Simulating the Climate of the Last Millennium

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Introduction

Climatic changes during the last thousand years have received great interest. Uncertainty in climate reconstruction is smaller than in earlier periods and the external forcing factors of the climate system are relatively well known, making comparisons with 20th century climate well suited to assess the influence of human activities. Numerical modelling complements the efforts to reconstruct past climates from proxy records. The goals of climate modelling are to reduce uncertainties in future climate change through consistency tests with empirical reconstructions, to provide hypotheses on the climatic evolution at locations or variables not covered by proxy data, and to improve process understanding, including distinguishing between internal variability and the effects of varying external forcings, and understanding feedback mechanisms.

Types of climate models and simulations

The simplest climate models are zero- or one-dimensional energy balance models (EBMs), which have low computational costs and clear links between simulated processes and climate. At the other end of the spectrum are quasi-realistic, computationally expensive, general circulation models (GCMs), which usually feature sub-models for the atmosphere, the ocean and the sea ice on 3-dimensional grids with typical horizontal spacings of a few hundred kilometers and 15-100 vertical levels. GCM components for the carbon cycle, chemical processes, land ice, and vegetation dynamics are currently in development. In between EBMs and GCMs are a variety of models with varying numbers of dimensions and complexity, for instance earth system models of intermediate complexity (EMICs), which describe the atmosphere and ocean dynamics in less detail, but which place more emphasis on the role of vegetation and chemical processes in the climate system.

Climate models are mainly used in two different ways. In equilibrium experiments the forcing factors for the climate system, such as solar irradiance, the atmospheric composition, or the earth's orbit, are held constant, but may vary between different runs. These simulations represent the mean climate and the statistics of internal climate variability. Transient, forced simulations also include the climate response to time-varying forcings using historical estimates. Since the evolution of the climate system is not completely determined by external forcings but also contains a stochastic component even a perfect model, with all forcing mechanisms included, will yield only one out of many possible climate realizations consistent with the forcings. This realization will be different from the realization that took place in the real world. Therefore any comparison between model and reconstruction will be probabilistic in nature.

Results

By the mid 1990s coupled GCM equilibrium experiments for preindustrial conditions were typically around 100 years long, but the first runs with lengths of about 1000 years became available at some modelling centers (GFDL , MPI and UKMO). These simulations were used, for instance, to clarify the roles of the atmosphere and the ocean in generating internal climate variability (Manabe and Stouffer, 1996), or to estimate natural variability, the basis for detection and attribution of climate change (Hegerl et al., 1996). However the agreement among models on the spatial structure and magnitude of natural variability was only moderate, and deviations from observations became evident (Barnett, 1999). A very long simulation of 15000 years of the GFDL model with a relatively low resolution suggested that large-scale, multi-decadal temperature anomalies with very strong amplitudes of about 6-10 standard deviations could be generated merely by internal processes (Hall and Stouffer, 2001). Recently 1000 year long equilibrium runs with higher resolutions (about 300 km) have been conducted at UKMO (Collins et al., 2001) and MPI aiming to test paleoclimatic reconstruction methods on decadal to centennial time scales (Zorita and González-Rouco, 2002; Zorita et al., 2003).

Many transient simulations begin in the middle of the 19th century to investigate the climatic effects of anthropogenic greenhouse gases and aerosols (e.g. Stott et al., 2000). The climatic response to changing solar forcing was investigated with a coupled GCM forced by estimates for solar variability from 1700 to the present (Cubasch et al., 1997). The spatial pattern associated with solar forcing was found to be similar but not identical to the signal of changing greenhouse gas concentrations, the pronounced insolation decrease during the Dalton Minimum (DM) around 1820 caused global cooling. Some of the recent work focuses on the Late Maunder Minimum (LMM). A transient simulation with an EBM, forced by solar and volcanic activity, anthropogenic greenhouse gases and aerosols, produced a global temperature well correlated with proxy reconstructions (Crowley, 2000), in particular a cooling during the LMM was found. A LMM cooling was also found in a 1000 year long run with a two-dimensional zonally averaged atmosphere-ocean model (Bertrand et al., 2002). It should be noted however, that the climate sensitivity to changes in the forcing can be tuned in both models. A 1000 year long run with an EMIC (Bauer et al., 2003) used similar forcings but also information on deforestation. Northern Hemisphere temperatures correlated well with proxy reconstructions. During the LMM and the DM pronounced cooling took place, due to solar and volcanic forcing. During the last half of the 19th century deforestation led to cooling.

