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The Impact of North Atlantic-Arctic Multidecadal Variability on Northern Hemisphere Surface Air Temperature

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Abstract

The 20th century Northern Hemisphere surface climate exhibits a long-term warming trend, largely caused by anthropogenic forcing, and natural decadal climate variability superimposed on it. This study addresses the possible origin and strength of internal decadal climate variability in the Northern Hemisphere during the recent decades. We present results from a set of climate model simulations that suggest natural internal multidecadal climate variability in the North Atlantic-Arctic Sector could have considerably contributed to the Northern Hemisphere surface warming since 1980. Although covering only a few percent of the earth's surface, the Arctic may have provided the largest share in this. It is hypothesized that a stronger Meridional Overturning Circulation in the Atlantic and the associated increase in northward heat transport enhanced the heat loss from the ocean to the atmosphere in the North Atlantic region, and especially in the North Atlantic portion of the Arctic due to anomalously strong sea ice melt. The model results stress the potential importance of natural internal multidecadal variability originating in the North Atlantic-Arctic Sector in generating inter-decadal climate changes not only on a regional, but possibly also on a hemispheric and even global scale.

1. Introduction

Climate variability can be generated internally by interactions within or between the individual climate subcomponents (e.g., atmosphere, ocean, and sea ice) and externally by e.g., volcanic eruptions, variations in the solar insolation at the top of the atmosphere, or changed atmospheric greenhouse gas concentrations in response to anthropogenic emissions. Examples of internal variations are the North Atlantic Oscillation (NAO), the El Niño/Southern Oscillation (ENSO), the Pacific Decadal Variability (PDV), and the Atlantic Multidecadal Variability (AMV). Internally generated variations may project on global or hemispheric surface air temperature (SAT), thereby masking and complicating detection of anthropogenic climate change.

Northern Hemisphere (NH) averaged SAT has risen by about 1K during the 20^{th} century (Fig. 1a) and has contributed to about two thirds of global warming over this period. The long-term warming trend during the 20^{th} century has been attributed with high confidence mostly to anthropogenic forcing, specifically the increase in atmospheric greenhouse gas concentrations (Hegerl et al. 2007). Strong multidecadal fluctuations, however, are superimposed on the long-term NH warming trend, which can be readily identified in the observed record of annual mean SAT (Fig. 1a) without applying further time filtering. The "mid-century warming" (MCW) during 1910-1940, for instance, was replaced by a cooling trend in the period 1950-1970, which is also clearly seen in the Arctic SAT record (Fig. 1b). Thereafter, NH SAT increased again at a rate considerably stronger than the mean trend during the 20^{th} century (Trenberth et al. 2007).

Contributions of anomalous solar forcing, changes in volcanic and anthropogenic aerosols were suggested to explain the multidecadal variations of the observed temperatures including MCW (Broccoli et al. 2003; Stott et al. 2000). However, when considering the ensemble mean of the CMIP3 models forced by all known external forcing, anthropogenic and natural (Hegerl et al. 2007), the MCW in the NH can not be fully explained (Fig. 1a). An even smaller fraction of MCW can be attributed to external forcing in the Arctic (Fig. 1b). Comprehensive analysis by Wang et al. (2007) demonstrated poor simulation of the Arctic warming by climate models when driven with estimates of both observed natural and anthropogenic forcing.

At the same time, the models are capable of producing strong internal multidecadal fluctuations of the global climate similar to the observed (Delworth and Knutson 2000; Delworth and Mann 2000; Knight et al. 2005; Latif et al. 2004), and may even fully capture the MCW “by chance” in one of several climate change simulations with identical external forcing and different initial conditions (Delworth and Knutson 2000). These studies reveal the North Atlantic region as a source of strong multidecadal natural variability. Recent analyses of the multidecadal deviations between simulated (as given by the multi-model mean of the CMIP3 model ensemble) and observed global temperature changes in the last century (Kravtsov and Spannagle 2008; Ting et al. 2009) show that the strongest discrepancies are located in the North Atlantic and presumably related to internal oceanic variability in this region. The mechanism of the link between this regional climate variability and global climate changes has yet to be understood.

Another important feature of both MCW and the warming in recent decades is the so called “Arctic amplification”, a relatively high rate of warming in the northern high latitudes. The mechanism behind this phenomenon is still under discussion (Alexeev et al. 2005; Serreze and Francis 2006). Climate models reproduce it in global warming simulations, some of which assigning an important role to the oceanic poleward heat transport in accelerating high latitude warming (Holland and Bitz 2003). For the last decades of the 20th century, however, the CMIP3 multi-model ensemble mean shows less warming than observed in the northern North Atlantic and adjacent land areas (Figs. 2a, b). This may indicate that internal variability was important in addition to external forcing not only during MCW but also during the recent decades.

This study supports the hypothesis that a relatively strong contribution to Northern Hemisphere and hence global temperature change could possibly stem from internal multidecadal variability originating in the North Atlantic/Arctic (NA/Arctic) Sector. Previous climate model simulations (Zhang et al. 2007) report an important role of North Atlantic multidecadal sea surface temperature (SST) variability in shaping NH-SAT during the 20th century, but did not consider the role of the Arctic. Here we focus on two main questions. First, can internal multidecadal variability in the North Atlantic/Arctic Sector considerably contribute to the Northern Hemisphere SAT change? And second, what is the role of the Arctic in this? Section 2 describes the surface heat fluxes associated with AMV changes and the implied heat transports in climate models and re-analysis. In Section 3, the description of the experimental setup used to assess the impact of these fluxes on the Northern Hemisphere surface climate follows. The results of the numerical experiments are given in Section 4. A discussion of our main findings and their implications concludes this paper.

