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# SIMULATING THE EVOLUTION OF THE ARCTIC CLIMATE DURING THE LAST MILLENNIUM

Hugues Goosse[*]
Institut d'Astronomie et de Géophysique G. Lemaître, Université Catholique de Louvain, Belgium

Hans Renssen
Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, The Netherlands

## Abstract

Ensemble simulations have been performed with a global three-dimensional atmosphere-sea-ice-ocean model driven by both natural (solar and volcanic) and anthropogenic (increase in greenhouse gas concentrations and tropospheric aerosols) forcings during the last millennium. The model consists of ECBILT, a spectral T21, 3-level quasi-geostrophic atmospheric model, coupled to CLIO, a coarse resolution sea-ice ocean general circulation model. The five members of the ensemble display relatively mild temperatures averaged over the Arctic during the first centuries of the simulation, with surface temperature up to 0.6° C warmer than the long-term mean, and then a cooling that starts as early as 1250 AD. This gradually leads to minimum temperatures that occur in the model during the periods 1670-1700 and 1800-1830 AD when surface temperatures are about 0.5°C colder than the mean in the Arctic. After 1830 AD, the Arctic climate warms under the influence of both natural and anthropogenic forcings. If the latter are not included, the model reached a local maximum in the 1950's followed by a slight cooling. When taking into account all forcings, the absolute maximum in all the simulation is reached at the end of the 20th century. The analysis of the simulations allows showing that the response of the high latitudes to the forcing is significantly stronger than at lower latitudes.

## 1. INTRODUCTION.

The reconstructions of surface temperature averaged over the Northern Hemisphere display relatively warm conditions at the beginning of the 2nd millennium AD, sometimes called the 'Medieval Warm Period' (e.g., Mann et al. 1999; Crowley and Lowery 2000; Esper et al. 2002; Briffa and Osborn 2002). Although the amplitude and the timing of the variations can differ strongly between the different reconstructions, they generally agree that those warm conditions end before 1300 AD (Hughes and Diaz 1994; Bradley 2000; Grove 2001). It is followed by a gradual cooling, interrupted by relatively short, warm periods. The cold period, often referred to as 'the Little Ice Age', ends in the 19th century before a very pronounced warming during the 20th century.

The available records in the Arctic display a similar climate evolution (e.g., Jennings and Weiner 1996; Dahl-Jensen et al. 1998). In particular the reconstruction of Overpeck et al. (1997), based on a compilation of various paleoclimate archives covering the last four centuries, indicates that the recent warming observed in the instrumental records over the last 150 years (e.g. Polyakov et al. 2002; Morritz et al. 2002) marks the end of a relatively cold period in the whole Arctic that started before 1600. This picture of a warming during the late 19th century and the 20th century after a cold period is consistent with the reconstruction of the ice conditions in the Nordic Seas (Vinje, 2001), the Barents Sea (Vinje 1999), and around Iceland (e.g. Ogilvie 1992).

Climate model experiments may help improving our understanding of these past climate variations (e.g., Tett et al.. 1999; Crowley 2000; Bertrand et al. 2002). We have therefore performed ensemble simulations with a low resolution three-dimensional atmosphere-ocean model driven by both changes in natural and anthropogenic forcings during the 2nd millennium. In contrast to previous model studies, we are able to analyze the natural climate variability in the Arctic and its relation to different forcings over the last millennium. The general objectives are (1) to compare the model results with available observations to check if the model is able to reproduce reasonably well the evolution of the Arctic climate during the last millennium, (2) to estimate the relative influence of natural and forced variability in the model and to underline the major causes of the Arctic climate changes during the last millennium (3) to analyse the

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[*] *Corresponding author address*: H. Goosse, Institut d'Astronomie et de Géophysique G. Lemaître, Université catholique de Louvain , Chemin du cyclotron, 2, 1348 Louvain-la-Neuve, Belgium, e-mail: hgs@astr.ucl.ac.be.

processes responsible for the evolution of the Arctic climate and in particular to check if the polar amplification of future climate changes suggested by previous model studies is valid for the past evolution of climate. A brief overview of those different points is presented below.

