Climate Change and Ocean Forecasting

Climate variability and change

Hans von Storch and Klaus Hasselmann, Hamburg

Summary

The concepts of climate variability, due to natural processes, and of climate change, related to Man's activities, are illustrated. Different types of internal mechanisms, such as multiple equilibria and the integration of noise, are discussed. A systematic approach to discriminate between natural variability and anthropogenic change indicates that the latest warming trends in the observational record can no longer be understood as "variability" but is likely related to external processes, and in particular to the enhanced greenhouse effect. Finally we discuss briefly major challenges climate research will face in the coming decades.

1. Notions of climate variability and climate change

"Climate" is now firmly established in the public awareness as a major environmental problem. "Global Warming" has become a household term understood by everybody without further explanation (Ungar, 1992; Lacey and Longman, 1993; Stehr and von Storch, 1995). What is often overseen, however, by the general public as well as the scientific community is the presence of two competing processes in the observational record and in any reasonable scenario of expected future climate evolution. These two processes, climate change and climate variability, have similar signatures, namely low-frequency climatic modifications, and are therefore sometimes confused:

- "Climate Variability" arises from "natural" mechanisms unrelated to Man's actions. We may distinguish between external and internal natural variability.

  Examples of the response of the climate system (i.e., the coupled system composed of such diverse components as the physics and chemistry of the atmosphere and the ocean, and the biology of the surface of the Earth) to natural external forcing are volcanism (Graf et al., 1993,1994), variations in the energy output of the sun or the Milankovitch cycle.

  "Internal variability", on the other hand, is the low-frequency variability which arises from dynamical processes internal to the climate system. There are basically two processes which pump energy into the low-frequency part of the spectrum: non-linear interactions (e.g. James et al., 1994) and the accumulation of short time-scale "weather noise" (Hasselmann, 1976; see review by Frankignoul, 1995).

  An example of such free climate variability is shown in Figure 1, which represents a time series of 5-year mean anomalies of the number of ice-

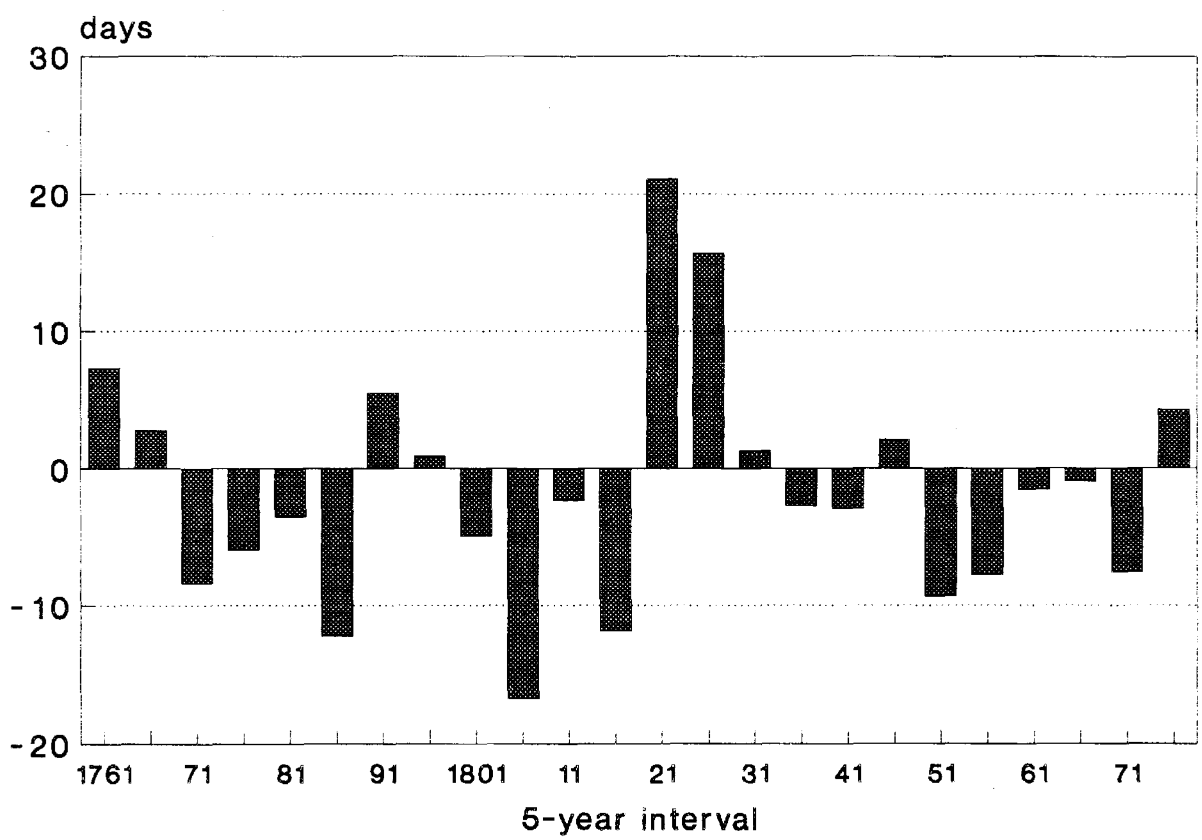


Figure 1. 5-year mean anomalies of the number of ice-free days on the river Newa at St. Petersburg (Russia) from 1761-1880. The anomalies are formed relative to the 1816-80 mean. Adapted from Brückner, 1890.

free days on the river Newa from 1761–1880. The fluctuations are random and reflect the time-integrated weather history in Western Russia.

- We reserve the term "Climate Change" to denote the formation of persistent climatic anomalies which are related to activities of Man. Examples of such actions (see, for example, Cotton's and Pielke's monograph, 1992) are urbanization (i.e., the modification of surface fluxes in the boundary layer through buildings and streets), desertification and deforestation, and anthropogenic emissions of soot (gulf-war in 1991; Bakan et al., 1991), aerosols and greenhouse gases. The emission of CO_2, CFCs and methane, in particular, have been the subject of widespread concern because of their implications for global warming.

  Figure 2 shows as an example of man-made climate change the observed urban warming in the developing city of Sherbrooke in Canada, which is absent in the record of the nearby rural weather station Shawinigan.

In the following we discuss first the dynamics of internally generated climate variability (Section 2; mainly based on material provided by Rahmstorf, 1994, 1995; Claussen, 1994 and J. von Storch, 1994) and then the state-of-the-art of modelling the expected climate change due to increased *greenhouse gas concentrations in the troposphere* (Section 3; *mainly* following Cubasch et al., 1995). The results of these simulations are indispensable ingredients in the subsequent statistical discrimination between the natural variability and man-made climate change in the observational record of

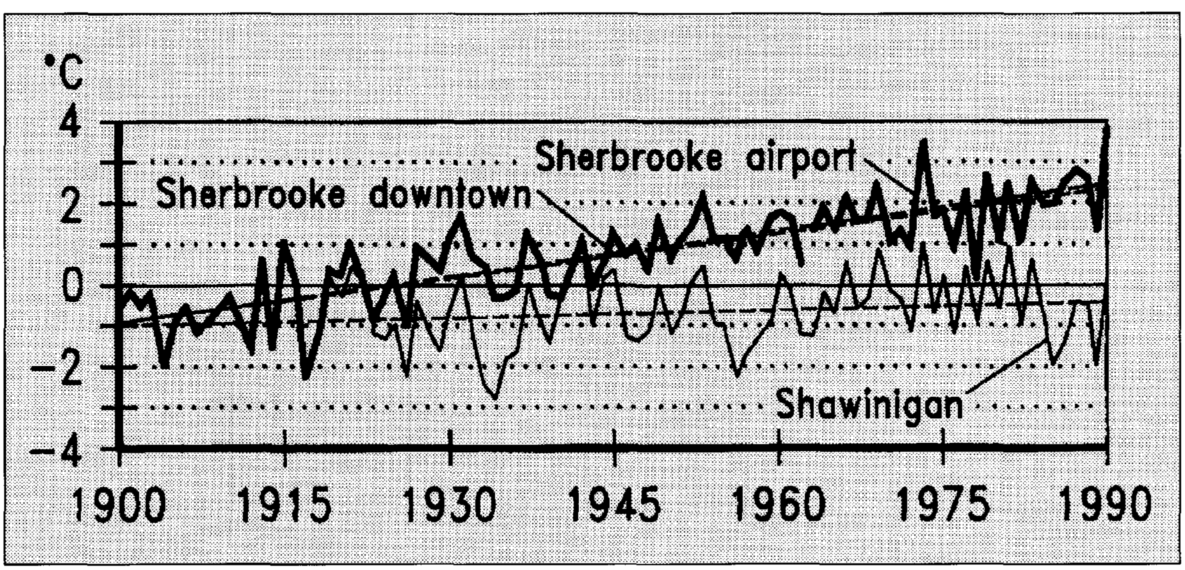


Figure 2. Mean temperature at two neighbouring weather stations in Quebec (Canada). The urban station Sherbrooke exhibits a marked trend due to urbanization whereas the rural station Shawinigan is almost trend-free. From von Storch and Zwiers, 1996.

near-surface temperatures (Section 4; mainly following Hegerl et al., 1995). We find that we may reject with a risk of less than 2.5% the null hypothesis that the most recent warming trends are due to climate variability - provided that our estimate of the natural variability is correct. In the concluding Section 5 we discuss some problems of current climate research.

2. Dynamics of climate variability

In Section 1 we listed the two principally possible contributors to internally generated low-frequency variability, namely nonlinear dynamics and the accumulation of noise. In the following subsections we review two interesting numerical experiments which exhibit the nonlinear behaviour of multiple equilibria (Subsections 2.1 and 2.2), and several cases in which climate models produce red or almost red spectra through the integration of high-frequency noise (Subsection 2.3 and 2.4).

2.1. Multiple equilibria of the North Atlantic ocean circulation

The North Atlantic circulation has a major influence on the regional climate of Europe. It has been speculated that the sudden return of ice age conditions 11 k years bp, the "Younger-Dryas"-event, was caused by a reduction of the North Atlantic overturning circulation (Berger and Killingley, 1982) triggered by a major inflow of (fresh) melt water from the Laurentide Ice Sheet (Broecker et al., 1989; Maier-Reimer and Mikolajewicz, 1989). More recent model experiments, in which the ocean was exposed to a sudden injection of a moderate influx of fresh water, showed that the meridional transport of the North Atlantic overturning circulation is able to adopt a whole suite of locally stable states (Rahmstorf and Willebrand, 1994; Rahmstorf, 1994, 1995). After every injection of fresh water the system attains a new locally stable state (Figure 3, upper curve).

This rather startling behaviour might, however, be an artifact of the experimental set-up. The relative magnitudes of negative feedback-terms for salt and temperature anomalies are crucial in determining the final outcome. Rahmstorf and Willebrand (1995) made experiments with different combinations of the strength of the negative feedback terms for salt and temperature. They modelled the negative feedback of the temperature as a function of the spatial scale, and found that the previous instability of the overall transport disappeared (Figure 3). The system maintains the same level of transport also after major injections of fresh water. However, the spatial pattern of convection exhibits various locally stable distributions (Figure 4).