2. Atlantic multidecadal variability and associated heat transport changes

The possibility is investigated that internal multidecadal variability originating in the North Atlantic (Manabe and Stouffer 1999; Schmittner et al. 2007) that is accompanied with a strong oceanic heat loss to the atmosphere in the North Atlantic and especially in the Arctic Sector (Bengtsson et al. 2004) has considerably contributed to the NH SAT change during the recent decades. The observed SAT trend pattern during 1978-2007 (Fig. 2a) supports this, projecting strongly onto the positive phase of the Atlantic Multidecadal Variability (AMV) (Kerr 2005; Knight et al. 2006; Knight et al. 2005; Sutton and Hodson 2005) which is characterized by anomalous warming in the North and anomalous cooling in the South Atlantic. AMV is hypothesized to be linked to Meridional Overturning Circulation (MOC) variability and consequently to changes in the northward oceanic heat transport in climate models (Delworth et al. 1993; Latif et al. 2004), and AMV-related North Atlantic SST changes do project onto NH and global SAT in these models. The latter is demonstrated by analysis of correlation between AMV and global (hemispheric) SAT anomalies in control simulations with an extensive set of climate models (Table 1).

The multi-model ensemble mean SAT trend pattern during 1978-2007 obtained from 20th century climate model simulations with observed external forcing (Fig. 2b), natural and anthropogenic, shows considerable differences to the observed trend pattern, with less warming in the North Atlantic and more warming in the South Atlantic. Although other natural internal decadal climate modes may have contributed to the mismatch to the observed trend, the Atlantic signature of relatively warm north and cold south Atlantic suggests that the SAT trend observed during the recent decades may contain a considerable contribution from AMV. Multidecadal NH-SAT variations as those observed (Fig. 1) are simulated by climate models in control integrations without time-varying external forcing, as described above. An example (Fig. 2c) is shown from one particular model (MPI, exp. D16), in which the multidecadal North Atlantic SAT changes are forced by MOC changes, as demonstrated by Latif et al. (2004).

The pattern of SAT difference between two 30-year segments corresponding to a negative and a positive AMV extreme simulated by this model (Fig. 2c) resembles somewhat the observed SAT trend pattern observed during the recent decades (Fig. 2a). The particular MOC variation was selected, since it was connected with coherent warming in the North Atlantic and the Arctic similar to what was observed during the MCW and the warming in recent decades. In particular, the simulated warming during the chosen period displayed poleward amplification. The realization that we used below in our experiments with a coupled atmosphere/mixed layer model (AGCM-ML) is in terms of anomalous North Atlantic SST of the same order of magnitude as the observed warming trends during the MCW and the recent decades. The SST averaged over the region [50°W-10°W, 40°N-60°N] (used as an index for AMV in Latif et al. 2004) has varied by 0.7K (minimum to maximum) for the MCW and by about 0.8K for the increase from the mid-seventies to the present. Yet both warming trends contain most likely some contribution from external forcing, especially during the recent decades. The internal change that we have chosen to force the AGCM-ML exhibits an SST anomaly in the same region of 1.0K, exceeding the observed variations by some 20%. The basin-wide SST change in the North Atlantic (0°-60°N), however, amounts to 0.65K and 0.47K for the observed trend during 1978-2007 and the coupled model trend, respectively.

We turn now to the heat fluxes associated to this particular realization of internal variability. The simulated anomalous heat loss to the atmosphere due to the turbulent sensible and latent heat fluxes is mostly concentrated in the northern North Atlantic and along the sea ice border in the Atlantic opening of the Arctic Ocean (Martin and Ruprecht 2007). The pattern of anomalous turbulent heat flux (Fig. 3) associated with the AMV variation in the climate model consists of two major maxima, in the North Atlantic mid-latitudes where corresponding SST anomalies occur, and between 70°N and 80°N, indicating a role of the sea ice variability. This structure is further illustrated by zonal mean heat fluxes (Fig. 4). Among a number of control climate simulations (see Table 1), we selected those which exhibited North Atlantic AMV similar to that observed during the 20th century in respect to multi-decadal frequency, amplitude and a sign of coherent changes in the North Atlantic and the Arctic. Associated zonal heat flux anomalies between selected AMV extremes are shown including the anomaly from the MPI D16 simulation, which corresponds to the temperature trend pattern shown in Fig. 2c. Empirical estimates from NCEP re-analysis (Kalnay et al. 1996) may be illustrated by two recent transitions from the high AMV phase in 1951-1955 and the low phase in 1968-76, and back to high phase in 1998-2006 (Fig. 4b). The latter estimates are only indicative of internal AMV variation as (in contrast to the control climate model simulations) they contain externally forced signal. However, the structure is somewhat similar and amplitude of the anomalies compares well to the model estimates.

Changes of the Arctic sea ice, associated with the AMV, cause intense heat loss in winter time and were found to have a strong impact on the atmosphere (van der Swaluw et al. 2007). Sea ice anomalies, in particular in the Barents Sea, induced by anomalous oceanic heat transport may be further amplified by a positive feedback between the heat inflow and sea ice (Bengtsson et al. 2004; Mysak and Venegas 1998; Semenov 2008), and this Arctic heat loss of the order of up to about 30W/m^2 annually in some regions (Fig. 3) is of particular importance here. The implied heat transport change over the NA/Arctic Sector (40-90°N, 90°W-60°E) estimated from the turbulent heat fluxes corresponds to 0.09PW in the MPI D16 simulation. Estimates between high and low AMV phases from control integrations with the other global climate models are also of the order of about 0.1PW, corresponding to about 10% of the total northward heat transport by the MOC at 25°N. Hydrographic data from the second half of the 20th century confirm this estimate (Huck et al. 2008). The implied heat transport change from the 1970s up to present [(1998-2006)-(1968-1976)] estimated from NCEP re-analysis amounts to about 0.14PW. However, it should be pointed out again that observational estimates contain an externally driven component.

