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Applying Coupled Ocean-Atmosphere Models for Predicting, Detecting and Specifying Climate Change

Detailed climate models which feature realistic atmosphere and ocean models are applied for several purposes: Firstly, they are an invaluable tool for understanding the dynamics of the earth's climate system. Secondly, to some extent they allow for the description of climate on large spatial scales, and the possibility to envisage the climate change caused by anthropogenic emissions of CO_2 and sulfur. These model simulations are an essential tool for detecting climate change in observations. It is shown that the observed climate change coincides with model scenarios and disagrees (with a certain statistical risk) with the notion of natural climate variability unrelated to anthropogenic forcing. However, for applying model scenarios to estimate the damages associated with climate change, regional specifications are needed. Such information is not directly available from the climate model output but may be obtained by various "downscaling" techniques.

1. Introduction

Global Coupled Ocean Atmosphere General Circulation Models (COAGCMs) generally consist of circulation models for the atmosphere and the ocean, plus a sea-ice component. Typically each model is based on conservation equations which are solved numerically, using a representation of the earth by a limited discretization (either in terms of spherical harmonics or a finite number of grid points).

Results of COAGCMs predict a change in the mean state of climate due to the anthropogenic increase of atmospheric greenhouse gas concentrations (in particular in CO_2 levels caused by the burning of fossil fuels) and tropospheric aerosols (via the emissions of sulfate). This raises two questions to be addressed in this paper. The first question

Is a large-scale model-predicted climate change signal present in recent observations?

is fundamental as it clarifies whether we are dealing with a real and significant effect. The second question

What are the regional scale characteristics of the model-derived anthropogenic climate change?

is the essential prerequisite for dealing with the socio-economic and ecologic consequences of climate change whose reality has to be verified, or falsified, by the answer to the first question.

In the following two sections we deal with these two questions. First we demonstrate a successful strategy to confirm the hypothesis of ongoing anthropogenic climate change - and emphasize some important caveats of this finding. Subsequently we review different "downscaling" techniques for specifying regional details of climate change.

2. Detecting anthropogenic climate change with optimal fingerprints

The question of whether the model predicted climate change due to human activity can in fact be observed, can be further divided into two subquestions:

- Do the observations contain a significant climate change?
- If there is a climate change, can it be attributed to anthropogenic forcing (such as emission of greenhouse gases or aerosols into the atmosphere)?

The first question can be answered by performing a statistical test with the null hypothesis that the observed warming is part of climate's natural variability. The model derived pattern of climate change (the "fingerprint") can be used as a statistical tool to condense the space-time dependent observations into a one-dimensional "detection variable" (Hasselmann, 1979; Barnett et al., 1991), by projecting the observations on the fingerprint. The statistic of the detection variable is estimated by calculating the detection variable with natural variability patterns, obtained from observations (possibly after subtracting the effects of external forcing) and long "control" integrations with

COAGCMs without external forcing.

The detection strategy builds upon the statistical model that the observed climate state is composed of a, possibly zero, signal of climate change and linearly superimposed climate noise. The idea of an optimized detection method is to modify the fingerprint such that climate noise is suppressed by weighting the model-derived pattern towards low-noise directions (Hasselmann, 1979, 1993). The signal-to-noise ratio is optimal if the fingerprint vector is chosen as the model-predicted fingerprint multiplied with the inverse of the noise covariance matrix. This optimal fingerprint method relates to optimal weighting or the use of an optimal filter proposed by other authors (Hegerl and North, 1995). It also provides a best guess for the amplitude of the climate change signal.

We have implemented Hasselmann's optimal fingerprint method for the spatial pattern of 20- and 30- year trends of near surface temperature (for details see Hegerl et al., 1995). The observations are based on instrumental data of near surface temperature from 1854 to 1994 (Jones and Briffa, 1992). The data are gridded by a $5^o \times 5^o$ longitude $\times$ latitude grid with increasing coverage over time. We rely upon the area covered regularly since 1949 (about 75% of the globe). The fingerprint is obtained from a "transient" model simulation forced with observed greenhouse gas forcing from 1935 to 1985 and a scenario of the development of anthropogenic forcing thereafter (Cubasch et al., 1994). The noise estimate used for the optimization (i.e. for computing the noise covariance matrix of 20- and 30-year trends) is derived from a 1000 year integration with the same COAGCM. Fig. 1 shows the evolution of the detection variable for running 20- and 30-year trend patterns from the observations. The same exercise has been done for the transient model simulation, allowing a comparison of the evolution of the climate response to greenhouse gas forcing between observations and climate models.

We formulate the null hypothesis that the latest observed trend pattern originates from natural climate variability. The information on the statistics of the detection variable for 20- and 30-year trend patterns is derived from the control runs of two other coupled COAGCMs. Note that the model control simulations represent purely internal variability of the coupled climate system, disregarding naturally occurring forcing mechanisms such as volcanism or solar output variability. Additionally, the observations are used as another independent realization of climate noise, after subtracting a purely model-dependent estimate of the greenhouse warming signal.

The results indicate that the recent temperature trends deviate from the model internal variability and also from observed variability with a risk of less than 2.5%; i.e. they represent a significant climate change. Similar results are obtained using a recent model simulation forced with observed greenhouse gas and aerosol forcings from 1880 to 1985 and a scenario of the development of anthropogenic forcing thereafter (Hasselmann et al., 1995). In that case the evolution of global mean near surface temperature and that of the detection variable agrees better with the observations than with a simulation forced with greenhouse gases only. Projecting the observations and model data synchronously onto a purely greenhouse gas induced model signal, and onto the combined signal including the response to the aerosol forcing, shows that at present and with the present approach, both signals cannot be separated due to climate noise.

