Transient Polar Amplification in Arctic Observations and Climate Simulations

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Amplification of Arctic surface warming is a well known feature of climate model predictions for the mid and late 21st century. However, as of 2004, observed Arctic surface warming is not yet significantly higher than the whole northern hemisphere. Here we compare surface warming in the Arctic and the northern hemisphere for the past 150 yr in observations and large ensembles of historical runs from two climate models. Single realization of the models also lack significantly higher Arctic warming in the last half century, and one model lacks significantly higher Arctic warming for the last 150 yr. The agreement between models and observations in the past indicates that polar amplification cannot be ruled out in the future. Using historical runs and future scenarios to estimate trends and internal variability, we predict Arctic warming won't be significantly greater than the northern hemisphere until at least 2020.

1. Introduction

The term "polar amplification" usually refers to greater climate change near the pole compared to the rest of the hemisphere or globe in response to a change in global climate forcing, such as the concentration of greenhouse gases or total solar irradiance [see e.g., *Moritz et al.*, 2002]. It is often used to describe the amplified rate of surface warming over the Arctic compared to the rest of the globe in climate model scenarios of the 21st century [e.g., *Manabe and Stouffer*, 1980; *Holland and Bitz*, 2003].

Yet previous studies have argued that observational evidence of amplified warming in the Arctic during the 20th century is ambiguous [*Serreze and Francis*, 2005; *Polyakov et al.*, 2002; *Przybylak*, 2000]. The Arctic Climate Impacts Assessment concludes, "Over the past 100 years, it is possible [33-66% confidence] that there has been polar amplification, however, over the past 50 years it is probable [66-90% confidence]" [ACIA, 2005, page number will be available in Sept 2005]. This lead *Przybylak* [2000] to suggest that future projections from climate models disagree with past observation, while *Polyakov et al.* [2002] even question whether global warming will be amplified in the Arctic in the future.

Warming trends can be obscured by internal climate variability as well as the normal delay (or inertia) in the climate system, both of which vary regionally on Earth, owing in part to different surface types, such as land, ocean, and sea ice. In addition, warming rates depend on the climate forcing, which differs for the 20th and 21st centuries. The apparent contradiction between models and observations described above derives in part from comparing past Arctic warming trends that are strongly biased by land stations to model simulations of the 21st century over mixed surface types. These points were also made by *Serreze and Francis* [2005], who show more favorable comparisons of model projections of the next two decades to past observations.

Another reason why polar amplification has been questioned stems from inconsistent use of the term itself. We suggest polar amplification is the ratio of the *equilibrium* surface warming of the polar region to that of the entire hemisphere. However, one can only measure polar amplification in a *transient* sense because the climate system is never in perfect equilibrium with its climate forcing. A more practical concept is that of a "transient polar amplification", which is the ratio of the surface temperature trend in the polar region to a given hemisphere. According to climate models run to quasi-equilibrium, polar amplification is inherent to the climate system [*Hall*, 2004]. However, there may be certain intervals of time when polar warming is not amplified (i.e., the transient polar amplification is less than one).

In this study we compare model and observations to determine if the absence of amplified Arctic warming in the past is normal in historical climate simulations in models that nonetheless exhibit amplified Arctic warming in future scenarios.

2. Observed Transient Polar Amplification

Observed Arctic warming in the past few decades and over the 20th century is indisputable, but it is unclear whether the observed warming is significantly greater in the Arctic compared to the hemisphere as a whole. *Polyakov et al.* [2002] concluded it is not significantly greater at any time from 1875–2000. However, the spatial representation of their Arctic average

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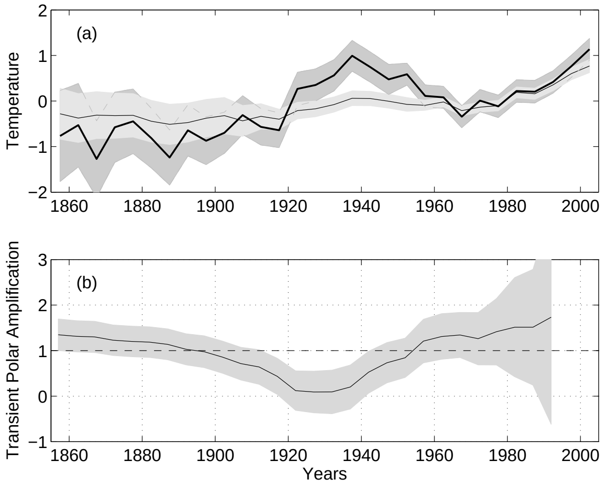