3. Model setup

The global climate response to an increase in heat transport in response to an internal multidecadal climate variation, which by definition does not contain an externally forced part, was studied with an atmospheric general circulation model (ECHAM5) coupled to a fixed-depth (50m) mixed-layer ocean model (ML), hereafter referred to as ECHAM5-ML (Roeckner et al. 2003), by driving it with the anomalous AMV-related heat flux from the MPI D16 simulation. This flux (monthly mean climatology) was calculated, as for SAT (Fig. 2c), as a difference between the same two 30-year periods corresponding to a negative and a positive AMV extreme. The annual mean pattern is shown in Fig. 3. The atmosphere model was run at T31 horizontal resolution with 19 vertical levels. The coupled model ECHAM5-ML uses Q-flux derived from a stand-alone integration with ECHAM5 forced by observed SST/sea ice (AMIP2, (Hurrell et al. 2008).

Three sensitivity integrations have been conducted. In one, the heat flux pattern is applied over the NA/Arctic Sector (ocean area: 40°N-90°N, 70°W-80°E) covering less than 6% of the NH area. In two others, the forcing was further restricted either to the NA [40°N-60°N, 70°W-80°E] or Arctic region [60°N-90°N, 70°W-80°E] (see denoted regions in Fig. 3). All experiments described here have a length of 100 years, and the last 80 years were used in the analyses below. There is no long-term drift in the experiments, but a considerable amount of interannual to decadal variability. The experimental setup allows estimating the effect of persistent regional surface heating of the atmosphere caused by deep ocean dynamics. Similar to Zhang et al. (2007), we attempt to quantify the contribution of AMV to NH and global SAT variability. Here, however, we focus on solely internally generated changes not only in the NA but also in the Arctic Sector, and assess the relative contributions of these two regions. We note that this experimental setup does not allow a separation of internally and externally forced SAT changes observed in the recent decades. Instead, it provides an assessment of whether internal generated AMV may have potentially contributed to the recent acceleration in NH warming since 1980.

4. Results

The annual mean SAT response to the imposed heat flux forcing averaged over the Northern Hemisphere amounts to 0.39°C and globally to 0.24°C (Table 2). The observed warming during 1978-2007 obtained from the GISS dataset amounts to 0.68 and 0.45°C, respectively. The zonally averaged NH-SAT response in all experiments with ECHAM5-ML is shown in Fig. 5 in comparison with NCEP reanalysis data, different observational estimates of the temperature trend for 1978-2007 and the multi-model mean trend simulated by the CMIP3 model ensemble (for the same period) in the 20^{th} century integrations with observed natural and anthropogenic forcing. Also shown is the linear superposition of the NA and Arctic experiments. CMIP3 multi-model mean yields stronger warming in the Tropics and weaker warming in the Polar Region in comparison to the observations. Although there is considerable spread among the observational estimates, this result appears to be robust. The horizontal SAT response pattern (Fig. 2d) compares well with the observed trend pattern during 1978-2007 (Fig. 2a) in the Northern Hemisphere with strongest warming over the NA/Arctic Sector and a realistic latitudinal structure in the Atlantic. This lends further support to the picture that an internal multidecadal fluctuation in the North Atlantic could have considerably contributed to the recent Northern Hemisphere warming.

The two sensitivity experiments with the forcing restricted to either the NA or Arctic region reveal that the Arctic part of the anomalous forcing contributes about 60% to the total NH-warming in the NA+Arctic-experiment (Fig. 2f, Fig. 5, Table 2). Although the linear superposition of the two responses basically adds up to the NH and globally averaged SAT changes in the combined (NA+Arctic) experiment (Table 2), this is not the case everywhere. This is expected given the nonlinear nature of the atmospheric circulation and not further discussed here. The results are qualitatively reproduced by a simple zonally averaged energy balance model with diffusive heat transport (North 1975), which is not shown here.

An MOC-driven heat release in the Northern Hemisphere may be compensated by an opposite anomaly in the Southern Hemisphere, an issue which we did not directly address by our experiments. However, the comparison of the original climate model SAT anomalies (Fig. 2c) with those simulated by ECHAM5-ML when forced only in the NA/Arctic region (Fig. 2d) shows that mostly the Southern Hemisphere and thus global SAT will be affected by the compensation. Indeed, the SAT change averaged over the Northern Hemisphere is virtually identical in the two runs, while the globally averaged SAT change is, as expected, considerably weaker in the original climate model run (0.18K vs. 0.24K).

The Northern Hemisphere winter (DJF) sea level pressure (SLP) response in the full (NA+Arctic) experiment (Fig. 6a) exhibits some similarities to the linear trend pattern observed during the recent decades as obtained from NCEP re-analysis (Fig. 6b). ECHAM5-ML simulates anomalously low pressure over the Arctic and anomalously high pressure further to the south over the North Atlantic and North Pacific, features also seen in the NCEP trend pattern, although the latter is (as expected) characterized by a much "noisier" pattern. Furthermore, the simulated and observed centers of action do not correspond well. The model response in the centers of action is statistically significant at the 95% level applying a t-test. The response pattern over the North Atlantic strongly projects onto the pattern of the North Atlantic Oscillation (NAO). The observed SLP trend in the recent decades projects only weakly. We note, however, a rather strong sensitivity to the exact period chosen. The simulated teleconnection to the North Pacific may explain the surface warming in the western North Pacific (Fig. 2d) due to reduced cold air advection.

