Effects of simulated natural variability on Arctic temperature projections

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[1] A five-member ensemble with a coupled atmosphere-sea ice-ocean model is used to examine the effects of natural variability on climate projections for the Arctic. The individual ensemble members are initialized from a 300 years control experiment, each starting from different strengths and phases of the Atlantic Meridional Overturning Circulation. The ensemble members are integrated for 80 years with a 1% per year increase in the atmospheric concentration of CO_2. The main findings are that on decadal time scales, multi-model spread of estimated temperature changes in the Arctic may potentially be attributed to internal variability of the climate system. During weak CO_2 forcing the internal variability may mask the strength of the anthropogenic signals for several decades. The implications of the findings are that attribution of any Arctic climate change trends calculated over a few decades is difficult.
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1. Introduction

[2] The northern high latitudes have for many years been recognized as the region most sensitive to anthropogenic climate change, with projected temperature changes being typically 2 times larger than the global mean change [e.g., *Intergovernmental Panel on Climate Change* (*IPCC*), 2001; *Holland and Bitz*, 2003; *Hu et al.*, 2004, *McBean*, 2005]. Due to the low moisture content, changes in greenhouse gasses have the potential to become more important in the Arctic than at lower latitudes. In addition the complicated interaction between the atmosphere, ocean and cryosphere give rise to a variety of climate feedbacks as such as ice-albedo and cloud feedbacks. The direct effect of the ice-albedo feedback is that anomalous melting of snow and ice reduces the albedo and thus increases the absorption of incoming solar radiation [e.g., *Manabe and Stouffer*, 1980; *Curry et al.*, 1995]. For the latter, enhanced evaporation from more open water leads to increased cloud amount and increased long-wave radiation to the surface [e.g., *Curry et al.*, 1996]. The cloud effect strongly depends on season and cloud type. Measurements during the SHEBA program [*Uttal et al.*, 2002] indicated a cloud-induced surface warming throughout most of the year, with long-wave climate sensitivity being close to 0.65 W m^{-2} per percent change in cloudiness [*Shupe and Intrieri*, 2004].

[3] Less known are the potential dynamical feedbacks that may be associated with global warming. Most model simulations suggest a general decrease in the meridional oceanic heat transport south of 60°N, and a slight increase poleward of this latitude [*Covey et al.*, 2003]. The inter-model differences are, however, substantial. For the large-scale atmospheric circulation the uncertainties are even larger, although there is a tendency for a strengthening of the North Atlantic westerlies in many of the model simulations [*Osborn*, 2004; *Kuzmina et al.*, 2005].

[4] *Randall et al.* [1998] point out that poor understanding of key physical processes in the region causes a considerable part of the uncertainty associated with Arctic climate projections. In atmosphere, the most critical processes are turbulent transport in stable boundary layers, radiation, cloud formation, and complex interactions among them. Central processes in the ocean are freezing and melting of sea-ice, sea-ice dynamics, turbulent mixing in the upper part of the water column, and the poleward transport of heat. The lack of process knowledge and process interactions has led to a variety of numerical formulations and parameterizations. This in turn has produced a wide spread in the representations of present day control climate and responses to anthropogenic forcing [*IPCC*, 2001; *Räisänen*, 2001].

[5] A second kind of uncertainty is related to the large internal variability at high latitudes. An example of such variability is the early warming of the 1930s and 1940s, which, although primarily an Arctic mode, was sufficiently strong to show up in globally averaged temperature compilation [*Bengtsson et al.*, 2004]. Since natural variability will add "noise" to the climate signal, averaging over a long time period or over many model realizations is necessary to get statistically reliable estimates of human-induced climate change signals.

[6] The use of sufficiently long averaging time periods is, however, problematic for many observational-based time series since these are in general short, especially in the Arctic. An additional complication is that the 20th century anthropogenic climate forcing has given climate responses that are still weak and comparable to the amplitude of the natural climate variability modes. Climate models and increasing availability of computational resources can, however, be used as a laboratory to explore how the signal-to-noise ratio varies as function of averaging time and strength of the signal.

[7] In this study we quantify the uncertainties related to insufficient sampling of internal variability of the Arctic

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surface temperature based on results from ensemble simulations with a numerical coupled atmosphere-sea ice-ocean climate model.

[8] In section 2 the methodology and experimental setup of the model system are described. The projected Arctic temperature changes in the model ensemble are presented in section 3, and discussed in section 4. In section 5 the paper is summarized with the main findings and the implications for Arctic climate projections.