## 2. MODEL DESCRIPTION AND EXPERIMENTAL DESIGN.

The atmospheric component of the coupled model is ECBILT2 (Opsteegh et al. 1998), a global spectral quasi-geostrophic model, truncated at T21 with simple parameterisations for the diabatic heating due to radiative fluxes, the release of latent heat and the exchange of sensible heat with the surface. The model contains a full hydrological cycle that is closed over land by a bucket model for soil moisture. Synoptic variability associated with weather patterns is explicitly computed. ECBILT2 is coupled to the CLIO model (Goosse and Fichefet 1999) that is made up of a primitive equation, free-surface ocean general circulation model coupled to a comprehensive thermodynamic-dynamic sea ice model. The horizontal resolution of CLIO is 3 degrees in latitude and longitude, and there are 20 unevenly spaced vertical levels in the ocean. The coupled model includes realistic topography and bathymetry. There is no local flux correction in ECBILT-CLIO. However, it is necessary to artificially reduce the precipitation by 10% over the Atlantic and by 50% over the Arctic basins (Goosse et al. 2001). The model sensitivity to a $CO_2$ doubling is 1.8°C, which is in the low range of coupled atmosphere-ocean-sea-ice models. The coupled model has been used previously to study the evolution of the climate during the Holocene (Renssen et al. 2001, 2002), natural variability of the present-day high-latitude climate (Goosse et al. 2001, 2002, 2003) and the future evolution of the climate (Goosse and Renssen 2001, Schaeffer et al. 2002), using exactly the same parameters and configuration as in the present study.

A five-member simulation experiment has been performed with ECBILT-CLIO, forced by the main natural (i.e. solar and volcanic) and anthropogenic forcings (increase in greenhouse gases and in sulphate aerosols) over the period 1000-2000 AD. The evolution of solar irradiance follows the reconstruction of Lean et al. (1995) extended back in time by Bard et al. (2000). In contrast with previous studies analysing shorter time periods (Shindell et al. 2001), the model does not include a representation of the effect of changes in solar irradiance on stratospheric ozone concentration. The effect of volcanism is derived from Crowley (2000) and is included through changes in solar irradiance. The influence of sulphate aerosols is taken into account through a modification of surface albedo (Charlson et al. 1991). The five members differ only in their initial conditions that were taken from model states at 250 years interval of a long control simulation and of an experiment driven by natural forcings only. Each member represents an equally probable evolution of the climate system. The scatter between those five simulations gives thus an estimate of the amplitude of the natural variability simulated by the model during the last millennium. To analyze the separate contributions of anthropogenic and natural forcings, we have performed a second five-member experiment that is only driven by solar and volcanic (i.e. natural) forcings.