The vertical structure of the Northern Hemisphere temperature response is compared to the trend derived from NCEP re-analysis for 1978-2007 (Fig. 7). Consistent with NCEP, the model simulates considerable warming of the whole troposphere north of 30°N, with strongest warming in the lower Arctic troposphere (Fig. 7a). The model's troposphere warming is weaker, as expected without the inclusion of external forcing, and it does not extend into the Tropics and the Southern Hemisphere, but, overall, the results suggest that internal variability could have significantly contributed to the observed change in the vertical temperature structure. The stratosphere cooling, a prominent feature of the observed trend pattern (Fig. 7b) and one of the most robust fingerprints of enhanced greenhouse warming (Hegerl et al. 2007), cannot be simulated with our model setup considering only the effect of internal variability. This indicates the important role of anthropogenic forcing played during the recent decades in driving global climate change.

5. Discussion

We have investigated the atmospheric response to surface heat flux anomalies in the North Atlantic/Arctic Sector originating from a peak-to-peak change in the Atlantic Multidecadal Variability (AMV). This was performed by forcing a coupled atmosphere-ocean mixed layer model by regionally confined surface heat fluxes that were simulated in a control run with a global climate model in association with one particular AMV realization. The latter is by definition internally driven and does not require external forcing. The heat flux forcing was restricted to the North Atlantic/Arctic Sector in order to specifically study the impact of that region on Northern Hemisphere and global climate. The results show that such an internal and regionally confined climate variation can drive relatively large surface climate anomalies on regional, hemispheric and even global scale. The Arctic plays an important role in this, explaining about 60% of the total Northern Hemisphere surface air temperature (SAT) response in our experiment.

What are the implications of our work? First, concerning the hypothesis as to whether a strong AMV change could have considerably contributed to the Northern Hemisphere surface warming during the recent decades. Our model experiments suggest that natural internal multidecadal variability originating in the North Atlantic and associated processes in the Arctic could have played an important role, as the response is relatively large and statistically significant, and since the simulated patterns resemble some of the large-scale parts of the observed trend patterns during the recent decades. Ocean model simulations with prescribed observed surface forcing show indeed strengthening of the MOC during the recent decades and a stabilization during the recent years (Boning et al. 2006). One may therefore speculate that there is an increasing probability that the AMV may return back to neutral or negative state within the next few years or decades counteracting the long-term anthropogenic warming trend. This could potentially offset global warming for some time until the AMV swings back, which would be in line with the prediction of Keenlyside et al. (2009). However, our results should be considered as suggestive, but by no means as proof for internal variability being a major contributor to the global warming acceleration in the recent decades. We have shown that AMV changes do at least have the *potential* to strongly affect Northern Hemisphere averaged SAT, which is also confirmed by a number of global climate models. We would like to emphasize that this study does not question the existence of a long-term anthropogenic warming trend during the 20th century.

A second implication relates to tipping points (Lenton et al. 2008), delicate thresholds where a slight rise in the Earth's temperature can cause a dramatic change in the environment that itself triggers a far greater increase in global temperatures. The Arctic sea ice loss has been dramatic during the recent years and a critical threshold may have been crossed (Lindsay and Zhang 2005; Stroeve et al. 2007), which would lead to an unavoidable complete loss of sea ice in the Arctic summer during the next decades. If a threshold has been really reached, it may not have been crossed so soon without the internal fluctuation. This indicates that the presence of strong internal variability could lead to extreme climate changes even in the presence of an only moderate anthropogenic signal.

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List of Figures

Fig. 1. Observed NH (a) and Arctic (b) annual mean surface air temperature (SAT) anomalies (°C) from CRUTEMP3 (red) and the ensemble of 20th century simulations with the CMIP3 models using both anthropogenic and natural radiative forcing. The ensemble mean is given by the thick black line; the shading shoes the range in which 90% of the individual model realizations lie. Model data were masked (in respect to missing values) as the observational data.

Fig. 2. (**a**) The SAT trend pattern (°C/30yr) during 1978-2007 from GISS observations and (**b**) the multi-model ensemble mean in comparison to the simulated SAT anomalies (°C) in (**c**) the climate model ("coupled GCM") control run from which the forcing for ECHAM5-ML was derived, in (**d**) the "NA+ARCTIC" experiment in which the forcing was applied in both the North Atlantic and the Arctic, in (**e**) the "NA"-only experiment in which the forcing was applied only in the North Atlantic, and in (**f**) the "Arctic"-only experiment in which the forcing was applied only in the Arctic. Numbers in the upper right of the panels are global and (in brackets) NH averaged values.

Fig. 3. Annual mean turbulent fluxes (W/m^2) from the MPI D16 control simulation, associated with a transition from cold to warm AMV phase, used in the experiments with the ECHAM5-ML model. The figure shows also the different regions to which the forcing was applied in the different experiments. A positive sign indicates a flux from the ocean to the atmosphere.

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Fig. 5. The zonally averaged observed surface air temperature (SAT) changes (°C) in the period 1978-2007 from reanalysis [NCEP (red)], two observational datasets, [HadCRU (blue), GISS (purple)] and from the ensemble mean of the CMIP3 models (black) driven with observed natural and anthropogenic forcing. The thin lines denote the individual simulations from the CMIP3 model ensemble. Also shown are the different numerical climate model experiments with ECHAM5-ML. The "NA+Arctic" experiment is shown in olive.