2. Model Description and Analysis Methods

[9] The numerical model used is the Bergen Climate Model (BCM) [*Furevik et al.*, 2003]. It consists of the global atmospheric model ARPEGE/IFS [*Déqué et al.*, 1994] and a global version of the ocean model MICOM [*Bleck et al.*, 1992], the latter including a dynamic and thermodynamic sea-ice model based on *Semtner* [1976] thermodynamics and *Hibler* [1979] rheology. In this version of BCM, ARPEGE/IFS uses a spectral truncation at wave number 63 with a horizontal grid mesh of about 2.8° by 2.8° and 31 vertical levels from surface to 10 hPa. MICOM is set up with a horizontal resolution of approximately 2.4° by 2.4° with 24 layers in the vertical. The horizontal resolution in the ocean increases towards the two model poles located over Siberia and Antarctica. To resolve the equator-confined dynamics, the meridional resolution gradually increases to 0.8° in the tropics. In order to avoid drift from climatology, the heat and fresh water fluxes are modified based on seasonally varying flux-adjustment terms derived from the spin-up of the model.

[10] A detailed description of the technical details and performance of the BCM system is given by *Furevik et al.* [2003]. In addition, detailed descriptions of the simulated North Atlantic Oscillation (NAO) and the Atlantic Meridional Overturning Circulation (AMOC) variability modes are presented by *Kuzmina et al.* [2005] and *Bentsen et al.* [2004], respectively.

[11] A five-member ensemble has been generated based on initial conditions taken from a 300-year control integration. Except for a 1% per year increase in atmospheric CO_2, the atmospheric constituents and aerosols are kept constant in the ensemble integrations. This is the same kind of experiment as carried out in the second phase of the Coupled Model Intercomparison Project (CMIP2) [*Meehl et al.*, 2000; *Covey et al.*, 2003]. As the strength of AMOC and the associated northward heat transport by the ocean have most energy on decadal to inter-decadal time scales [e.g., *Bentsen et al.*, 2004; *Collins et al.*, 2005], each of the ensemble members are chosen to start at different phases of the AMOC in the control integration (Figure 1). This ensures a larger spread in initial conditions than what is achieved by the traditional method in which the atmosphere state is slightly perturbed around a fixed and in general an arbitrary chosen, ocean state.

3. Projected Changes in the Arctic Climate

[12] The linear trends in the zonal-mean temperature, taken over the full integration length (80 years) of the BCM ensemble members shows a strong polar amplification, with a typical warming of 0.5–1.2°C/decade at high northern latitudes (Figure 2a). Comparing the single-model BCM ensemble with the 15-model ensemble in CMIP2, the former shows less then average warming in the 30°N to 40°N latitude band, but stronger warming than the CMIP2 ensemble mean in the Arctic.

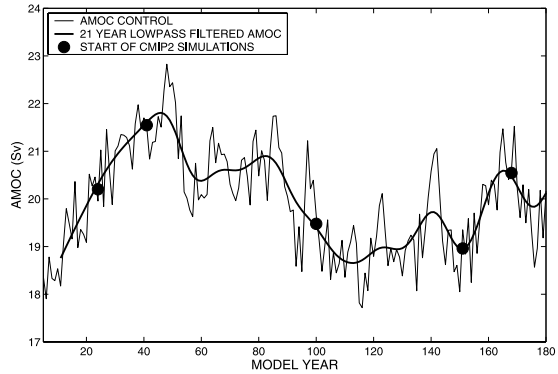

Figure 1. Maximum strength of the AMOC from the BCM control run (solid) and 21-year lowpass filtered values (solid, bold). The bullets indicate the starting points of the five ensemble members.

[13] Qualitatively, a measure for the internal variability of a system is the spread between the various members of an ensemble. Comparing the BCM spread with the CMIP2 spread over the first 25 years of the perturbation experiments (representing a CO_2 forcing up to 35% higher than the present day level), the northern latitude spread of BCM is almost as large as the CMIP2 spread and twice as large as the average temperature change (or warming signal) (Figure 2b). Thus over the first 25 years of the perturbation experiments, the signal-to-noise ratio is very low, and it is therefore difficult to separate an anthropogenic signal from internal climate variability.

[14] In the tropics and subtropics the spread among the various BCM members is much less than the multimodel spread, while the southern ocean and Antarctica are characterized by a small warming signal and a large spread.