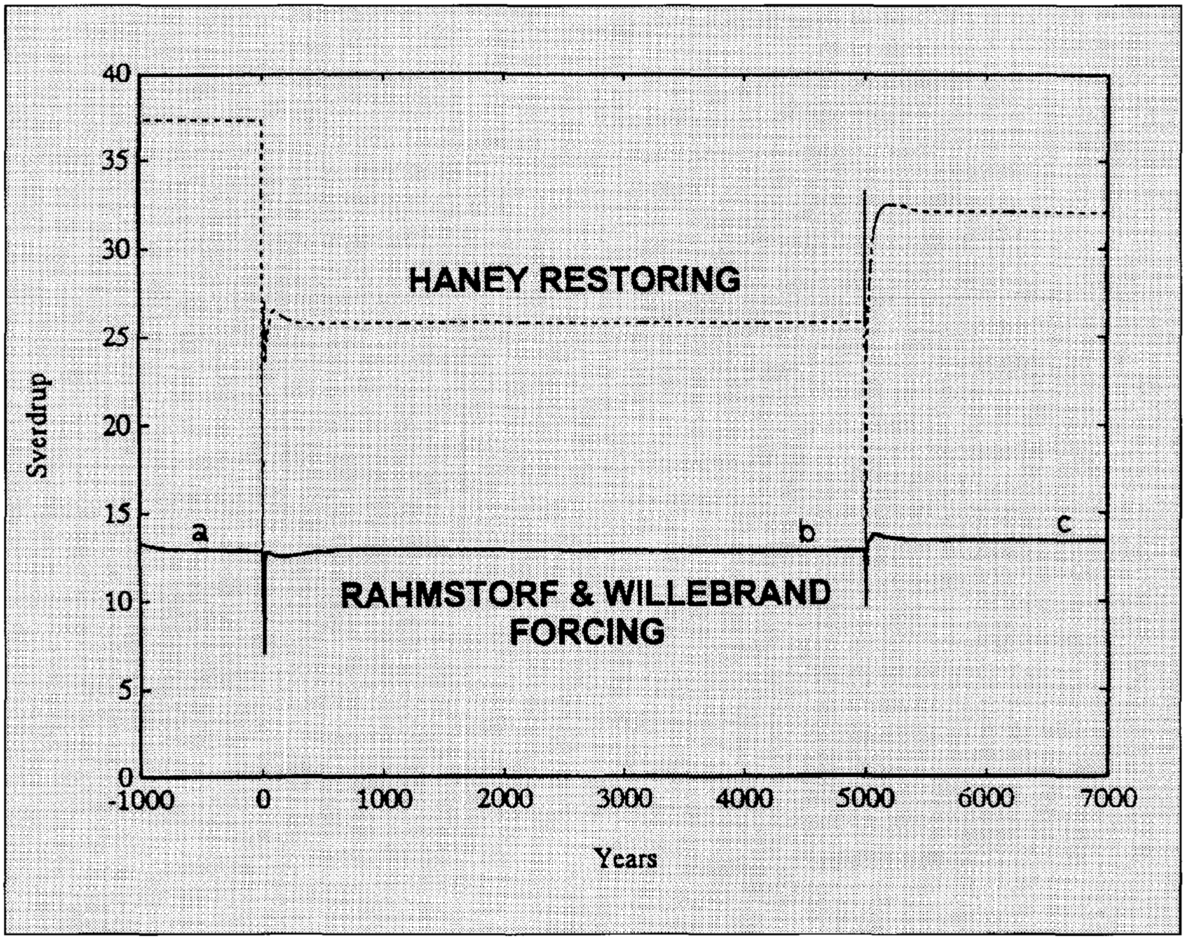


Figure 3. Transport of the meridional overturning cell in the North Atlantic for different numerical experiments involving moderate injections of fresh water at high latitudes. (See also Figure 4). From Rahmstorf, 1995.

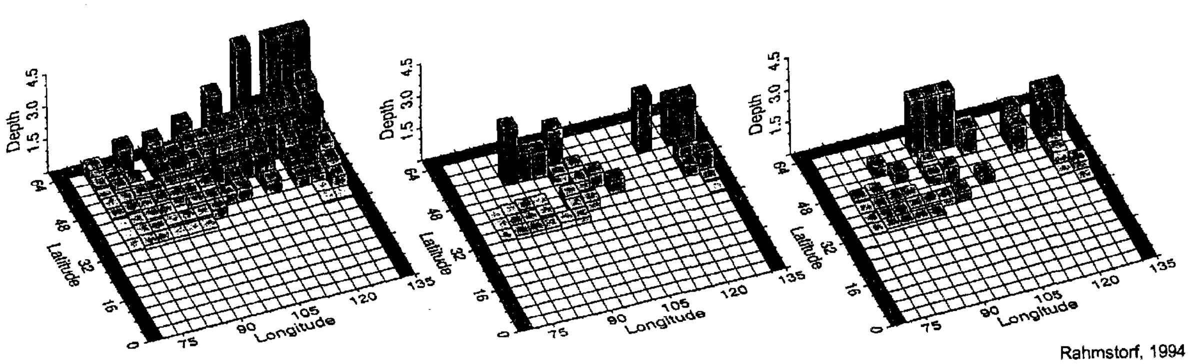


Figure 4. Patterns of convection in a numerical experiment with an ocean general circulation model after the injection of a moderate amount of fresh water at high latitudes during phases a, b, and c of the lower curve in Figure 3. The depth (km) of convection in each grid cell is plotted as a vertical bar. From Rahmstorf, 1994.

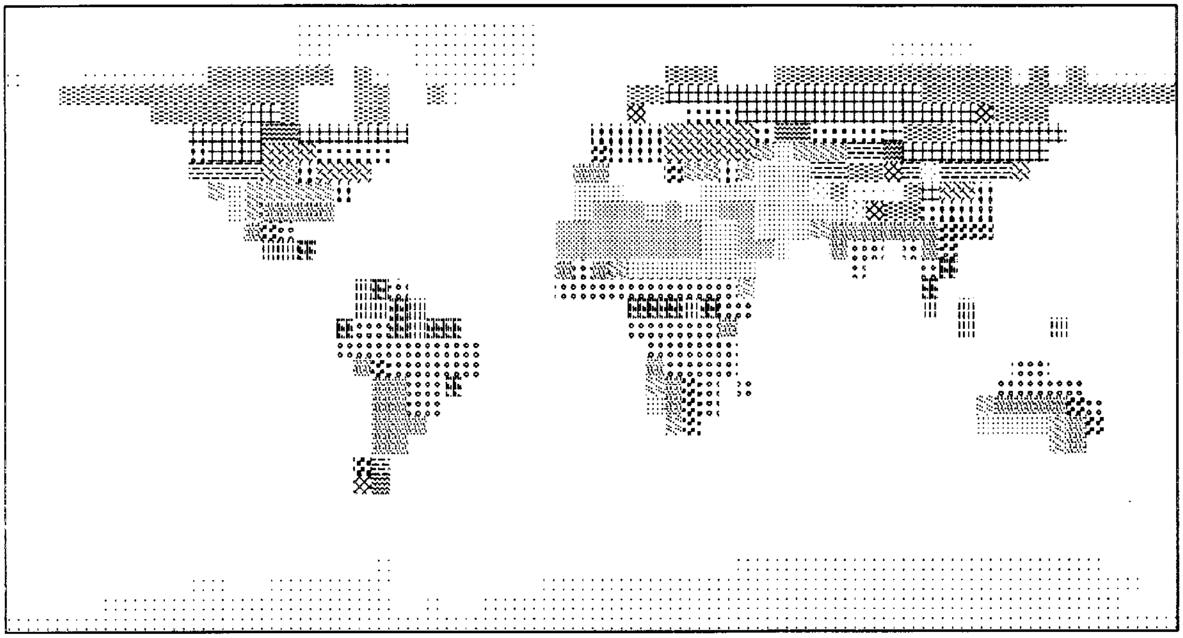
2.2. *Multiple equilibria of a biome distribution*

Our second case concerns the role of the biota for the physical state of the climate system. The form of vegetation on the surface of the earth modifies the fluxes of energy and momentum (and matter) between the surface and the boundary layer. The plant community, or the *biome*, prevailing at a certain location depends on the local climate. Biome and local climate are assumed to be in equilibrium. But note that the local climate is in part controlled by the large-scale climate.

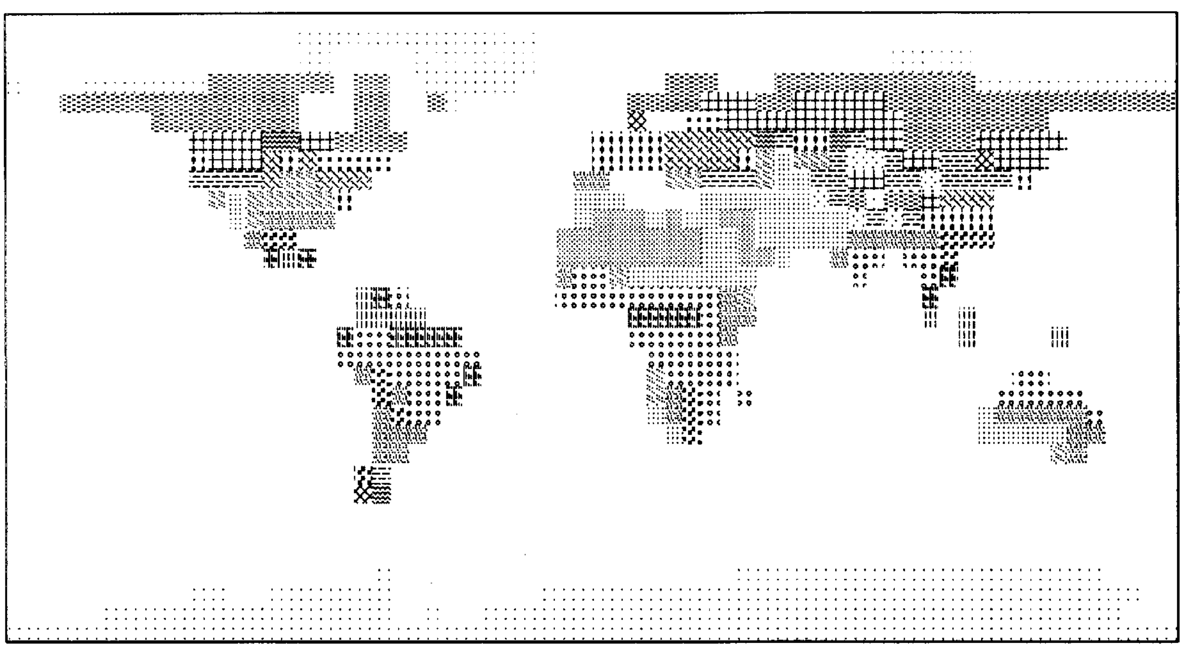
Prentice et al. (1992) model this dependency by first creating a table which specifies plant functional types depending on the local climate (in terms of extreme temperatures, temperature sums, and annual soilwater availability). For any combination of temperature and water availability, the biome model specifies which plant functional type can occur. Then, potentially dominant plant types are selected and, finally, biomes are defined as combinations of dominant plants. Figure 5a shows the biome distribution for present climatic conditions. (The modelled biome distribution of Figure 5a fits the observed biome distribution well, which is to be expected since the determining table has been selected to achieve this.)