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List of Tables

Tables

Model	correlation (NH-SAT, NA-SAT)	regression (NH-SAT, NA-SAT)	correlation (Global SAT, NA-SAT)	regression (Global SAT, NA-SAT)	years
OBSERVATIONS	0.786	0.490	0.510	0.286	130
IAP FGOALS1.0.G run1	0.964	0.158	0.930	0.079	340
IAP FGOALS1.0.G run2	0.962	0.156	0.938	0.078	340
IAP FGOALS1.0.G run3	0.961	0.156	0.941	0.078	340
CSIRO MK3.0 run2	0.860	0.146	0.697	0.064	70
NCAR CCSM3.0 run2	0.816	0.142	0.764	0.076	490
CSIRO MK3.5	0.816	0.222	0.587	0.094	990
MIUB ECHO.G	0.801	0.266	0.599	0.126	330
UKMO HADGEM1	0.781	0.259	0.739	0.138	230
NCAR CCSM3.0 run1	0.776	0.153	0.659	0.069	220
CSIRO MK3.0 run1	0.764	0.180	0.594	0.093	370
GISS AOM run1	0.665	0.241	0.736	0.200	240
CNRM CM3	0.637	0.557	0.253	0.177	490
MIROC3.2 HIRES	0.586	0.177	0.515	0.077	90
GFDL CM2.0	0.580	0.224	0.518	0.186	490
GISS AOM run2	0.576	0.121	0.300	0.055	240
CCCMA CGCM3.1.t63	0.548	0.122	0.456	0.077	340
BCCR BCM2.0	0.547	0.400	0.462	0.291	240
NCAR PCM1 run2	0.520	0.199	0.330	0.099	580
INGV ECHAM4	0.490	0.116	-0.224	-0.034	90
CCCMA CGCM3.1	0.486	0.057	-0.210	-0.018	990
UKMO HADCM3 run 1	0.479	0.161	0.437	0.084	340

IPSL CM4 run2	0.473	0.123	0.276	0.046	490
MPI ECHAM5	0.470	0.233	0.328	0.123	500
IPSL CM4 run1	0.458	0.127	0.299	0.055	310
GISS MODEL.E.R	0.449	0.133	0.444	0.095	490
GFDL CM2.1	0.393	0.239	0.190	0.090	490
INMCM3.0	0.386	0.419	0.115	0.121	320
NCAR PCM1 run1	0.295	0.152	0.349	0.101	340
MIROC3.2 MEDRES	0.276	0.154	0.200	0.084	490
MRI CGCM2.3.2A	-0.018	-0.005	0.093	0.022	340
GISS MODEL.E.H	-0.075	-0.046	-0.187	-0.088	390
UKMO HADCM3 run 2	-0.103	-0.028	0.307	0.057	70

Table 1. Correlations and linear regression coefficients (°C/°C) between the North Atlantic SST index and Northern Hemisphere and globally averaged SAT in the different climate model control integrations. The length of the integrations is shown in the last column.

Exp.\Mean	NH	SH	GLOB
NA+Arctic	0.39 (0.37)	0.08 (0.08)	0.24 (0.23)
NA	0.17 (0.16)	0.04 (0.04)	0.10 (0.10)
Arctic	0.24 (0.21)	0.06 (0.05)	0.15 (0.13)
OBS	0.68	0.22	0.45

Table 2. SAT changes (relative to the control simulation, in °C) averaged for the Northern hemisphere (NH), Southern hemisphere (SH), and the Globe (GLOB) as simulated by the ECHAM5-ML model forced by the anomalous surface turbulent heat fluxes over water in the northern North Atlantic and Arctic regions. The North Atlantic/Arctic (NA/Arctic) region is defined as the average over 40-90°N and 90°W-60°E, the northern North Atlantic (NA) region as the Atlantic portion of the region 40-60°N, and the Arctic as 90°W-60°E, 60-90°N. The last row denoted by OBS is the observed trend 1978-2007 computed from the GISS dataset. Numbers in the brackets indicate the model SAT changes after masking the model data using the same missing data regions as in GISS data.