[15] The regional distribution of the warming signal show strongest change between Greenland and the North Pole and in the northern Kara Sea, where the temperature increase over the 80 year period exceeds 1°C/decade (Figure 3a). This is the area where the sea-ice cover in the control run has maximum thickness [*Furevik et al.*, 2003]. Typical warming over the northernmost continental areas is of the order of 0.5–0.7°C/decade. The spread among the various BCM members is typically between 0.1 and 0.2°C/decade, with lowest values over the continents and highest values in the areas showing the strongest warming signal. Typically the warming signal is 3 times the spread.

[16] Comparing the warming signal from year 1–25 with years 1–80, it is seen that the pattern is similar, but with strongest warming north of the Canadian Archipelago and in the northeastern Barents Sea, with values being 0.6–0.9°C/decade over the Arctic Ocean. The spread among the ensemble members is larger than the warming signal over most of the Arctic with a maximum spread over the central Arctic where it exceeds 2°C/decade. As seen in Figure 1, this indicates that there is no consensus among the ensemble

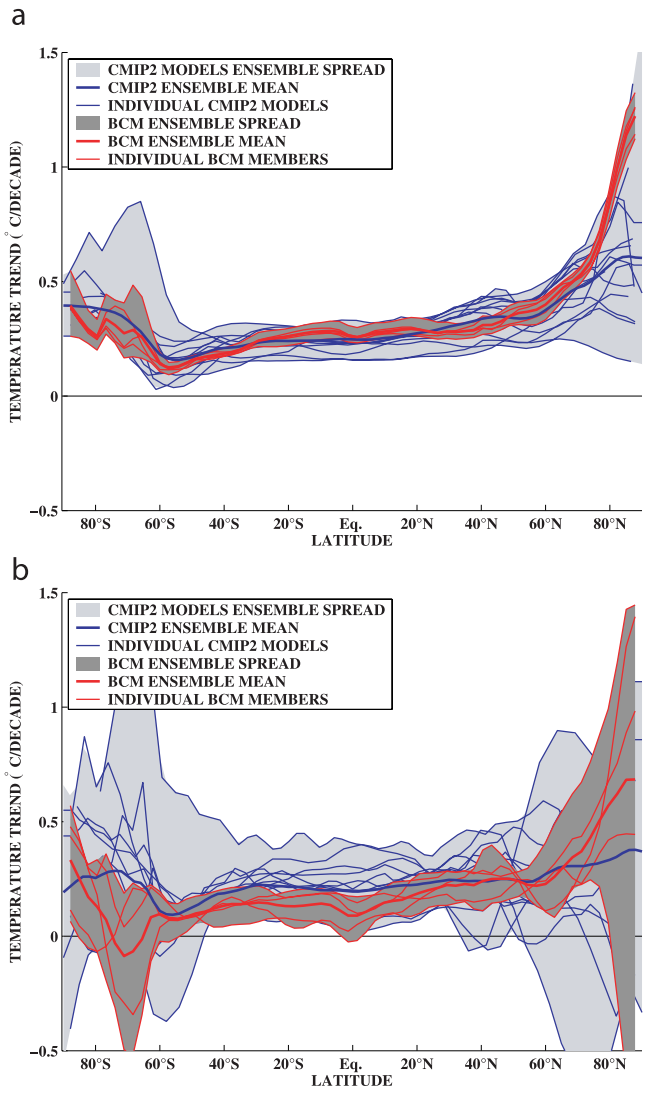

Figure 2. (a) Zonal-mean 2 m temperature trends (°C/decade) as simulated by the CMIP2 and BCM ensembles over years 1–80. Trends in control integrations have been subtracted. Light shading is the spread of the CMIP2 members [e.g., *Hu et al.*, 2004]; dark shading is the spread of the BCM ensemble. The thick blue (red) curve shows the ensemble mean of the CMIP2 (BCM) members, and the thin blue (red) curves the individual CMIP2 (BCM) ensemble members. (b) Same as Figure 2a but for years 1–25.

members on the sign of the Arctic temperature trend over this time period.

4. Discussion

[17] All of the BCM ensemble members show strong warming in the high northern latitudes when trends are calculated over the whole 80 year time period. The main reason for this is a realistically distributed but too thin sea-ice cover in the control run [*Furevik et al.*, 2003] that melts when the greenhouse gas forcing increases. The melted sea-ice exposes the Arctic atmosphere to relatively warm open waters instead of a perennial ice cover [see *Holland and Bitz*, 2003; *Hu et al.*, 2004].