Claussen (1994) coupled the biome model to an atmospheric GCM (the Hamburg model ECHAM, c.f., Roeckner et al., 1992) by the following procedure. The biome distribution, as specified by present day conditions, is taken as lower boundary condition for the GCM, which is then integrated over six years. After a spin-up period of 1 year, a new climate is computed from the subsequent 5 years, and a new biome distribution is specified according to the newly formed climate. Then the GCM is integrated another five years, after which the biome is again adjusted. Claussen (1994) integrated this coupled system for 24 years. The system settled to an equilibrium (Figure 5b) which is close to the initially prescribed biome distribution and the observed climate.

In a second experiment, Claussen (1995) modified the initial biome distribution arbitrarily by specifying a desert in regions where in reality tropical rain forest prevails and vice versa (Figure 6a). The coupled system quickly moves away from this initial biome distribution and reaches a new equilibrium (Figure 6b) which is in most areas like the observed distribution. However, in some areas, such as North Africa, another equilibrium is found. Thus the equilibrium climate with its associated equilibrium biome distribution is not unique.

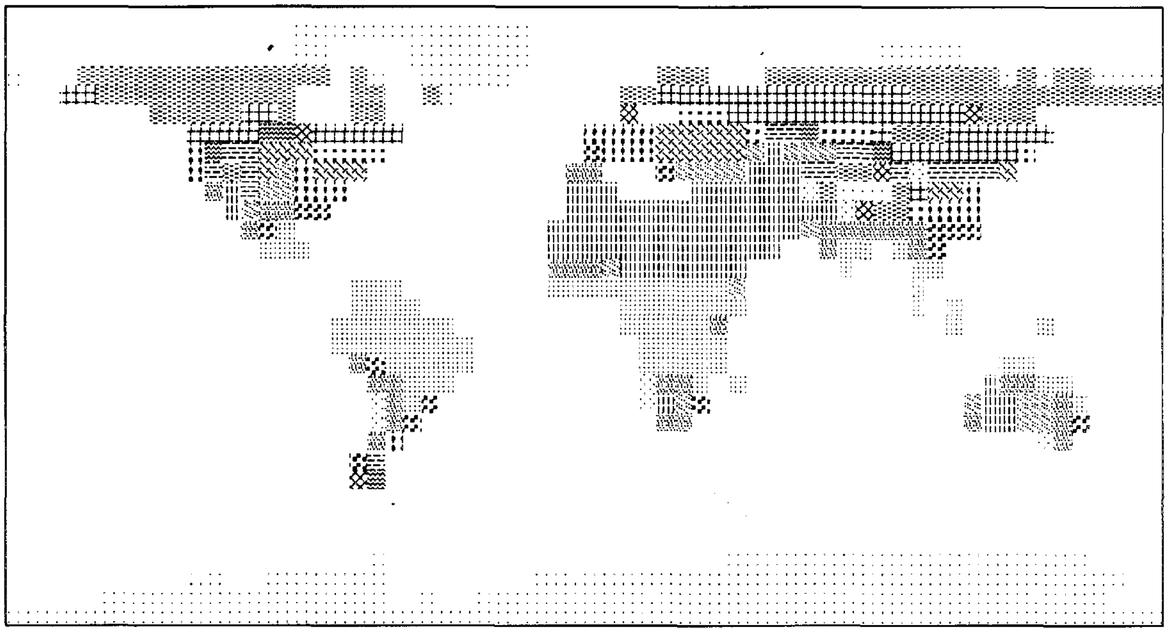


a) Initial condition with present day distribution

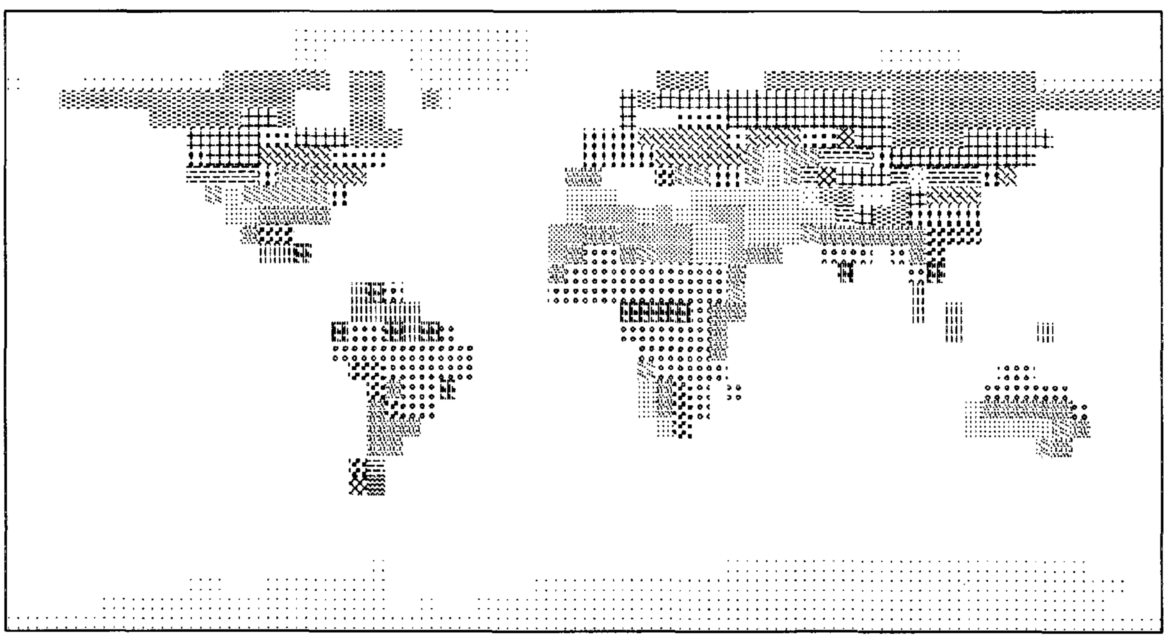


b) Biome distribution after 30 years of integration

Figure 5. (a) Biome distribution for present day conditions. (b) Biome distribution after 30 years of integration with the coupled biome-atmosphere model using the distribution (a) as initial condition. From Claussen, 1995.



a) Perturbed initial biome distribution



b) Biome distribution after 30 years of integration

Figure 6. (a) Artificially modified biome distribution used as initial condition in a numerical experiment with a coupled biome-atmosphere model. (The areas of desert and tropical rainforest are interchanged relative to Figure 5a.) (b) Biome distribution after 30 years of integration with the coupled biome-atmosphere model using the distribution (a) as initial condition. From Claussen, 1995.

2.3. *Excitation of low-frequency variability by high-frequency noise - ocean modelling*

Even linear systems, which feature exclusively damped modes, may exhibit marked low-frequency variations when forced by short time-scale noise (Hasselmann, 1976). After demonstrations of the power of this concept by fitting simple models to time series of sea-surface temperature and sea-ice (see the review by Frankignoul, 1995), two numerical experiments with a realistic ocean GCM were conducted by Mikolajewicz and Maier-Reimer (1990) and Weisse et al. (1994).

In both cases the ocean GCM (the Hamburg LSG = Large Scale Geostrophic Model, cf. Maier-Reimer et al., 1993) was first integrated with specified climatologically fixed boundary conditions for the surface fluxes of heat, momentum and fresh water until the model became stationary. Then, a time-variable fresh water flux was superimposed on the mean fresh water flux. This time-variable flux was specified as randomly drawn from a white-noise process with zero mean, zero correlation in time but finite correlation in space.

Mikolajewicz and Maier-Reimer (1990) made the experiment with a global ocean model, and found pronounced well organized low-frequency variations in many parameters, for instance in the mass transport through the Drake passage (Figure 7). A detailed analysis revealed that an eigen-mode oft the oceanic circulation had been excited. This mode, which shows quasi-oscillatory behaviour with a period of about 350 years, involves the entire

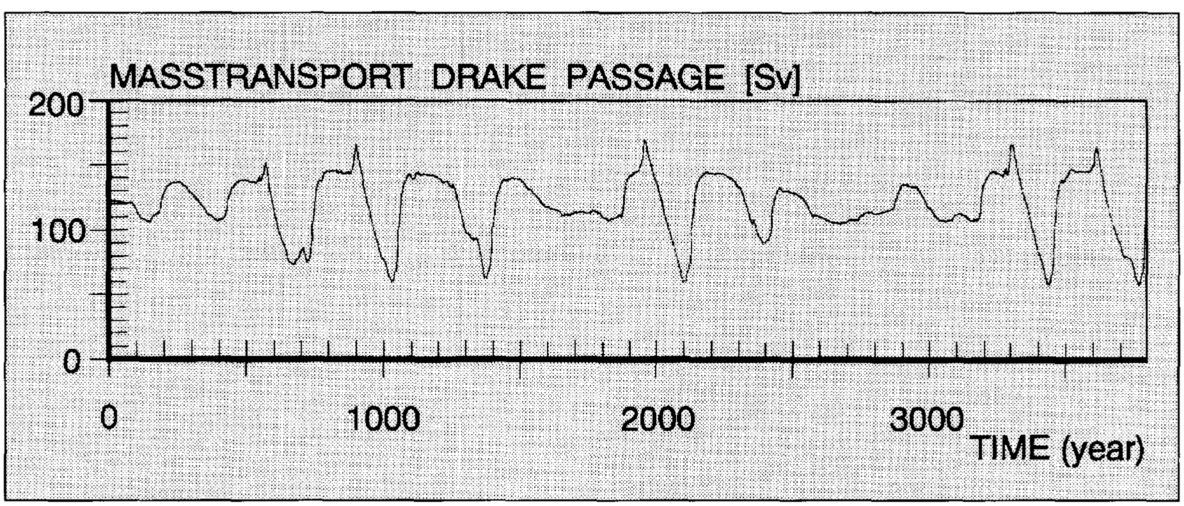


Figure 7. Intensity of the mass transport through the Drake Passage in a numerical experiment with an ocean GCM forced with white-noise fresh water flux. From Mikolajewicz and Maier-Reimer, 1990.

meridional circulation of the North Atlantic Ocean and extends into the Antarctic Circumpolar Current. As expected, its spectrum is almost red, apart from a spectral peak at the eigen-frequency of about 350 years (Figure 8).