Figures

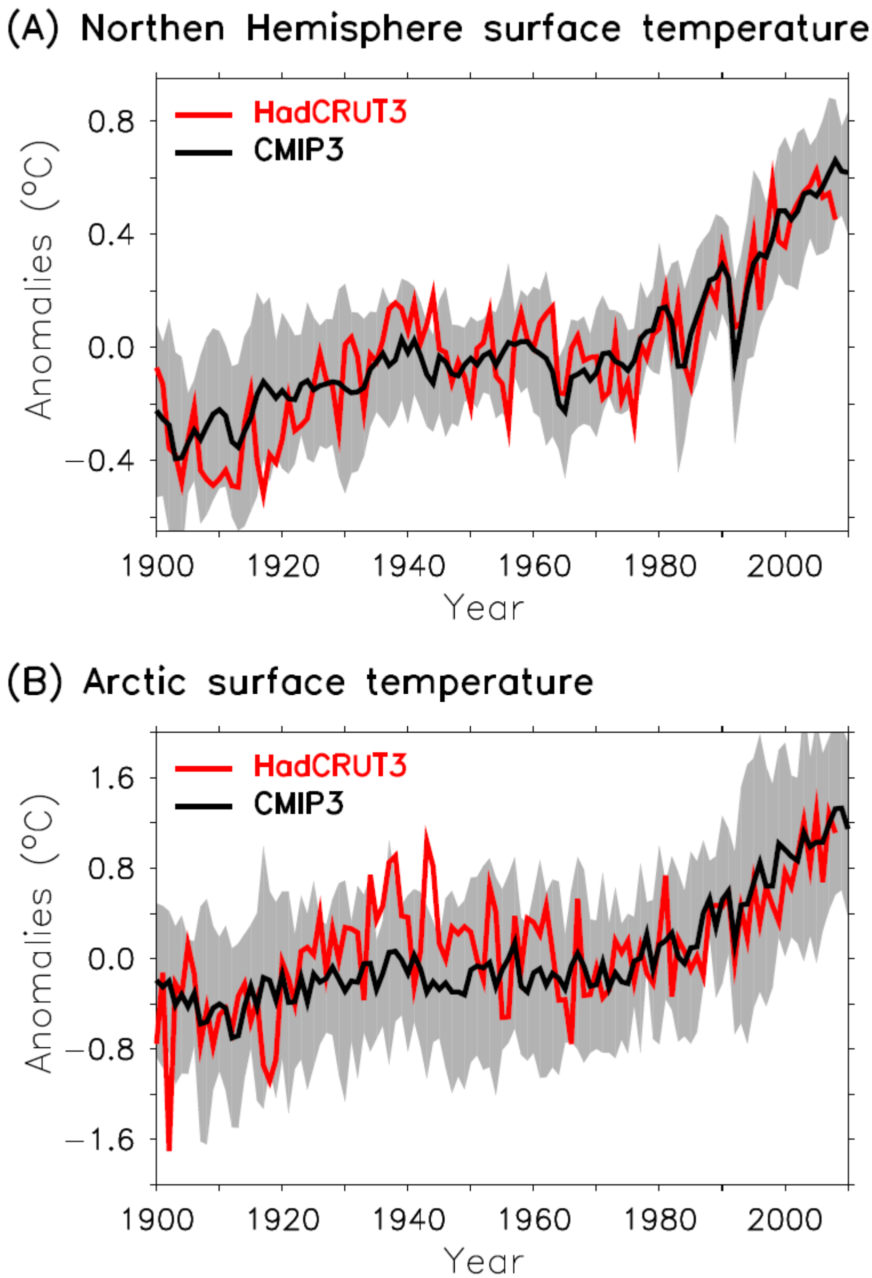
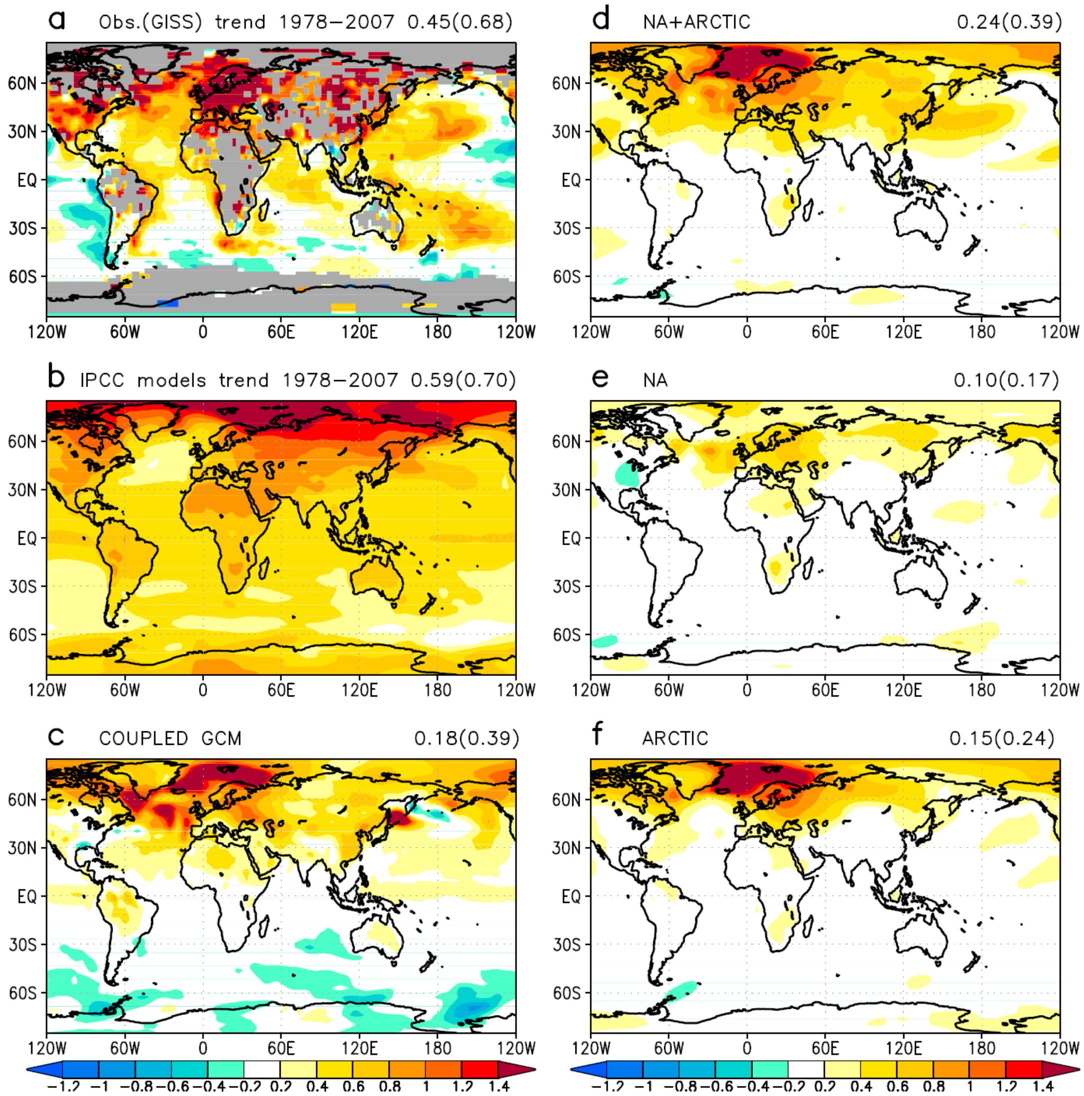


Fig. 1. Observed NH (a) and Arctic (b) annual mean surface air temperature (SAT) anomalies (°C) from CRUTEMP3 (red) and the ensemble of 20th century simulations with the CMIP3 models using both anthropogenic and natural radiative forcing. The ensemble mean is given by the thick black line; the shading shoes the range in which 90% of the individual model realizations lie. Model data were masked (in respect to missing values) as the observational data.



