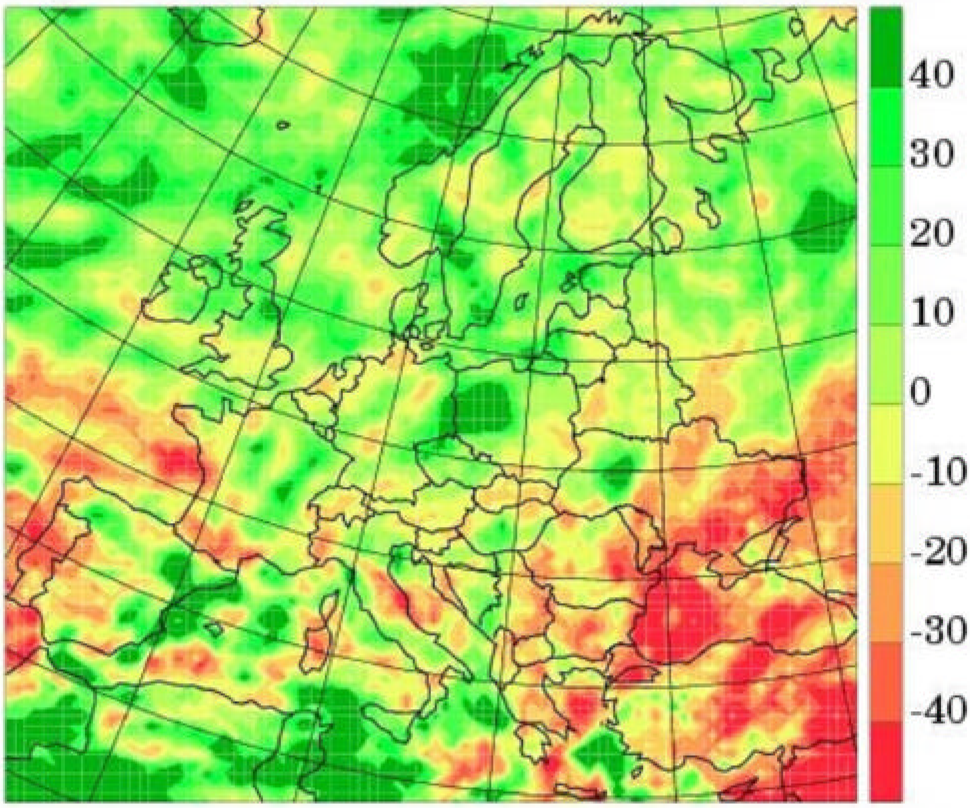

Figure 6: Change in precipitation intensity or the rare summer events as envisaged by a regional climate model for the end of the 21st century. The quantity shown is the change in five-day mean exceeding the 99th percentile (Christensen and Christensen, 2003)