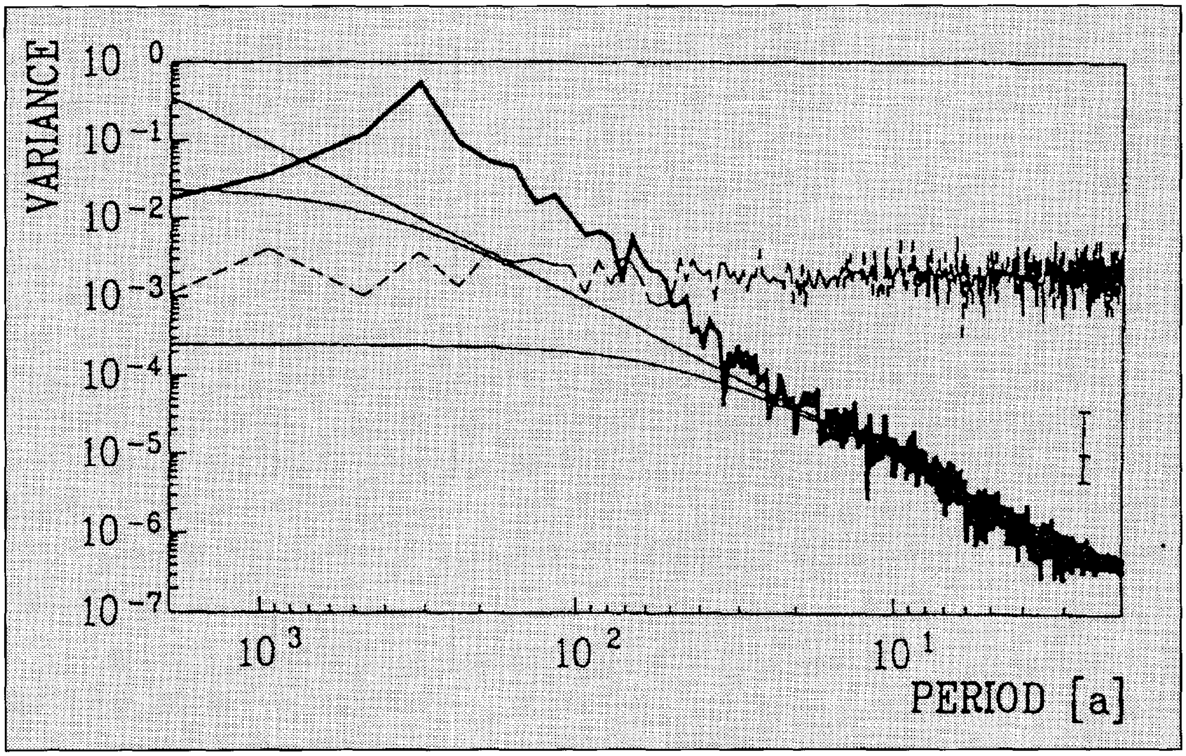


Figure 8. Spectrum of the variability represented in Figure 7. For comparison spectra of red-noise processes (pure integrator and Markov process) are also shown. The flat spectrum (dashed line) represents the driving white noise forcing. From Mikolajewicz and Maier-Reimer, 1990.

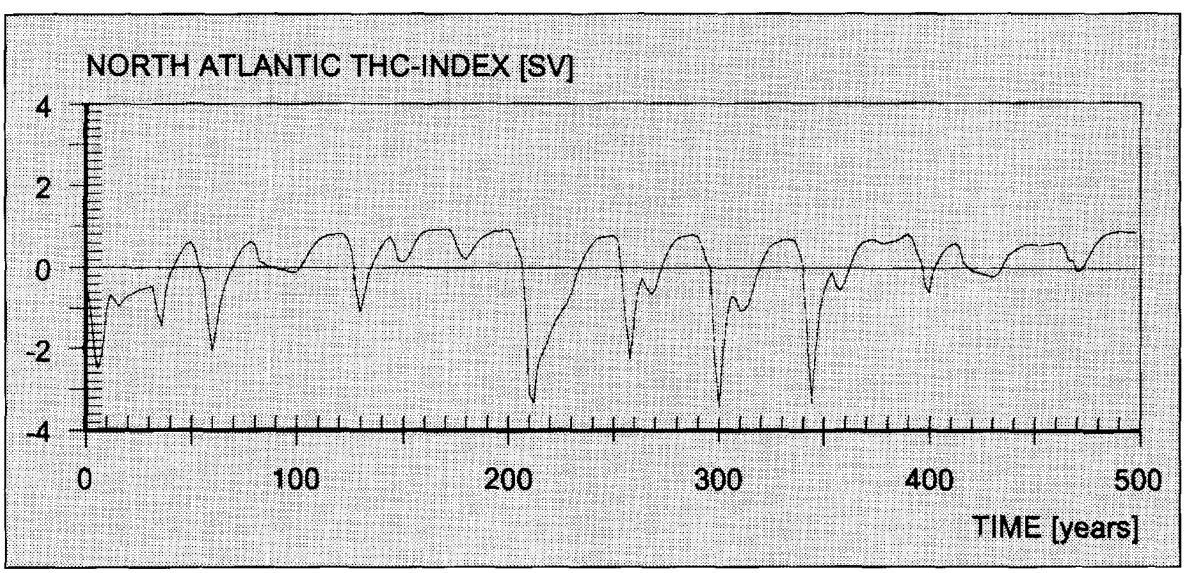


Figure 9. Intensity of meridional overturning in the North Atlantic Ocean (represented by a suitable index) in ocean GCM forced with white-noise fresh water flux. From Weisse et al., 1994.

Weisse et al. (1994) examined data from the same numerical experiment with respect to the variability in the North Atlantic Ocean. There, a charge-discharge mechanism was identified with the main action restricted to the Labrador Sea. This process affects the efficiency of the meridional overturning in the North Atlantic on multi-decadal time scales, as illustrated in Figure 9.

2.4. Excitation of low-frequency variability by high-frequency noise - atmosphere-ocean modelling

The rapid enhancement in computing power during the past years has now enabled fully coupled ocean-atmosphere GCMs to be integrated up to 1000 years. Figure 10 indicates the wide variety of processes which are represented, often in parameterized form, in a climate model. One such 1000-year experiment has been conducted with the model configuration LSG/ ECHAM1 T21 (Roeckner et al., 1992; Maier-Reimer et al., 1993) at the Max-Planck-Institut für Meteorologie (cf. J. von Storch (1994) for results of the first 325 years).

Figure 11 depicts the temporal evolution of the mass transport through the Drake Passage during the first 500 years of this experiment. The same index was shown in Figure 7 to demonstrate the excitation of free modes in the

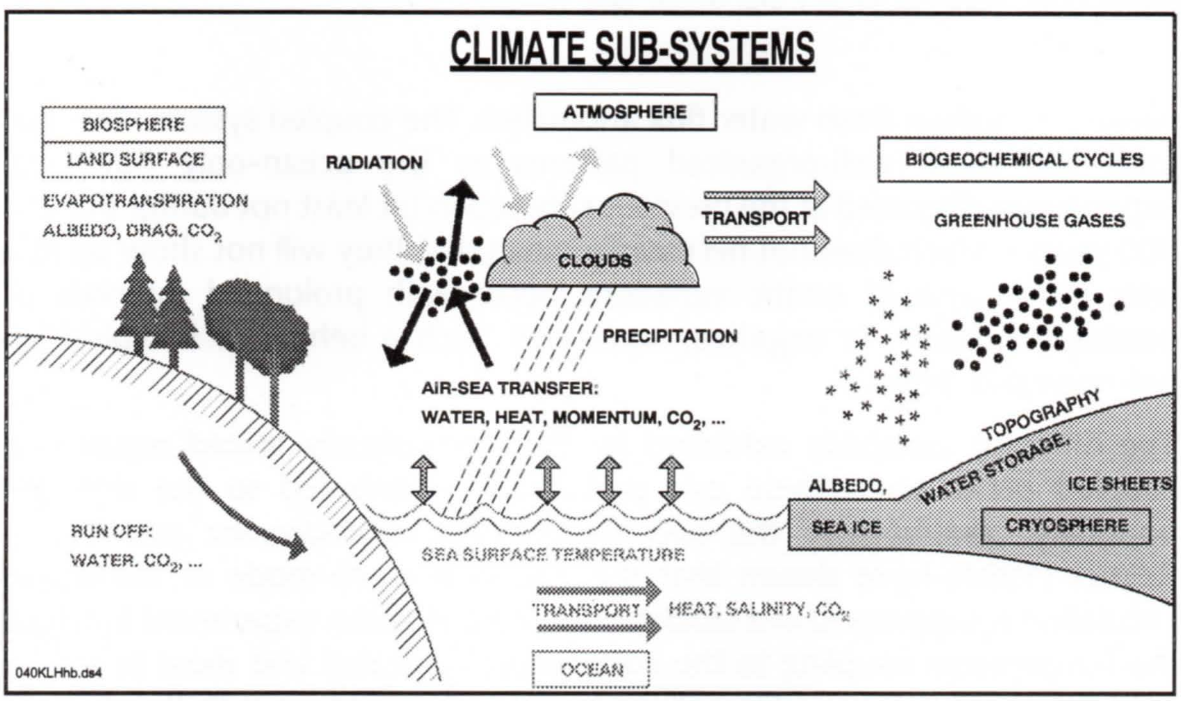


Figure 10. Processes represented in a climate model.

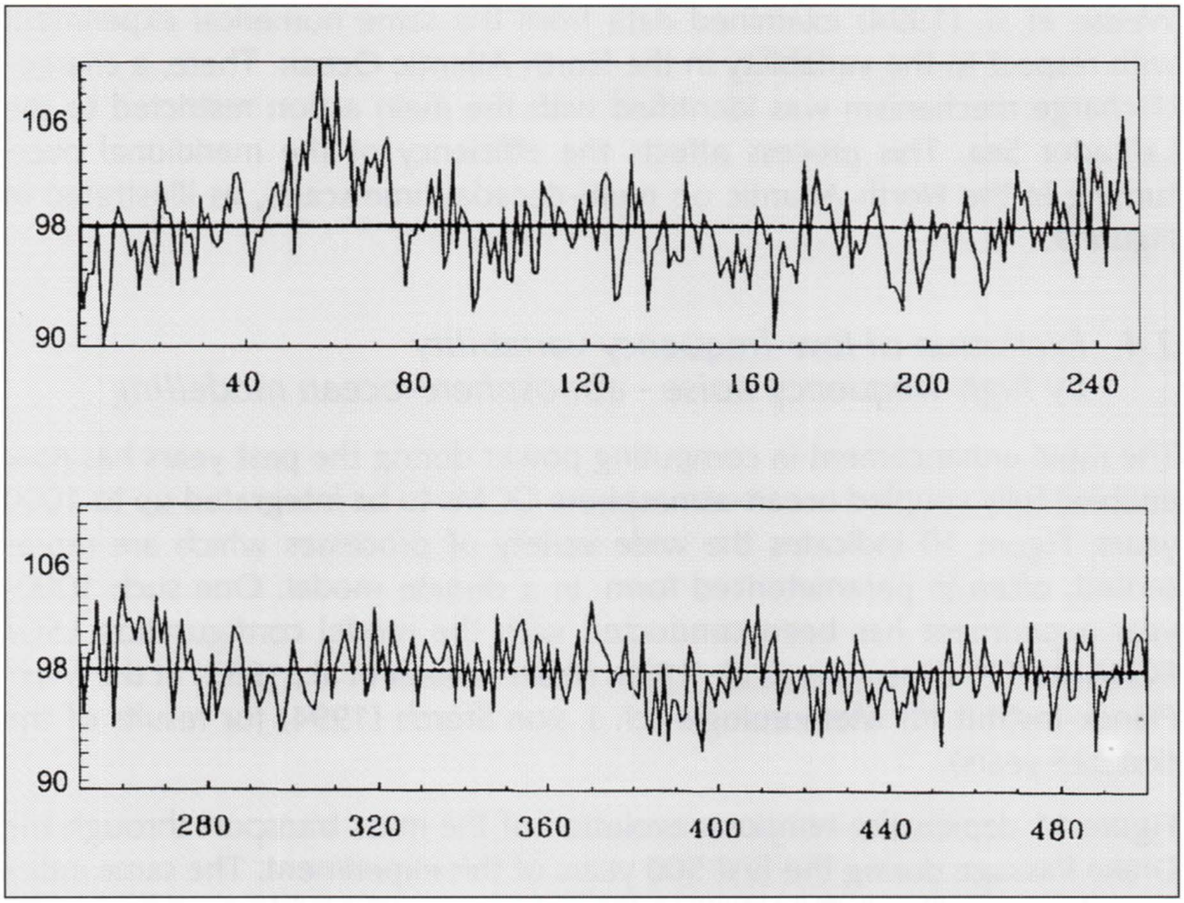


Figure 11. Temporal evolution of the mass transport through the Drake Passage simulated in the first 500 years of a 1000-year experiment conducted with a coupled ocean-atmosphere model. Units: Sverdrup. From J. von Storch, pers. comm.

ocean by random fresh water flux anomalies. The coupled system does not form the same well-organized patterns as the ocean-only numerical experiments discussed in the previous subsection (at least not during the first 500 years - which does not necessarily mean that they will not show up at a later time). Instead erratic variations occur with prolonged intervals of persistent positive, or negative, anomalies. Such a behaviour is typical for red-noise processes.