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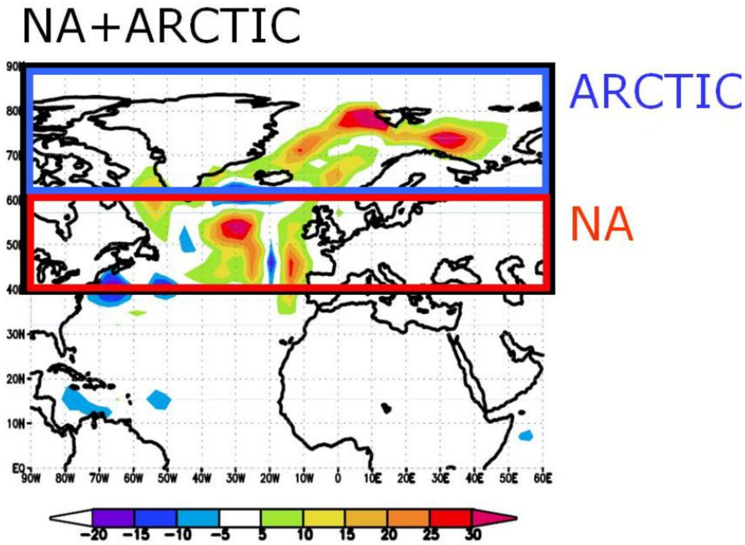

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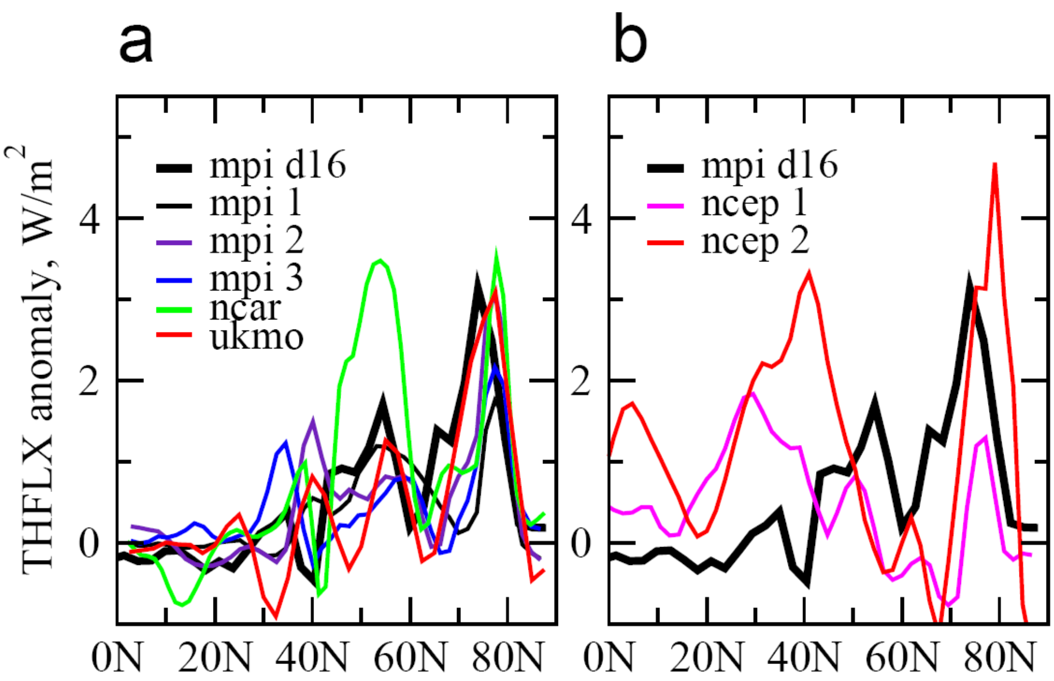

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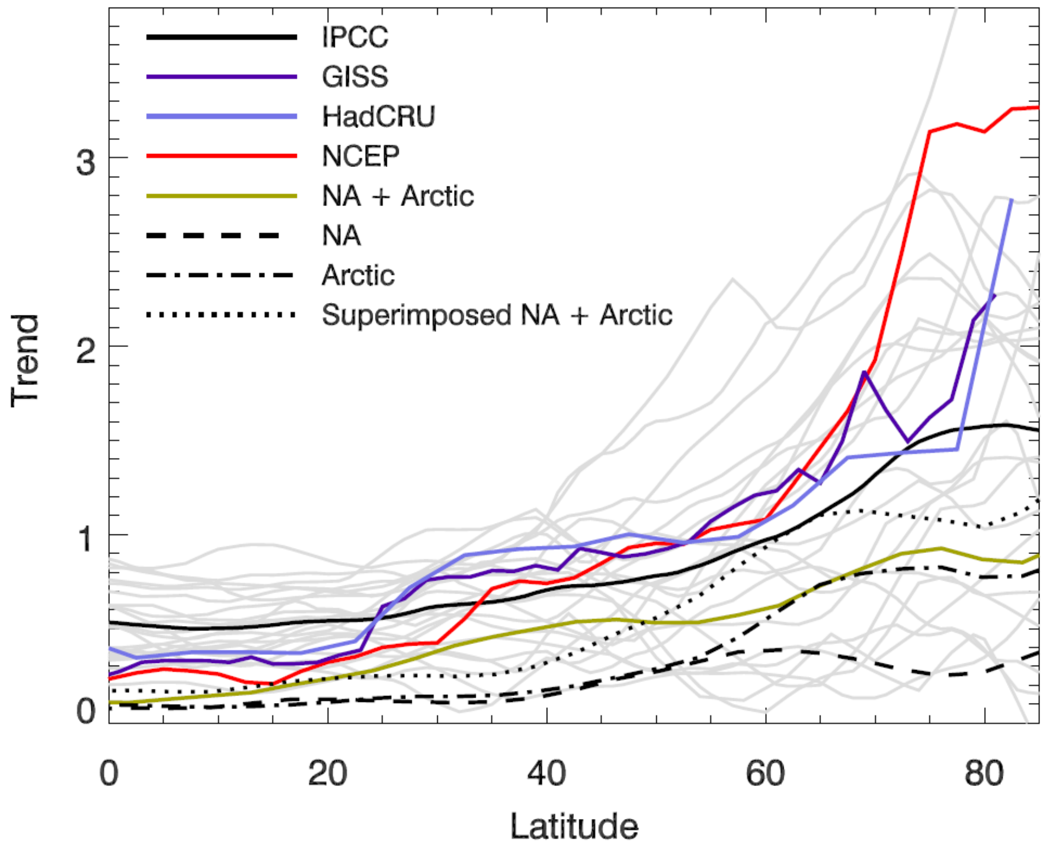