Shindell et al. (2001) used equilibrium runs of an atmospheric GCM with detailed ozone chemistry, coupled to a slab ocean model, to model the difference between the LMM and the period around 1780. During the LMM the surface air temperature over the continents was colder and over some oceans areas warmer than hundred years later. The temperature signal could be shown to be related to a change in the AO (Arctic Oscillation)/NAO (North Atlantic Oscillation), which in turn is driven by variations in the meridional temperature gradient. This temperature pattern appears partly consistent with evidence from proxy data, but there remain large areas without adequate proxy data to draw definite conclusions on the agreement between simulation and observations.

The LMM was also included in 500 year long transient runs of fully coupled atmosphere-ocean GCMs conducted by the GKSS Research Centre in collaboration with the MPI (ECHO-G, Fischer-Bruns et al. 2002) and by UKMO (HadCM3). Preliminary results from both models show a clear global-mean cooling during the LMM and the DM (Fig. 1), which is of similar magnitude in both models. The ECHO-G simulation is forced with the major anthropogenic and natural forcings while the HadCM3 was only forced with natural forcings. Both groups are currently carrying out simulations with natural only forcings and both natural and anthropogenic forcings respectively. Note the increasing divergence between the two simulations from the mid 19th century as the simulated effect of anthropogenic forcings becomes more important.

The cooling during the LMM has a spatial structure somewhat different from Shindell et al. (2001). Most noticeable is a strong cooling in the North-West Atlantic (Fig. 2), associated with increasing sea-ice extent in both simulations. Also apparent is a smaller cooling over Europe and other regions. In ECHO-G there is widespread cooling over the entire northern hemisphere with peak cooling to the west of Greenland of −2K. By contrast, HadCM3, while still having a large amount of cooling to the west of Greenland manages to sustain a larger land-sea contrast than that of ECHO-G.

A European Union funded project called SOAP (http:\\www.cru.uea.ac.uk\cru\projects\soap) has started which aims to do this and bring together scientists working with paleo data with those working with models.

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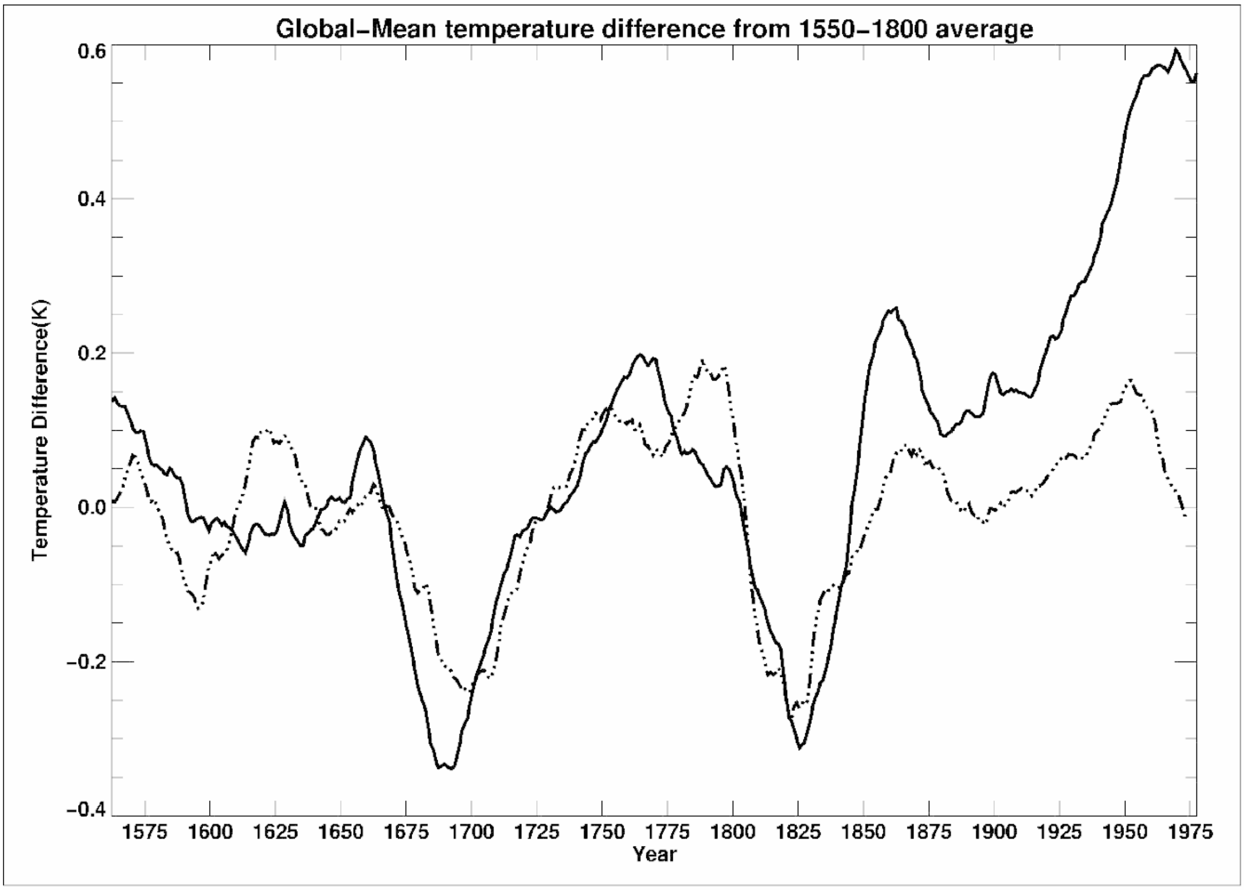