The different variability exhibited by the stochastically forced ocean and coupled ocean-atmosphere can probably be attributed to the different boundary conditions in the two experiments. Mikolajewicz and Maier-Reimer (1994) have shown that the 350 year eigen-mode of the ocean circulation is suppressed in a stochastically forced ocean experiment in which the temperature coupling to the atmosphere is weaker and more in accord with the coupled ocean-atmosphere model (in consistence with Rahmstorf's results mentioned earlier).

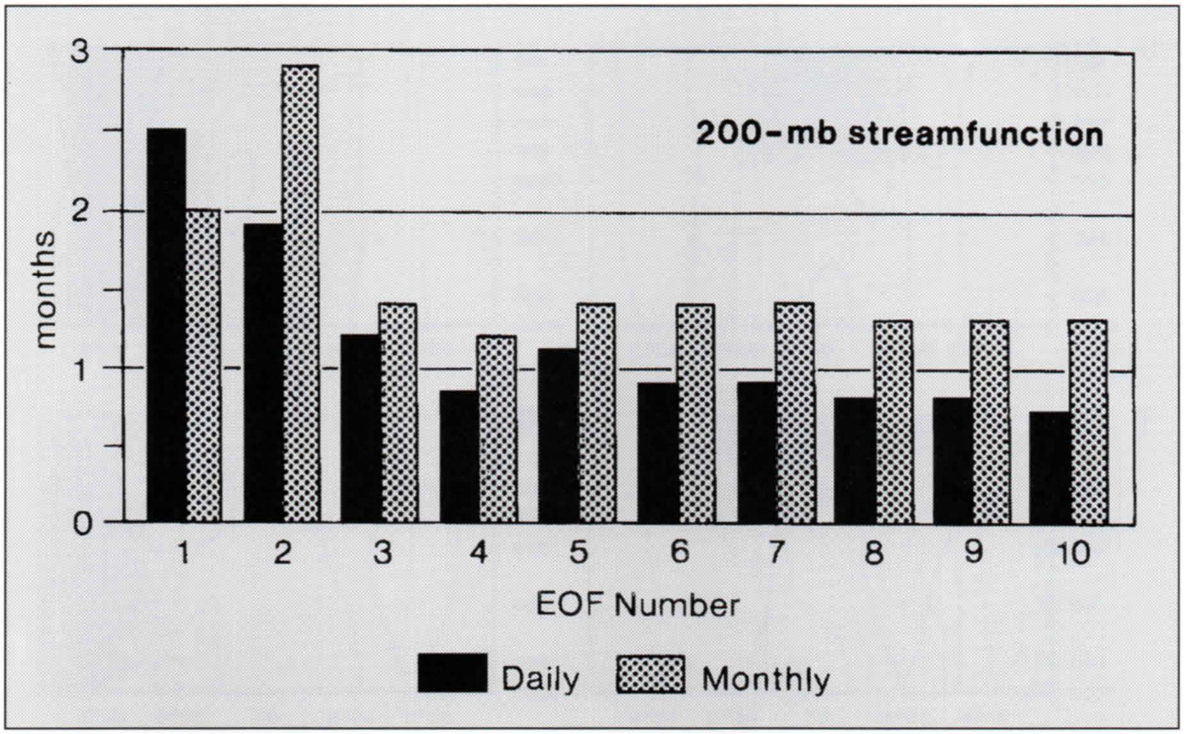


Figure 12. Correlation time scales of the leading EOFs of daily and monthly 200 hPa streamfunction, as simulated during the first 300 years of a 1000-year numerical experiment with a coupled ocean-atmosphere model. From J. von Storch, 1994.

An analysis of the global upper-tropospheric streamfunction reveals two modes (EOFs) with surprisingly long characteristic times (represented by the correlation time scale; Figure 12).

The first mode has a correlation time scale of more than 2 months and is associated with zonally averaged anomalies of zonal wind, temperature and vertical velocity (Figure 13). This mode has a signature only in the tropical troposphere, and is apparently unrelated to the surface and the ocean. The time series of the coefficient of this mode appears red and is highly correlated with the relative angular momentum of the model's atmosphere.

The characteristics of the second mode, represented by the zonally averaged zonal wind, temperature and vertical velocity, are depicted in Figure 13. The main action is in the southern hemisphere in the form of a large vertical cell (satisfying the thermal-wind relationship). This mode has some connection with the ocean, but a statistical analysis reveals that the mode appears only in the upper part of the ocean and the atmospheric anomalies are not generated by the underlying ocean. The mode coefficient has a red spectrum and is highly correlated with the so-called Ω-component of atmospheric angular momentum (representing the change in angular momentum caused by a redistribution of the mass of the atmosphere).

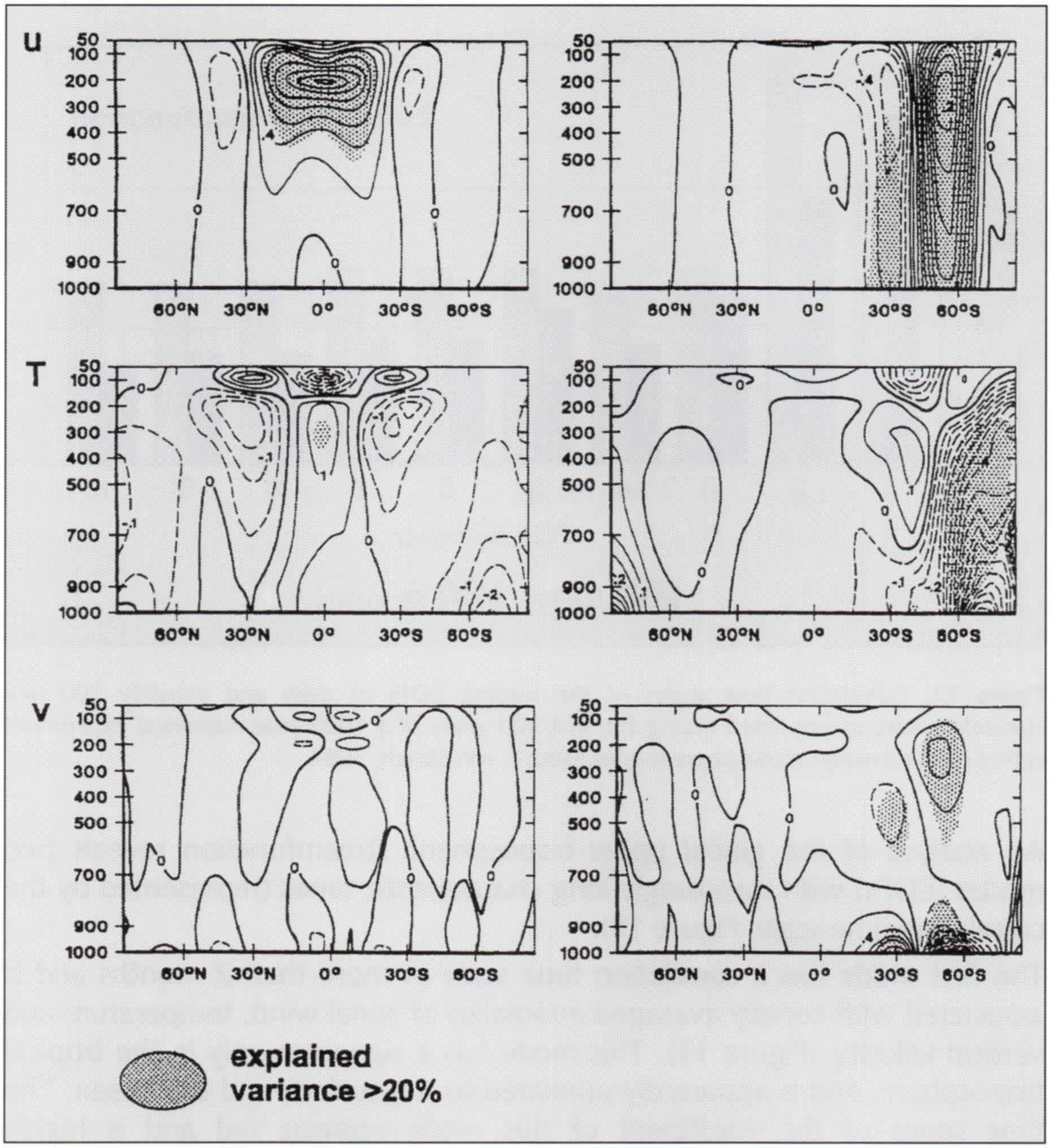


Figure 13. Characteristic patterns of the dominant two modes in the LSG/ECHAM1 T21 coupled run for zonally averaged zonal wind, temperature and vertical velocity. From J. von Storch, 1994.

3. Climate change - model results

We have seen in the preceding Section 2.4 that coupled ocean-atmosphere models are capable of simulating internal climate variability. Although the simulated variability is qualitatively consistent with the observed variability, it remains to be further investigated whether the model internal climate variability is truely realistic in terms of intensity and the spectral and spatial distributions.

Global climate models can also be used to simulate the impact of enhanced concentrations of greenhouse gases in the troposphere on the overall climate (Cubasch et al., 1992). Again, whether the numerical result is realistic in terms of intensity and pattern is not known a-priori. The reliability of the models can be tested only against the present day climate.