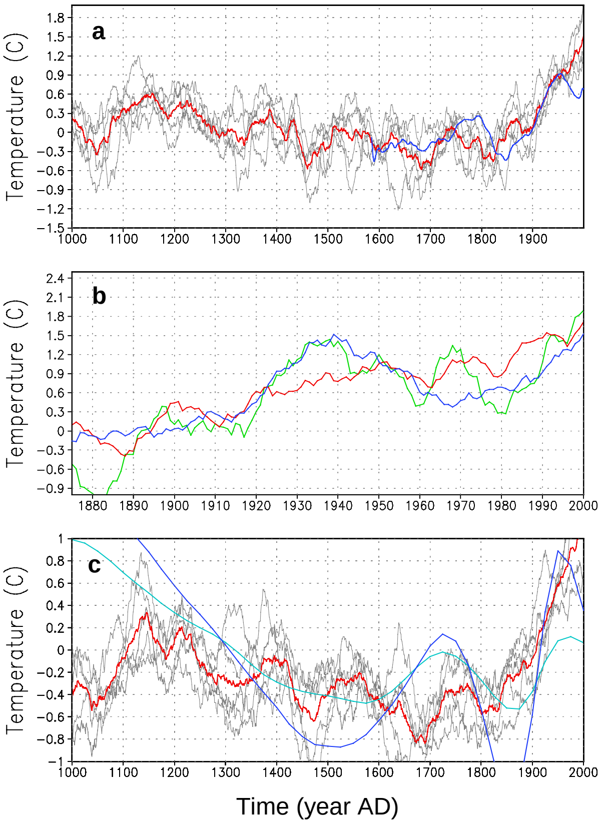

Fig. 1. (a) Anomaly of annual mean surface temperature averaged over the area north of 70°N in an ensemble of 5 simulations (grey) and their mean (red) during the period 1000-2000 AD. The reference period is 1000-1850 AD. The blue curve is the reconstruction of Overpeck et al. (1997). As Overpeck et al. (1997) only provide a relative time evolution, their data have been scaled by multiplying it by the mean standard deviation of the simulations. A 30-year running mean has been applied to all time series. (b) Same as (a) for the period 1850-2000. The red curve is the ensemble mean and the green one a particular simulation. The observed temperature evolution in the Arctic (Polyakov et al. 2002) is in blue. A 10-year running mean has been applied to all time series. (c) Anomaly of annual mean surface temperature averaged over Greenland in the 5 simulations (grey) and their mean (red) as well as the reconstruction of surface temperature based on borehole temperatures measured at GRIP (72.6°N, 37.6 °W, light blue) and Dye 3 (65.2°N,43,8°W) dark blue) on the Greenland ice sheet (Dahl-Jensen et al. 1998). A 50-year running mean has been applied to the time series but the reconstructions have a time resolution probably lower than that, in particular during the first part of the time series.

## 3. RESULTS.

### 3.1 *Response to total forcing*

Averaged over the areas northward of 70°N, the surface temperature simulated in the five members shows relatively warm conditions during the 12th century and early 13th century with a surface temperature about 0.5°C warmer than the mean over the period 1000-1850 (Fig. 1a). After this relatively mild period, the temperature decreases until the beginning of 19th century when the temperature is lower than the mean by 0.3 to 0.9°C in the various simulations. This general cooling is interrupted by warmer periods during the second half of the 14th century, the beginning of the 16th century and the 18th century. This is qualitatively similar to the results simulated in the model at hemispheric-scale and in good agreement with the various reconstructions.

The different simulations exhibit different evolutions illustrating the natural variability of the climate system. The mean over the 5 simulations of the ensemble smoothes out this variability as the warm and cold periods associated with the unforced variability tend to occur at different times in each simulation. The ensemble mean is thus a measure of the forced response of the model. In the Arctic, the standard deviation of the surface temperature of the ensemble mean reached 0.27°C, while the mean standard deviation of the temperature simulated in the five simulations is 0.39°C. The low frequency tendencies are also similar in all the simulations and in the ensemble mean. This shows that, averaged over a large area, the forcing in our model drives a large fraction of the Arctic climate evolution at centennial time-scale.

The instrumental records in the Arctic display a cooling trend during the years 1940-1970 (Fig.1b). In our simulations, the ensemble mean displays a quasi-linear increase of the temperature over the last 150 years with only a slight reduction of the warming trend during the 1950's. Nevertheless, one of the simulations shows a time evolution that is very close to the observations. This shows that the model can not reproduce the observed cooling if the internal variability of the system is not taken into account, as suggested in previous modelling studies (Delworth and Knutson 2000)

Because of their coarse time-resolution, the surface temperatures inferred from borehole temperature measurements are generally not included in large-scale reconstructions. They thus provide an independent test of the model results at low frequency. In Greenland, the temperature simulated by the model show a qualitative agreement with the temperature inferred from measurements at the Grip ice core, except during the 11th century (Fig. 1c). Various hypotheses can explain this disagreement. This can be due to the initial condition used in the simulations as the observed climate state at 1000 AD is not known, to uncertainties in the forcing during the early part of the simulation or to a too low sensitivity of the climate model. The error bars of the reconstruction are also relatively large, reaching more than 0.5 °C in 1000 AD (Dahl-Jensen et al. 1998). Furthermore, the maximum of the reconstructed temperature occurs around 900 AD. The warm condition obtained at 1000 AD, could thus be influenced by the earlier condition because of the low time-resolution of the record.

Compared to the temperature reconstruction at the Dye 3 ice core, the model systematically underestimates the amplitude of the variations. The differences between Dye 3 and Grip reconstructions are not well understood (Dahl-Jensen et al. 1998) but they are probably due to local or regional processes that are not well captured in the model.

The low-frequency temperature evolution of the ensemble mean is similar in the different latitude bands of the Northern Hemisphere (Fig. 2a). Nevertheless, the amplitude is significantly higher in Polar Regions. A similar behavior is noticed for each of the ensemble members, although the natural variability can make the picture more complex during some periods at the decadal to centennial time scale (Fig. 2b). This polar amplification of the temperature variations simulated by ECBILT-CLIO is consistent with instrument records during the last 150 years (Polyakov et al. 2002, Morritz et al. 2002) as well as with the reconstructions over the last 400 years (Mann et al. 2000).