Fig. 1: Time series of global-mean temperature. Shown are time series of global-mean temperature from ECHO-G (solid line) and HadCM3 (dashed line) simulations. Note that ECHO-G was forced with natural and *anthropogenic simulations while HadCM3 was driven only by natural forcings. Both simulations are shown as differences relative to the 1550-1800 average and are a 25-year running average.*

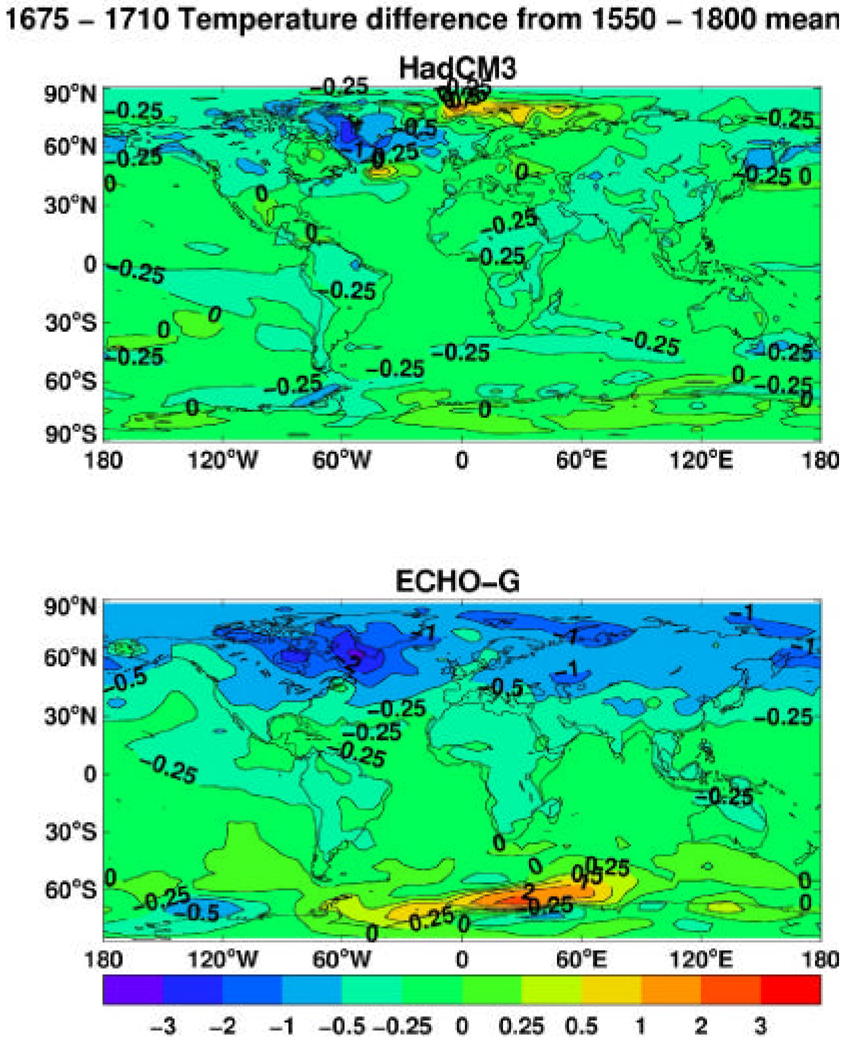

Fig. 2: LMM cooling (1675-1710). Shown are changes in near-surface temperature from HadCM3 (top) and ECHO-G (bottom) for the 1675-1710 period minus the long term average for 1550-1800. Contours are at ±3, 2, 1 , 0.5, 0.25 and 0 K. Global-average values are -0.21 and -0.28K.