In their "Early Industrial" (EIN) experiment Cubasch et al. (1995) integrated the coupled model already discussed in Section 2.4 over 150 years. The model was forced with gradually increasing greenhouse gas concentrations (Figure 14). For the first 50 years the forcing was prescribed as observed from 1935 until 1985. For the remaining 100 years the IPCC-scenario A ("business as usual"; Houghton et al., 1990) was used. Note that a simu-

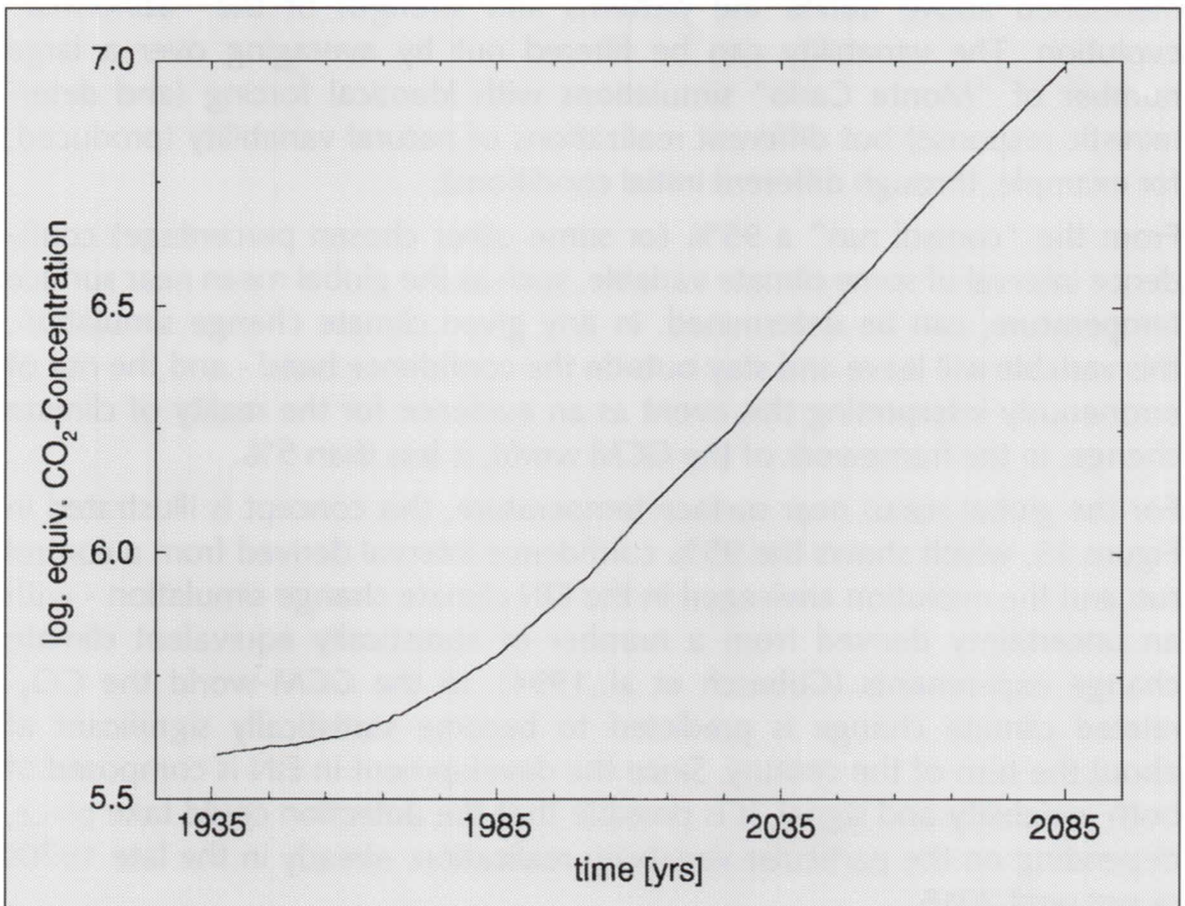


Figure 14. Prescribed atmospheric concentration of CO_2 in Cubasch et al.'s (1995) "Early Industrial" scenario experiment (EIN) with a coupled ocean-atmosphere model. The concentrations are specified in the first 50 years (1935-1985) as observed, and in the remaining 100 years (1986 - 2085) as envisaged by the IPCC in its "scenario A".

lated year, such as 1949, has no relationship to the real year 1949 and its weather apart from the CO_2-concentration in that year. The model result is a mixture of natural climate variability and climate change. While we hope that the computed "deterministic" climate change component is realistic, there is no reason to expect that the model generated "stochastic" climate variability in the model year 1949 has any relation to the particular realization of "stochastic" variability of the real world in the year 1949. This caveat is important to keep in mind when discussing results obtained for future "years" such as 2035.

The discrimination between climate variability and climate change is straightforward in case of the GCM world, since we can perform separate numerical experiments to create data sets representative of either. "Control runs", such as the extended "1000-year run" discussed in Section 2.4., define a range of "normality" for a regime entirely controlled by internal climate variability. Climate change experiments such as the EIN simulation mentioned above define the patterns and strength of the "abnormal" evolution. The variability can be filtered out by averaging over a large number of "Monte Carlo" simulations with identical forcing (and deterministic response) but different realizations of natural variability (produced, for example, through different initial conditions).

From the "control run" a 95% (or some other chosen percentage) confidence interval of some climate variable, such as the global mean near surface temperature, can be determined. In any given climate change simulation, this variable will leave and stay outside the confidence band - and the risk of erroneously interpreting this event as an evidence for the reality of climate change, in the framework of the GCM world, is less than 5%.

For the global mean near surface temperature, this concept is illustrated in Figure 15, which shows the 95% confidence interval derived from a control run and the evolution envisaged in the EIN climate change simulation - with an uncertainty derived from a number of statistically equivalent climate change experiments (Cubasch et al.,1994). In the GCM-world the CO_2-related climate change is predicted to become statistically significant at about the turn of the century. Since the development in EIN is composed of both variability and signal, it is possible that the detection could take place, depending on the particular variability realization, already in the late 1970s or not until 2015.

Thus, in the context of a climate model, the discrimination between climate variability and climate change is relatively simple. We will see below in Section 4 that the discrimination in the observational record is much less straightforward.

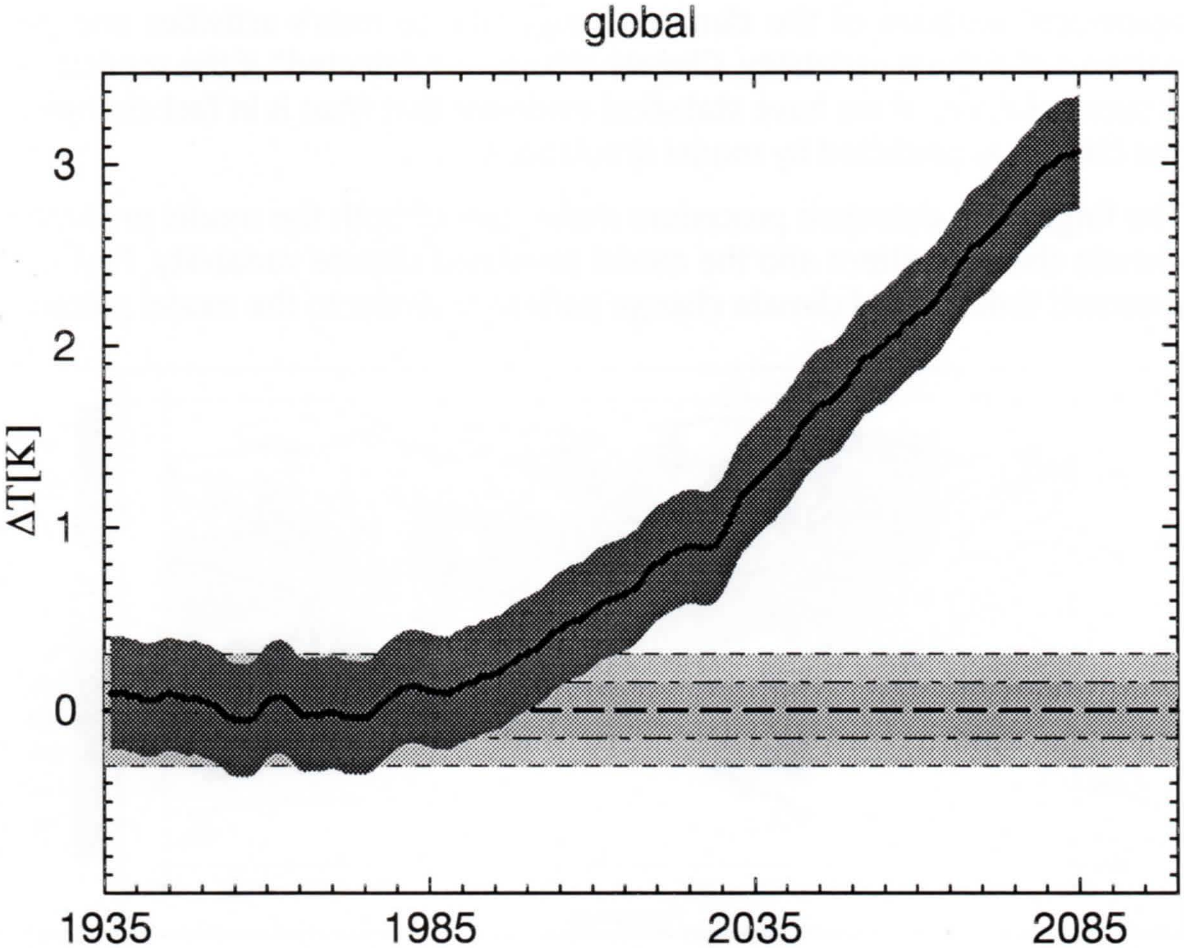


Figure 15. 95% confidence band representing natural climate variability in the GCM world (horizontal lines) and envisaged climate change (including variability-related uncertainty) in the "Early Industrial" (EIN) run simulating continously increasing CO_2 loadings in the atmosphere. From Cubasch et al., 1995.

4. Detection of climate change in the observational record

In case of the real world we do not have two separate data sets representative of climate variability and climate change. We have only one observational record, and this is furthermore essentially limited to the past 100 or 150 years. The variations in this data set are in part due to natural processes and in part due to man's activities, such as the emission of greenhouse gases and aerosols.

Therefore, a separation of signal (change) and noise (variability) cannot be carried out in the simple manner illustrated in Figure 15. Instead, a more involved algorithm is required (Hasselmann, 1993). This is based on a "fingerprint" method, which exploits the differences between the (expected) patterns of the climate change due to man's activities and the patterns of natural variability. Climate change is "detected" if the separation is successful, i.e., if we have statistical evidence that Man is in fact changing the climate as predicted by model simulations.

The fingerprint detection procedure makes use of both the model predicted climate change pattern and the model simulated climate variability. First it is assumed that the real climate change pattern is similar to the model pattern.