Figure 1. 5-yr means (pentads) of Arctic (heavy line) and northern hemisphere (light line) annual surface air temperature anomalies from land stations (a) and TPA (b), which is the ratio of trends (from a least-squares linear fit) of the timeseries in (a) where the year on the horizontal axis is the first year in the trend period and the final year is always 2004. Anomalies are computed relative to 1961-1990. The shading in (a) indicates the uncertainty due to sampling error, estimated by subsampling a global climate model (CCSM3, see section 3) at station locations and comparing to the mean over all land points in the model. The sampling error includes systematic (error in capturing trends estimated from an ensemble of historical runs) and random (error in capturing internal variability estimated from a long control run) components. The shading in (b) represents uncertainty from the sampling error plus variability in the timeseries. All uncertainties are estimated from the 95% confidence interval. See auxiliary materials for an expanded description of uncertainty estimates.

timeseries changes in time — specifically they have few ice/ocean points prior to 1979 and an uneven number of land stations throughout the period. The ACIA report concluded the 20th century possibly exhibited polar amplification by comparing trends for Arctic land-stations compared to land and ocean for the whole northern hemisphere. Here we compare trends over like-surface (land only) with four additional years of data in the 21st century. In addition, we extend our analysis back in time to 1855 and carefully assess the sampling error to account for uneven data coverage. For the Arctic, we use 59 stations north of 64N, supplied by *Overland et al.* [2004] and selected for their approximately uniform coverage in space and time. For the whole northern hemisphere, we use the University of East Anglia gridded dataset with variance correction [see *Jones et al.*, 2001].

Figure 1 shows the timeseries of Arctic and northern hemisphere surface air temperature and transient polar amplification (TPA). TPA is the ratio of trends from the temperature timeseries where the year on the horizontal axis denotes the first year that was used to compute the trend, and the final year is always fixed at 2004. By construction, the time interval always includes the most recent past, which has the largest anthropogenic greenhouse gas concentration. If TPA were significantly greater than one, the most recent time it occurred would indicate when observations are first needed to detect significantly amplified Arctic warming by 2004.

The anomalously warm period from about 1930–1950 [see e.g., *Overland et al.*, 2004] is clearly above our estimate of the sampling error in the station data. Outside of this early 20th century warm period, TPA in Fig. 1b approximately asymptotes to 1.3. However, because of the large uncertainty, TPA is never significantly greater than one. Next we examine surface air temperature in climate models to see if models also lack significant TPA in the past.

3. Modeled Transient Polar Amplification

We present results from two very different climate models, both global coupled atmosphere, ocean, sea ice, and land models. The first is the Community Climate System Model Version 3 (CCSM3), which incorporates state-of-the-art-physics at relatively high resolution. The second is a so-called intermediate complexity model called ECBILT-CLIO-VECODE (ECV). This model is much simpler that CCSM3, so it may be run many times to obtain good statistics. See auxiliary materials for an expanded description of the models.

ECV and CCSM3 have higher equilibrium polar amplification (EPA, i.e., the equilibrium surface warming in the Arctic divided by the northern hemisphere) than all other climate model archived at PCMDI for IPCC AR4 (not shown). EPA is estimated by doubling CO_2 and running to equilibrium with a full-depth ocean in ECV but only a slab ocean in CCSM3. EPA over land surfaces only in ECV is 1.7 and CCSM3 is 1.6.

For each model, we analyze (i) historical simulations with time-varying forcing reconstructed from observations and proxy data and (ii) control simulations with annually periodic forcing. For CCSM3, we have a nine-member historical and future ensemble for 1870–2100 and a 500-yr long control. For ECV, we have a ninety-member historical ensemble for 1000–1999 and a 1000-yr long control. Time-varying forcing in the historical runs include greenhouse gases (CO_2, CH_4, N_2, Halocarbons), the direct effect of sulfate emissions, solar and volcanic variability, ozone, and aerosols. Beyond year 1999, CCSM3 was forced with the SRES A1B scenario. Forcing and model climatologies are described for CCSM3 by *Meehl et al.* [2005] and ECV by *Goosse et al.* [2005].