[18] Another feature of BCM compared to the CMIP2 integrations is a reduced warming signal at 30°N to 40°N (not shown). An explanation for this is a substantial strengthening of the NAO in BCM [see *Kuzmina et al.*, 2005], shifting the North Atlantic drift eastwards leading to colder sea surface temperatures in this region. This process reduces the warming in the Northwest Atlantic and enhances the warming of the Nordic Seas [e.g., *Otterå et al.*, 2004]. Other models with a strengthened NAO show similar features with a cold northwest Atlantic and a warm Arctic [cf. *Holland and Bitz*, 2003; *Kuzmina et al.*, 2005].

[19] The spread among the various CMIP2-models in Figure 2 implies large uncertainty in the climate projections, and consequently in any climate impact assessments, of the Arctic. As demonstrated by the five-member BCM ensemble, any trend estimates taken over a few decades are subject to large uncertainties due to internal variability of the climate system. As long as the number of years used in the trend estimates are the same the ratio between the BCM spread and multiomodel ensemble spread is relatively constant regardless of starting point. For example the mean

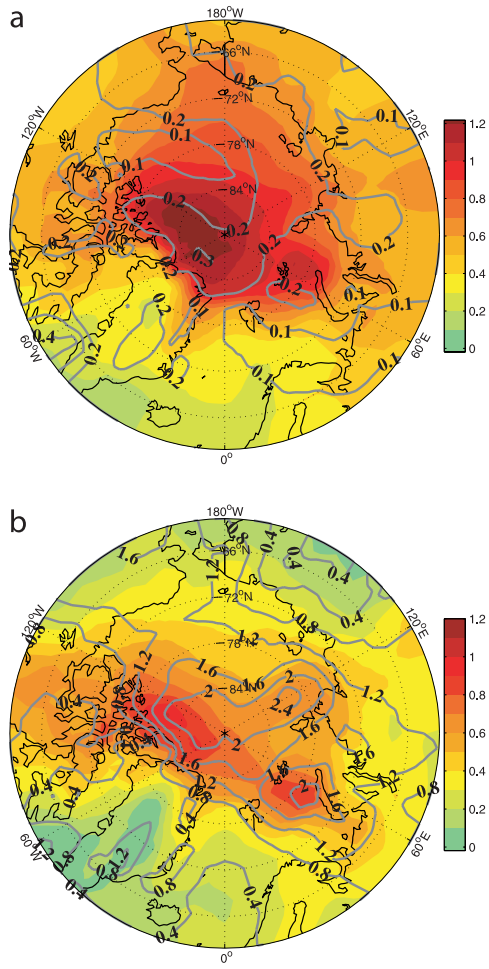

Figure 3. (a) Projected Arctic temperature trends over years 1–80 and (b) years 1–25. Color shading indicates ensemble-mean 2 m temperature trends (°C/decade), and solid lines show the spread in trends among the various ensemble members (contour interval is 0.1 and 0.4°C/decade for Figures 3a and 3b, respectively).

ratio between the BCM and multimodel spread over the latitudinal bands north of 60°N was 40–60% for trends calculated over different 25 year periods (year 1–25, 25–50 and 50–75). Increasing the years used in the trend estimates from 25 to 50 reduced the spread among the BCM members by 30–40% and the spread is further reduced (over 70%) when all 80 years was used in the trend estimates (Figure 2b). The reduction in the multi-model spread is much less pronounced as different representations of the feedback processes in the climate models increases the multi-model spread.

5. Conclusion

[20] A 5-member ensemble of BCM, compared to a 15-member multi-model ensemble, is used to examine the effects of natural variability on climate projections for the Arctic. The main findings are:

[21] – When the changes in the external forcings are small a significant part of multi-model differences for climate projections for the Arctic may potentially be explained by internal climate variability and not necessarily real model differences

[22] – Internal climate variability may mask the strength of the anthropogenic signal for several decades.

[23] – Trend estimates exceeding the time scales of the leading low frequency internal climate variability modes, or trends over many model realizations, increases the signal-to-noise level and makes the climate projections considerably more robust against uncertainties related to insufficient sampling of internal variability.

The multi-model spread in estimated Arctic warming confirms the poor understanding of high latitude physical processes and their response. This represents a great challenge for observationalists, theoreticians and modelers alike in the years to come.

[24] It is important to realize that the trend estimates based on 25 years as in Figures 2b and 3b is comparable to the period with satellite observations of several Arctic climate variables, and it is also consistent with a common time horizon for societal and industry planning and decision making.

[25] Implications of the presented findings are that observed or simulated Arctic climate change trends calculated over a few decades may be strongly influenced by internal variability, making it hard to attribute the changes to any specific external forcings.

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