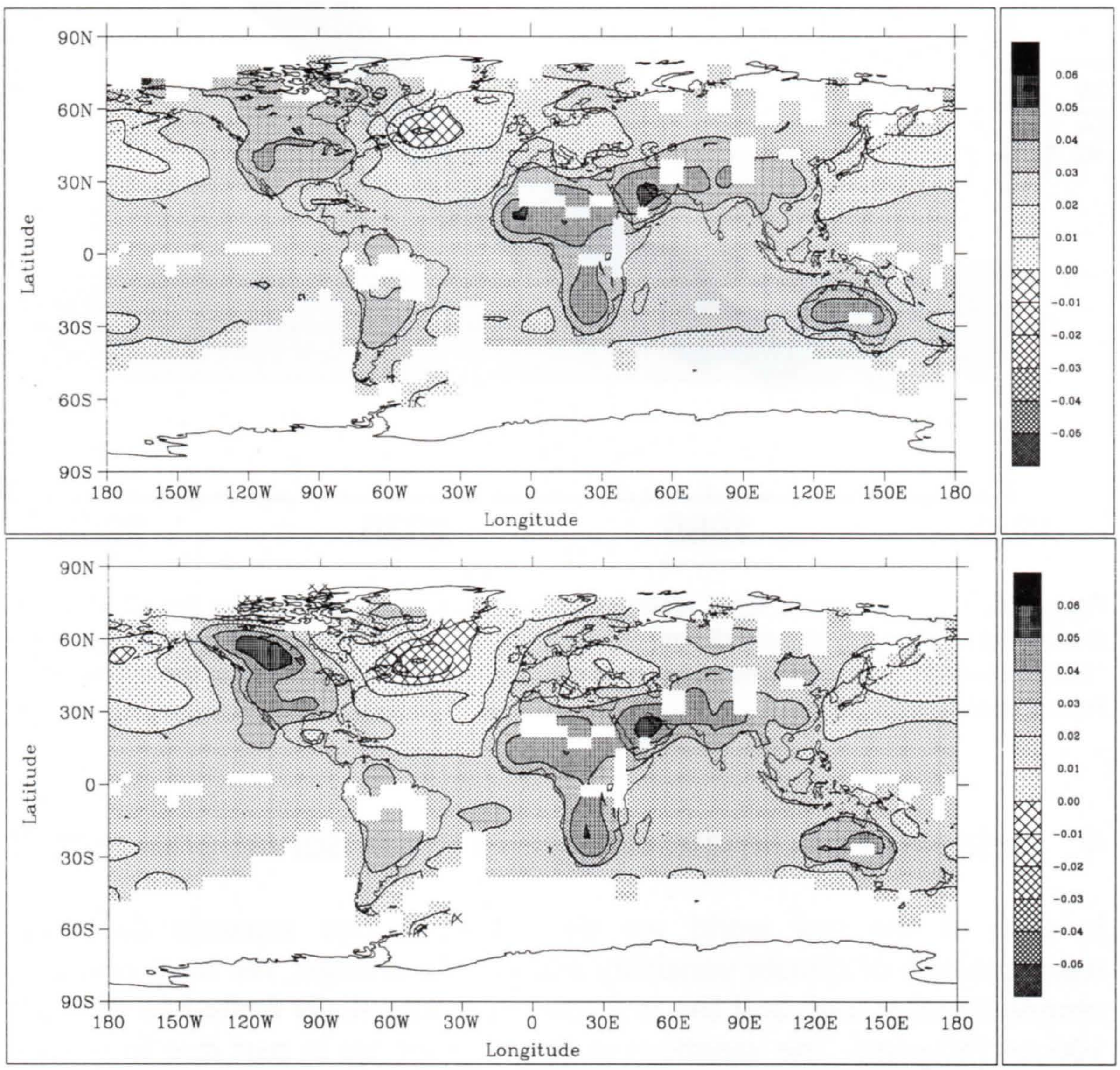


Figure 16. GCM-generated patterns for detecting climate change in the observational record of near-surface temperature. The white areas have been removed from the analysis because of insufficient observational density. The 20-year trends of observed near-surface temperature are multiplied with these patterns; the resulting coefficient is named the "detection variable" (see Figure 17). Top: Unmodified guess pattern derived from the EIN experiment.
Bottom: Optimized fingerprint designed to maximise the signal-to-noise ratio of the detection variable. From Hegerl et al., 1995.

Therefore the observed data, which in all practical cases do not cover the whole earth but a well monitored sub-area, is projected on the GCM generated climate change pattern (the "guess pattern"). The pattern of near-surface temperature change simulated in the EIN experiment discussed above, limited to the area of adequate observational density, is shown in Figure 16 (top).

Use is then made of the model simulated natural climate variability to modify the "guess pattern" to a "fingerprint pattern" such that the projection of the observational data onto the modified pattern maximizes the signal-to-noise ratio. In the "fingerprint pattern" the signal pattern is enhanced in regions of low natural variability and reduced where the natural noise level is high. Applying the variability from the first 385 years of the 1000 year experiment leads to the fingerprint pattern shown in Figure 16 (bottom). The modified pattern is generally similar to the original guess pattern, with positive values almost everywhere, but major changes are seen in the North Atlantic and northern North America, where negative values prevail in the optimized fingerprint pattern.

In the Hegerl et al. (1995)-study the "detection variable", obtained by multiplying the observed 20-year temperature trends by the fingerprint, is compared with the expected variability of this variable in the absence of an anthropogenic change. The variability is derived either from the observational record itself after applying an appropriate filter to remove the estimated climate-change signal, or by using the output of a control run. (To avoid mixing the information used in the assessment of the detection variable with the design of the detection strategy the control run was made in this case with another coupled ocean-atmosphere GCM, rather than using the 1000 year control run mentioned above. For details see Hegerl et al. (1995).)

The detection variables derived from the unmodified guess pattern and from the optimized fingerprint are shown in Figure 17. The 95% confidence intervals inferred from the observations and from the two control runs are indicated by the horizontal lines. For comparison, the result for the same exercise applied to the GCM climate-change experiment is also shown as a dotted line.

The detection variable derived with the unmodified guess pattern (which is rather similar to a plain spatial mean of near surface temperature) approaches the highest of the three 95% confidence limits, so that the null hypothesis "all variations are due to natural variability" can be rejected with a risk of 2.5% if the largest (most conservative) estimate of natural variability

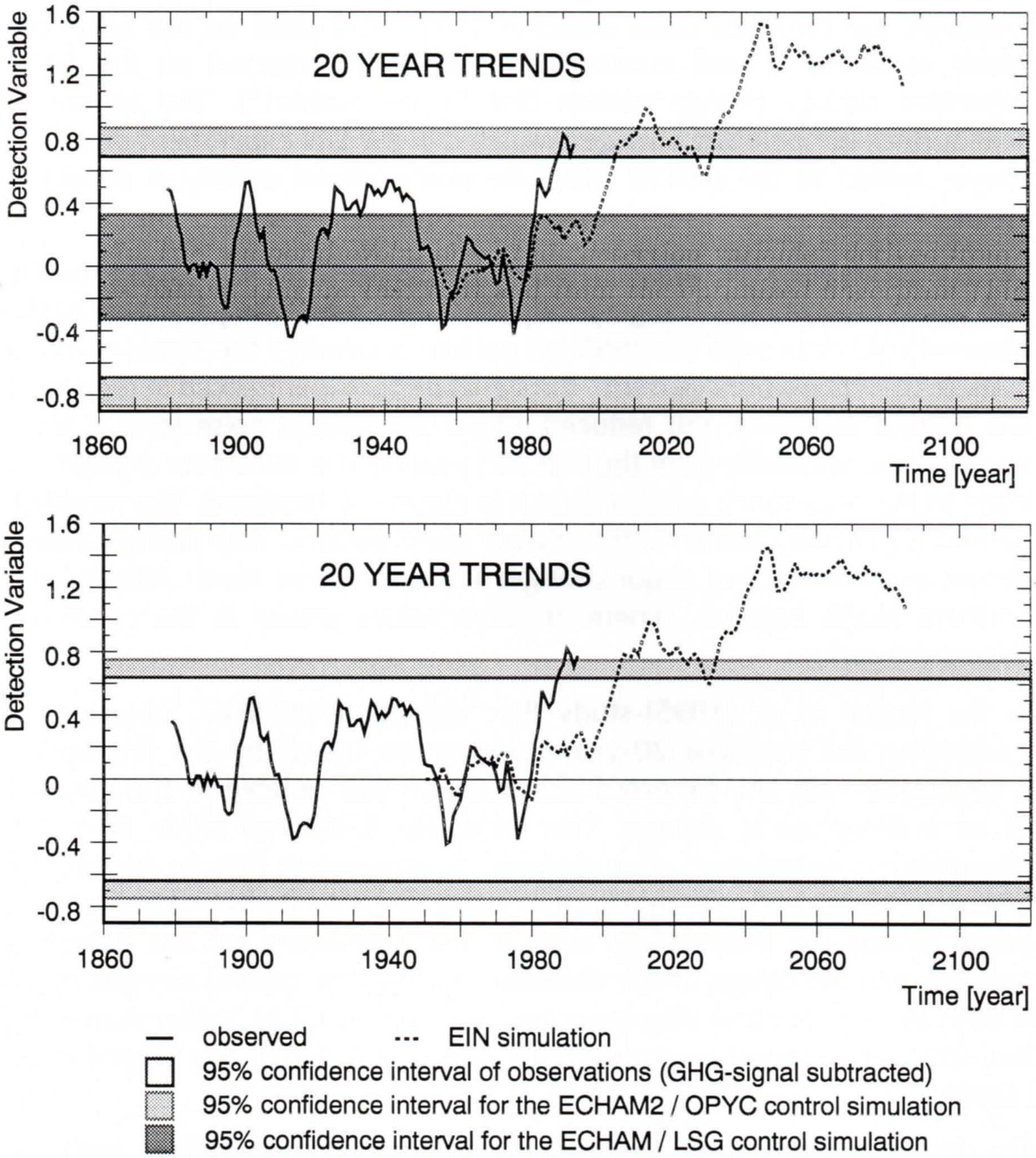


Figure 17. The temporal evolution of the "detection variable" derived from the original guess pattern (Figure 16a; top) and from the optimized fingerprint (Figure 16, bottom). The solid line is the detection variable of the 20-year trend of near surface temperature derived from the observational record, the dotted line representing the evolution in the EIN greenhouse warming simulation for comparison. The stippled bands are 95% confidence intervals derived from observations (after removing of the estimated signal) and from a control run. The probability of the detection variable surpassing the positive 95% confidence level is 2.5% if all variability is of natural origin. In the lower panel the ECHAM/LSG ocean-atmosphere model is used for the optimization and has therefore not been used to estimate the level of natural variability, which was inferred from another ocean-atmosphere model and from the observational record. From Hegerl et al., 1995.

is used. The optimized fingerprint returns markedly higher significance levels - the latest trends contradict the null hypothesis with a risk of less than 2.5%.

From this finding we conclude that the most recent warming can no longer be understood as a manifestation of the natural variability but must be taken as statistical evidence that anthropogenic climate change is really taking place. However, we make the following important caveat: this statement depends crucially on our assessment of the natural variability. If this variability is strongly underestimated our conclusion is not correct.

The detection variables derived from the modelled temperature trends are consistent with the detection variable derived from observational data, although detection takes place somewhat later in the model. During the first decades the detection variable stays within the 95% confidence interval. After a first episode above the critical threshold the curves return to within the 95% confidence interval, later leaving the interval again to increase further with increasing CO_2 concentration. The precursor "detection episode" illustrates well the transition from less certain to more certain detection in a record containing both signal (climate change) and noise (variability). We appear to be in this transition regime today.

5. The challenges of the 1990s

In the 1980s the main challenge of climate research was to build realistic dynamical models of various climate sub-systems, particularly the ocean, the atmosphere and the coupled atmosphere-ocean system. The models have now reached a reasonable level of maturity, even though several aspects, such as the modelling of sea ice or the incorporation of biological and chemical processes, need to be improved. At several laboratories suites of so-called community climate models are now offered to scientific researchers, who apply these models as tools to carry out various kinds of numerical experiments.

These advances in modelling have set the stage for new challenges:

- The availability of well-tested models, together with enhanced computing power has enabled the initiation of scientific programs aiming at understanding, and possibly forecasting, the dynamics of climate variability on time scales of not only months and years, but also decades and centuries (cf. Latif and Barnett, 1994). Examples of such low-frequency climate anomalies are the medieval warm period, the little ice-age (e.g., Bradley and Jones, 1993) or the Maunder Minimum (e.g., Wanner et al., 1994). This is the main thrust of the major new Climate Variability and Prediction Program (CLIVAR, 1992) of the World Climate Research Program (WCRP) .

Long simulations such as the 1000-year control run with a coupled ocean-atmosphere model mentioned above (J. von Storch, 1994) create a wealth of physically consistent data. The degree of realism of such data must be established by comparison not only with instrumental data but also with proxy data such as ice cores and tree rings. The availability of such long data sets enables the investigation of a number of problems which have so far appeared intractable. This includes the question whether and how often the climate system visits the region of the phase space in which the multiple equilibria of the North Atlantic circulation discussed in Section 2.1 are located, the dynamics of such spectacular events as the Great Salinity Anomaly (Dickson et al., 1988), or the reality of the quasi-oscillatory variability on the decadal scale, whose existence was postulated in the last century (Brückner, 1890) and which has received renewed attention through recent tree ring data (Stocker, 1994).