Figure 2 shows the timeseries of Arctic and northern hemisphere surface air temperature averaged over land-only surfaces in CCSM3 and ECV with uncertainty derived from the distribution of temperature anomalies in their respective long control runs (i.e., the spread of

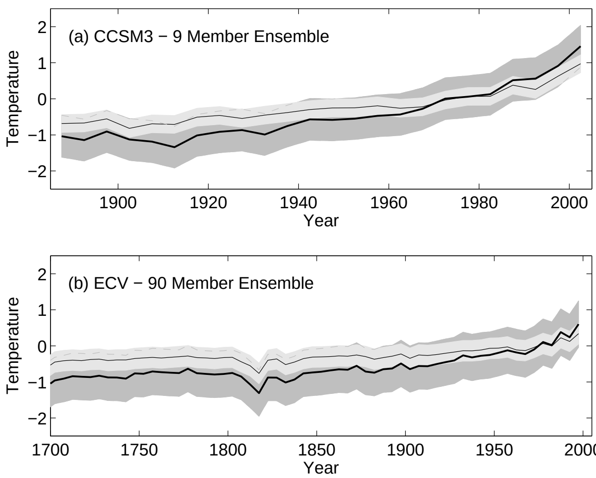

Figure 2. Timeseries of pentads for the Arctic (heavy line) and northern hemisphere (light line) surface air temperature anomalies averaged over land-only surfaces for 1885-2004 from CCSM3 (a) and for 1700–1999 from ECV (b). Shading is the uncertainty resulting from internal variability of a single realization (95% confidence interval) estimated from the long control runs. Hence timeseries from a very large number of runs should lie in this range roughly 95% of the time. Anomaly reference period as in Fig. 1.

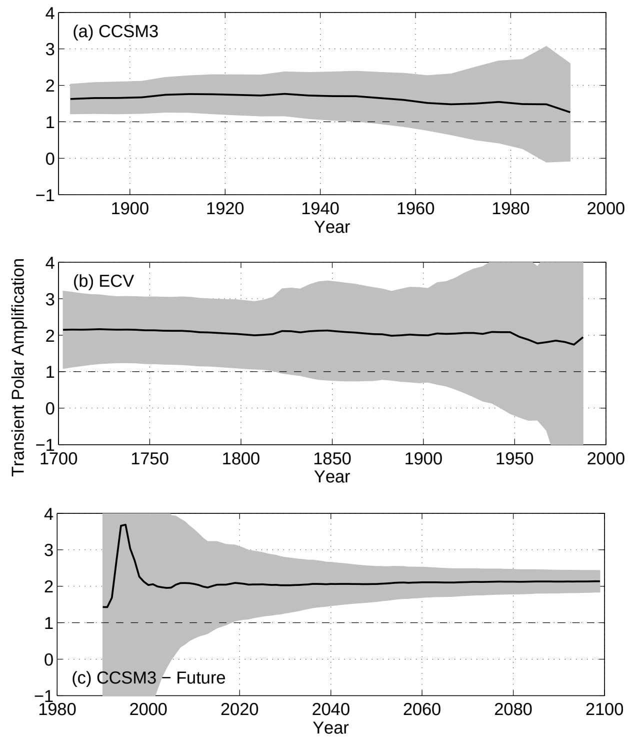

Figure 3. TPA of land-only surface air temperature from the historical runs in Fig. 2 of CCSM3 (a) and ECV (b). TPA in c is from historical and future scenarios from CCSM3 and is averaged over mixed surfaces. Shaded is an estimate of the uncertainty resulting from internal variability of a single realization at the 95% confidence interval. Internal variability is estimated by computing trends in segments of the long control simulations for each model. Uncertainty in c also includes measurement error, which is assumed to be 0.2°C for the Arctic and 0.1°C for the northern hemisphere (the results are not very sensitive to their precise value).

an idealized large ensemble). The uncertainty in ECV spans at least 95% of the observed pentads. In contrast, CCSM3 has only one sustained warm anomaly of a similar magnitude to the early century warming in its 500 yr control, which is too infrequent to give sufficient uncertainty in CCSM3 to span the observed early 20th century warm period.