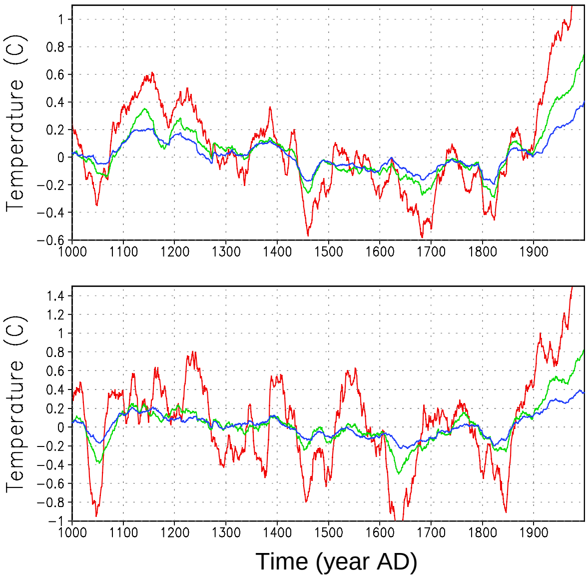

Fig. 2. Time series of the annual mean surface temperature during the period 1000-2000 AD averaged over the area 70°-90° N (red), 50°-70° N (green), 30°-50° N (blue) (a) averaged over the 5 members and (b) in one of the simulation. A 30-year running mean has been applied to all time series.

### 3.2 *Response to natural forcings*

Fig. 3 displays the results of simulations taking in account natural forcings only (i.e. change in solar irradiance and effect of volcanoes). During the 19th century, the surface temperature increases in the Arctic as a result of the increase in solar irradiance and the lower volcanic activity. During this period the influence of anthropogenic forcing is still weak. Besides, the warming during the 20th century can only be simulated if anthropogenic forcings are included, in agreement with previous studies (e.g., Tett et al. 1999, Crowley 2000, Bertrand et al. 2002). In particular, if only the natural forcing are included, the temperature decreases after 1980, mainly because of large volcanic eruptions in 1980 (St Helens, US), 1982 (El Chichon, Mexico) and 1991 (Pinatubo, Philippines).

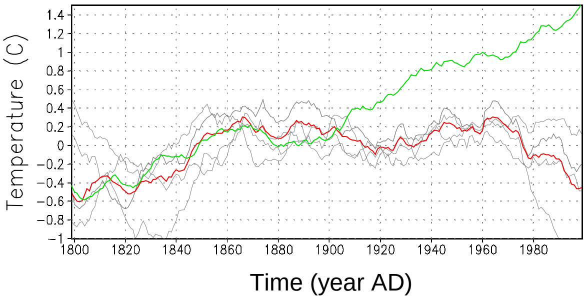

Fig. 3. Anomaly of annual mean surface temperature averaged over the area north of 70°N in an ensemble of 5 simulations (grey) and their mean (red) using natural forcings only. For comparison, the ensemble mean of the simulation including all forcings is also included (green). A 30-year running mean has been applied to all time series.

## 4. CONCLUSIONS

The overview of the results of the simulation performed with ECBILT-CLIO over the last millennium has allowed showing that

(1) The model results are in good agreement with instrumental records and with large-scale reconstructions based on various paleo-data. The agreement with temperature reconstruction based on borehole temperature measurements in Greenland is weaker, particularly during the 11th century when the model is significantly colder than the reconstruction.

(2) Averaged over the Arctic, the centennial scale variations are mainly due to a response of the climate system to the forcing while natural variability plays a smaller role.

(3) The amplitude of the temperature variations in the high latitudes are much higher than at lower latitudes in the model, denoting a polar amplification of climate changes over the last millennium.

In the near future, we will study the evolution during the second milllennium of the major modes of variability described in a control simulation performed with ECBILT-CLIO (Goosse et al. 2001, 2002, 2003). In particular, we will determine to what extent the modifications of the characteristics of those modes or of their frequencies are driven by changes in the forcing and are thus a component of the forced response of the system.

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