- The interaction of the general circulation of the atmosphere and the ocean with the biogeochemical cycles is a highly complex problem which is fundamental for our understanding of the distribution of ozone, aerosols and and many other problems involving the interrelation of climate and global change. To address these problems, a new suite of sophisticated three-dimensional dynamical chemistry models is needed.

- GCMs are not designed to simulate the small regional and local scales, which are of particular relevance for impact studies, but rather to reproduce the large-scale aspects of climate. With the growing interest in climate impact, climate modellers have been confronted with the challenge of reliably simulating or specifying small scale features such as regional rainfall (Robinson and Finkelstein, 1991; von Storch, 1995), or the frequency of extreme events or the statistics of local coastal sea level. The present global climate models provide useful information on large spatial scales, but because of the truncation of the non-linear energy cascade and lack of regional details, such as coastlines, lakes and mountains, the smaller scales which are particularly relevant for impact assessments, even when formally resolved, are unreliable. "Downscaling procedures" are therefore required (Hewittson and Crane, 1992; von Storch et al., 1993) which relate the reliable part of the climate model output on large scales by statistical or dynamical models to the relevant smaller scale impact variables (for instance rainfall characteristics, flowering dates of snow-drops, frequency of river flooding, or the succession in the eco-system of a lake).

- More generally still, the understanding and modelling of the interaction of physical change with non-physical systems such as the biosphere, the economy or social institutions such as international law is attracting increasing attention.

  How do ecosystems respond to climate variability and change in terms of distribution, abundance but also in terms of composition and succession (e.g., Lubchenco et al., 1993)? How can optimal economic strategies be defined to respond to a changing climate caused by man's economic activities (Nordhaus, 1991; Hasselmann, 1990; Tahvonen et al., 1994)? Can international treatises be devised and agreed upon to deal with the basic "problem of the commons" which is the degradation of the environment by a few benefactors of activities which harm all other nations? (cf. Harding, 1968).

  Natural scientists and social scientists have different concepts in mind when they refer to the "climate problem". To what extent is the "climate problem" of natural scientists the driving force for political actions (or non-actions)? Or is this policy driven by the "climate problem" as identified by social scientists, namely the perception of climate by people, the social construct of climate change and the creation of such constructs (Stehr and von Storch, 1995)?

This list of challenges, although far from complete, indicates the many exciting new areas of investigation which the progress of climate research in the last decade has made accessible, paving, in particular, the way for a stronger integration in the future of climate studies with the general problem of global change.

References

Bakan, S., A. Chlond, U. Cubasch, J. Feichter, H. Graf, H. Grassl, K. Hasselmann, I. Kirchner, M. Latif, E. Roeckner, R. Sausen, U.Schlese, D. Schriever, I. Schult, U. Schumann, F. Sielmann and W. Welke, 1991: Climate response to smoke from the burning oil wells in Kuwait. Nature 351, 367-371.

Berger, W.H. and J.S. Killingley, 1982: The Worthington effect and the origin of the Younger Dryas. J. Mar. Res., Suppl., 27-38.

Bradley, R.S. and P.D. Jones, 1993: "Little Ice Age" summer temperature variations: their nature and relevance to recent global warming trends, The Holocene 3, 367-376.

Broecker, W.S., J.P. Kennett, B.P. Flower, J.T. Keller, S. Trumbore, G. Bonani and W. Wolfli, 1989: Routing of meltwater from the Laurentide Ice Sheet during the Younger Dryas cold episode. Nature 341, 318-321.

Brückner, E., 1890: Klimaschwankungen seit 1700 nebst Bemerkungen über die Klimaschwankungen der Diluvialzeit. Geographische Abhandlungen herausgegeben von Prof. Dr. Albrecht Penck in Wien; Wien and Olmütz, E.D. Hölzel, 325 pp.

Claussen, M., 1994: On coupling global biome models with climate models. Climate Research 4, 203-221.

Claussen, M., 1995: Modelling biogeophysical feedback in the Sahel. In preparation.

CLIVAR, 1992: A study of climate variability and predictability. World Climate Research Programme.

Cotton, W.R. and R.A. Pielke, 1992: Human Impacts on Weatherand Climate:. ASTeR Press Ft. Collins (ISBN 0-9625986-1-5), 288pp.

Cubasch, U., K. Hasselmann, H. Höck, E. Maier-Reimer, U. Mikolajewicz, B.D. Santer and R. Sausen, 1992: Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model. Climate Dynamics 8, 55-69.

Cubasch, U., B.D. Santer, A. Hellbach, G. Hegerl, H. Höck, E.Maier-Reimer, U. Mikolajewicz, A. Stössel and R. Voss, 1994: Monte Carlo climate change forecasts with a global coupled ocean-atmosphere model. Clim. Dyn. 10, 1-19.

Cubasch, U., G. Hegerl, A. Hellbach, H. Höck, U. Mikolajewicz, B.D. Santer and R. Voss, 1995: A climate change simulation starting from 1935. Clim. Dyn. 11, 71-84.

Dickson, R.R., J. Meincke, S.-A. Malmberg and A.J. Lee, 1988: The "Great Salinity Anomaly" in the northern North Atlantic 1968-1982. J. Phys. Oceano. 20, 103-151.

Frankignoul, C., 1995: Climate spectra and stochastic climate models. In: H. von Storch and A. Navarra (eds.) Analysis of ClimateVariability: Applications of Statistical Techniques. Springer Verlag, 25-51.

Graf, H.-F., I. Kirchner, A. Robock and I. Schult, 1993: Pinatubo eruption winter climate effects: model versus observation. Clim. Dyn. 9, 81-93.

Graf, H.-F., I. Perlwitz and I. Kirchner, 1994: Northern hemisphere tropospheric mid-latitude circulation after violent volcanic eruptions. Beitr. Phys. Atmos. 67, 3-13.

Harding, G., 1968: The tragedy of the commons. Science 162, 1243-1248.

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.

Hasselmann, K., 1993: Optimal fingerprints for the detection of time dependent climate change. J. Climate 6, 1957 - 1971.

Hegerl, G.C., H. von Storch, K. Hasselmann, B.D. Santer, U. Cubasch and P.D. Jones, 1995: Detecting anthropogenic climate change with an optimal fingerprint method. J. Climate (submitted); preprint: MPI Report 142.

Hewitson, B.C. and R.G. Crane, 1992: Regional-scale climate prediction from the GISS GCM. Paleogeography, Paleoclimatology, Paleoecology 97, 249-267.

Houghton, J.L., G.J. Jenkins and J.J. Ephraums (eds.), 1990: Climate Change. The IPCC scientific assesment. Cambridge University Press, 365 pp.

James, P.M., K. Fraedrich and I.A. James, 1994: Wave-zonal-flow interaction and ultra-low-frequency variability in a simplified global circulation model. Quart. J. Roy. Met. Soc. 120, 1045-1067.

Lacey, C. and D. Longman, 1993: The press and public access to the environment and development debate. Sociological Review 41, 207-243.

Latif, M. and T.P. Barnett, 1994: Causes of decadal variability over the North Pacific and North America. Science 266, 634-637.

Lubchenco, J., S.A. Navarette, B.N. Tissot and J.C. Castilla, 1993: Possible ecological responses to global climate change: Nearshore benthic biota of northeastern Pacific coastal ecosystems. In: H.A.Mooney, E.R. Fuentes and B.I. Kronberg "Earth System Reponses to Global Change". Academic Press, 147-166 .

Maier-Reimer, E. and U. Mikolajewicz, 1989: Experiments with an OGCM on the cause of the Younger Dryas. In: A. Ayala-Castañares, W.Wooster and A. Yañes-Arancibia (eds.) Oceanography 1988. UNAM Press México DF, 87-100.

Maier-Reimer, E., U. Mikolajewicz and K. Hasselmann, 1993: Mean circulation of the Hamburg LSG OGCM and its sensitivity to the thermohaline surface forcing. J. Phys. Oceano. 23, 731-757.

Mikolajewicz, U. and E. Maier-Reimer, 1990: Internal secular variability in an OGCM. Climate Dyn. 4, 145-156.

Mikolajewicz, U. and E. Maier-Reimer, 1994: 'Mixed Boundary Conditions' in OGCMs and their influence on the stability of the model's Conveyor Belt. J. Geophys. Res. 99, C11, 22633-22644.

Nordhaus, W.D., 1991: To slow or not to slow: the economy of the greenhouse effect. Econ. J. 101, 920-937.

Prentice, I,C., W. Cramer, S.P. Harrison, R. Leemans, R.A. Monserud and A.M. Solomon, 1992: A global biome model based on plant physiology and dominance, soil properties and climate. J. Biogeography 19, 117-134.

Rahmstorf, S. and J. Willebrand, 1995: The role of temperature feedback in stabilising the thermohaline circulation. J. Phys. Oceano. 25, 787-805.

Rahmstorf, S., 1994: Rapid climate transitions in a coupled ocean-atmosphere model. Nature 372, 82-85.

Rahmstorf, S., 1995: Multiple convection patterns and thermohaline flow in an idealised OGCM, submitted to J. Clim.

Robinson, P.J. and P.L. Finkelstein, 1991: The development of impact-oriented scenarios. Bull. Amer. Met. Soc. 4, 481-490.

Roeckner, E., K. Arpe, L. Bengtsson, S. Brinkop, L. Dümenil, M. Esch, E. Kirk, F. Lunkeit, M. Ponater, B. Rockel, R. Sausen, U. Schlese, S. Schubert and M. Windelband, 1992: Simulation of the present-day climate with the ECHAM model: Impact of model physics and resolution. Max-Planck-Institut für Meteorologie, Report 93.

Stehr, N. and H. von Storch, 1995: The social construct of climate and climate change. Climate Res. 5 (in press).

Stocker, T.F., 1994: The variable ocean. Nature 367, 221-222.

Tahvonen O., H. von Storch and J. von Storch, 1994: Ecomonic efficiency of CO_2 reduction programs, Climate Research 4, 127-141.

Ungar, S., 1992: The rise and relative fall of global warming as a social problem. Sociological Quarterly 33, 483-501.

von Storch, H., 1995: Inconsistencies at the interface of climate impact studies and global climate research. Z. Meteor. 4, NF, 82-85.

von Storch, H., E. Zorita and U. Cubasch, 1993: Downscaling of climate change estimates to regional scales: application to winter rainfall in the Iberian Peninsula. J. Climate 6, 1161 - 1171.

von Storch, H. and F.W. Zwiers, 1996: Statistical Analysis in Climate Research. Cambridge University Press (in preparation).

von Storch, J., 1994: Interdecadal variability in a global coupled model, Tellus 46A, 419-432.

Wanner, H., R. Brádzil, P. Frich, K. Frydendahl, T. Jónsson, J.Kington, C. Pfister, S. Rosenørn, and E. Wisman, 1994: Synoptic interpretation of monthly weather maps for the late Maunder Minimum (1675-1704). In: B. Frenzel (ed.) Climatic trends and anomalies in Europe 1675-1715. Palaeoklimaforschung 13, 401-424 (ISBN 3-437-30774-6).

Weisse, R., U. Mikolajewicz and E. Maier-Reimer, 1994: Decadal variability of the North Atlantic in an Ocean General Circulation Model. J. Geophys. Res. 99, C6, 12411-12421.