Thus, the observed climate change cannot be attributed uniquely to either the greenhouse gas forcing alone or a mixed forcing scenario. Additionally, other possible reasons of the climate change, e. g. natural and anthropogenic forcing mechanisms, which are not contained in the variability data, need to be systematically excluded. Further information is expected from a seasonal analysis of the data and a better representation of the time-evolution of the climate change signal.

This result holds under the significant caveat that the "natural" variability of climate is represented correctly by the model and observation data. However, the estimate of natural variability differs between the different models and more so with the observations (see fig.1). Even though paleoclimatic data seem to suggest that the observed record of temperature represents rather strong variability, thus providing a conservative estimate, paleodata are not without problems. Therefore, when we want to assess whether the recent developments are "normal" or are reason for concern about the changes of the atmospheric composition, then we must assume (we can not "know") that the instrumental record is good enough for estimating the basic statistics of climate variability, and that climate model and proxy data are good enough to further specify these statistics. All statements about the normality or non-normality of recent developments are then conditional upon this assumption.

3. Inferring regional-scale information from climate models

The basic paradigm of all downscaling procedures is the understanding

- that climate models fail to reproduce the regional details of the state of the atmosphere. There are several reasons for this failure. One reason is the truncation, another is the need for "parameterizations" of unresolved processes such as clouds and their interaction with radiation. To "parameterize" such a process means to approximate its average net influence on processes resolved by the grid scale. In all climate change simulations with such dynamical model the tacit, unproven assumption is made that the often empirically or heuristicially formulated parameterizations remain valid under different climatic conditions.

- that these details are of little or no importance for the large-scale state of the atmosphere. Present COAGCMs represent the large scale atmospheric and oceanic state well (Grotch et al., 1991; von Storch, 1995). However, features resolved by a few mesh sizes, i.e. scales of several hundreds or even thousands of kilometers, are in general not considered reliable and robust.
- that the regional facets of the atmospheric state are the result of an interplay between the large-scale state and the regional details such as topography, land-sea distribution, vegetation and the like.

Thus, the standard coarse-grid GCMs provide information on the large-scale which may be postprocessed together with the regional information to specify the regional details of the present climate and its sensitivity to changes in atmospheric composition or other "external" anomalies. This postprocessing can be done in different ways:

- In *time slice experiments*, as done by Bengtsson (1995a,b) or Cubasch et al. (1995). The distributions of sea-ice and of the sea-surface temperature are used as lower boundary conditions for a simulation with high resolution models of the atmosphere. With such models detailed structures such as hurricanes can be simulated. The postprocessing of the climate change scenario revealed that neither the frequency nor the intensity of hurricanes will increase when CO_2 concentrations double (Bengtsson et al., 1995b).
- Regional "nested" models (Giorgi, 1990; Mearns et al., 1995) are limited in their spatial domain and are forced with prescribed sea-surface temperatures as well as lateral time-dependent atmospheric boundary conditions. Typical spatial domains are of the size of North America.
- Computationally simple approaches exploit empirically derived relationships between fields representative for the large scale state, such as air-pressure, and local time series like precipitation. Such statistical approaches can be designed in many different ways, and have been applied for various aspects (see, for example, von Storch et al., 1993; Zorita et al., 1995, Gyalistras et al., 1994). Obviously, statistical approaches are based on the basic premise that the empirical determined link between the scales will remain unchanged under climate change conditions.

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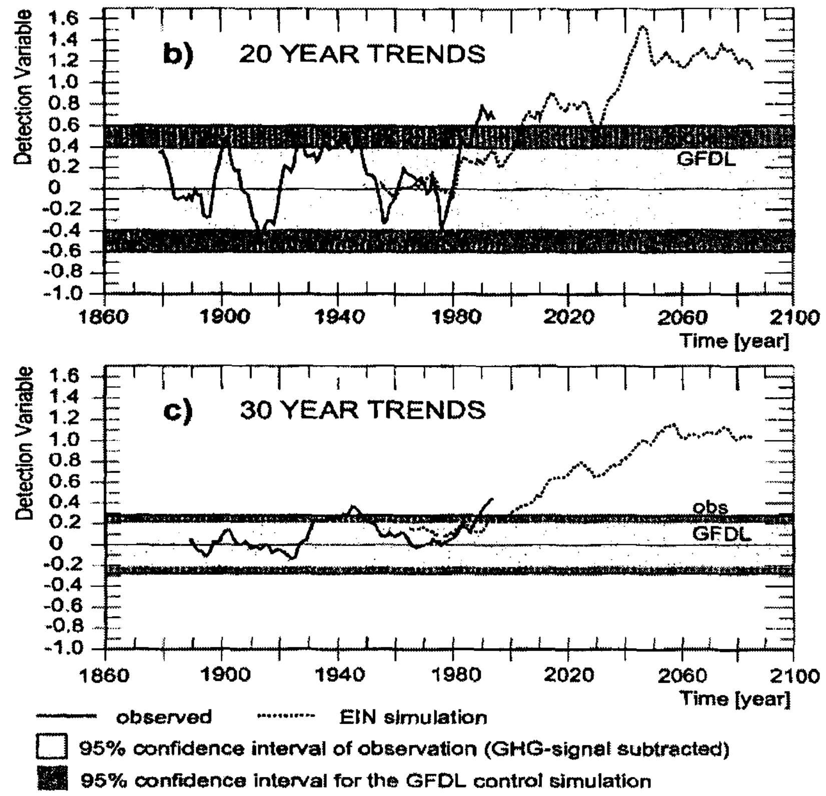

Figure 1: Evolution of the detection variable for 20- and 30-year trends

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