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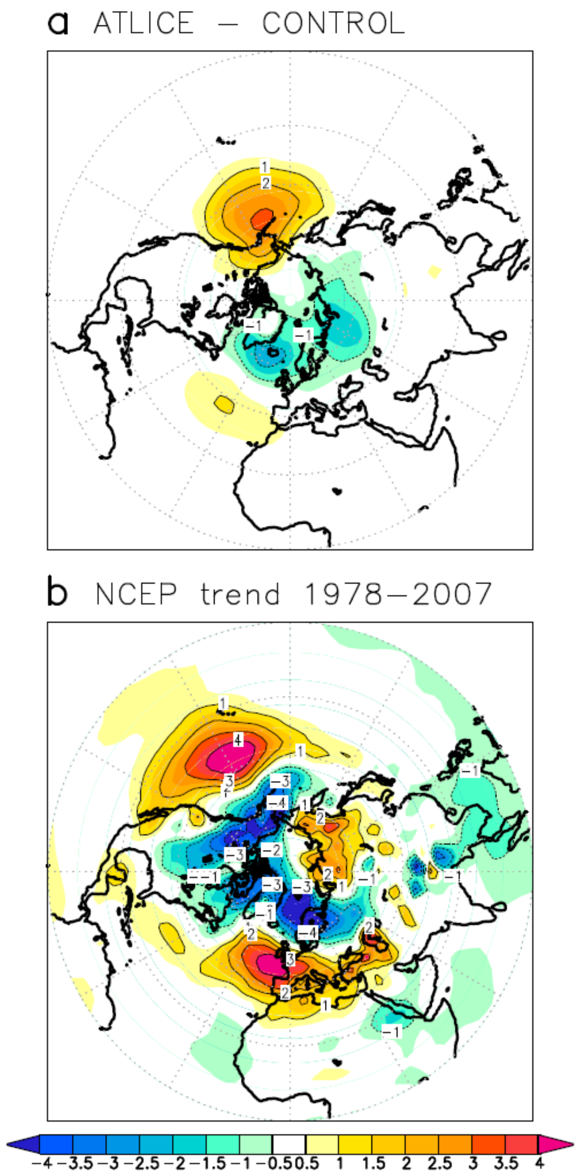

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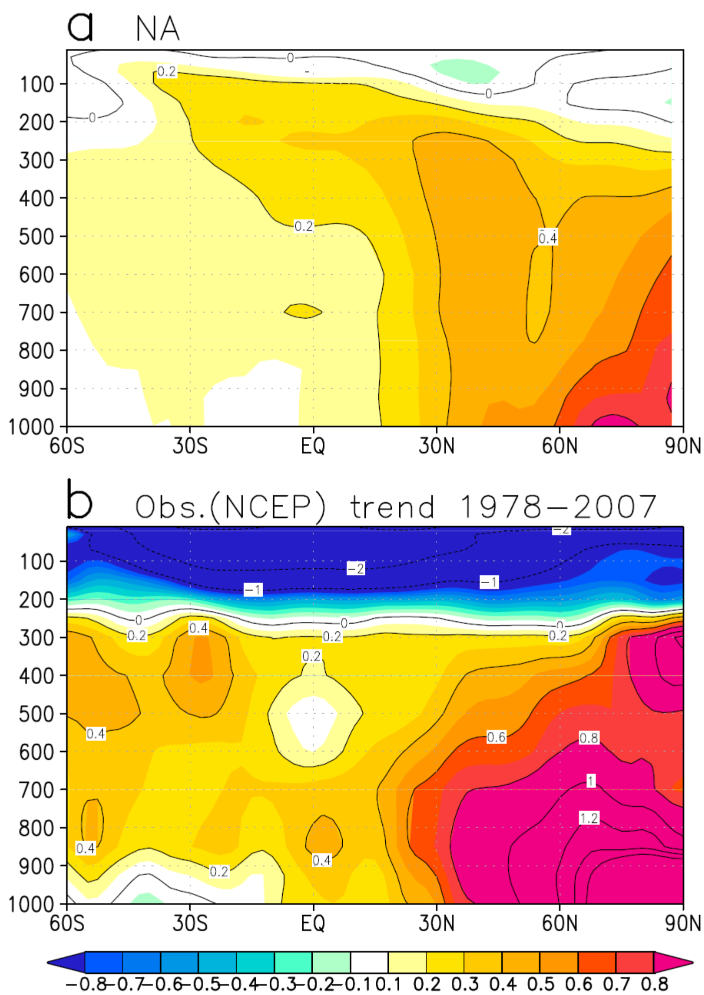

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