The warming trends are larger for the ensemble mean in CCSM3 than in ECV for both Arctic and northern hemisphere averages (see Table 1). ECV is consistent with the observations for both time intervals in Table 1. Even when we take into account the uncertainty, trends in CCSM3 are too large since 1900 by at least 0.15°C per century for the northern hemisphere and 0.62°C per century for the Arctic and since 1950 by at least 0.04°C per century in the Arctic.

Figure 3a and b show TPA for land-only surfaces in the models using the timeseries from Fig. 2. The magnitude of the ensemble mean (heavy lines) ranges from 1.2 to 1.8 for CCSM3 and 1.8 to 2.2 for ECV. The uncertainty in TPA (shaded area) indicates the range of TPA expected for individual realizations. Although TPA of the ensemble mean in the models tends to be higher than the observed TPA (Fig. 1b and Table 1), observations are statistically consistent with single realizations from either model for the last half of the 20th century. ECV has higher TPA than CCSM3, but, because of its high variability, the uncertainty of TPA in ECV spans the observations for the entire period that we considered. Because of too little internal variability and/or too large TPA, CCSM3 is not able to reproduce the observed low TPA in the early century.

Table 1. Land-only surface air temperature trends in °C per century and TPA with uncertainties as in Figs. 1–3.

	Observations 1900–2004	CCSM3 1900–2004	ECV 1900–1999
Arctic	0.70 ± 0.27	2.27 ± 0.68	1.03 ± 0.45
NH	0.82 ± 0.14	1.36 ± 0.25	0.52 ± 0.24
TPA	0.86 ± 0.35	1.67 ± 0.44	2.00 ± 1.29
	Observations 1950–2004	CCSM3 1950–2004	ECV 1950–1999
Arctic	1.40 ± 0.67	3.73 ± 1.62	1.62 ± 1.26
NH	1.66 ± 0.32	2.19 ± 0.69	0.83 ± 0.68
TPA	0.84 ± 0.43	1.65 ± 0.70	1.96 ± 2.21

4. Estimate of future transient polar amplification

How much longer will it take before observations can distinguish significantly amplified Arctic warming? Model scenarios of the future can help answer this question using a method similar to that shown in Fig. 3a and b, except TPA is computed for a time interval with a fixed initial date and a variable final date. Because the ratio of TPA to internal variability is biased high in CCSM3 compare to observations, estimates of the earliest date when TPA is significant in CCSM3 should be viewed as a lower limit.

The results presented so far were over land-only surfaces. From the ensemble mean of the models, we find TPA averaged over mixed (land, ocean, and sea ice) surfaces is about 40% higher than over land-only surfaces. Yet the uncertainty over mixed surfaces is not comparably larger, so TPA in the models is significantly greater than one in shorter time intervals when averaged over mixed surface than over land-only surfaces. Therefore we begin our trend analysis using the earliest date when good coverage of surface air temperature is available from satellites and buoys over sea ice, as well as ocean and land surfaces, which we take as 1980. Based on historical and future scenarios from CCSM3 averaged over mixed surfaces, Fig. 3c indicates the earliest date when TPA will be significantly greater than one is the year 2020.

5. Conclusions

Observations can only provide a measure of the transient polar amplification, which is considerably influenced by internal variability, surface type, and the magnitude of the climate forcing. Long-term observations are mostly from land station. According to our results, using temperature from models over mixed surface would lead to an overestimation of TPA by 40% compared to land-only estimates. Thus a meaningful comparison between models and observation should compare surface temperatures for the same period of time over the same surface type.

Our results confirm previous analysis that observed temperature records in the Arctic and northern hemisphere are too short to detect significant TPA (i.e., TPA>1). For the observational period 1855-2004, TPA=1.0 $\pm$ 0.5 from land-only stations. The two models, CCSM3 and ECV, used in this study are in statistical agreement with the lack of significant TPA over land in observations for the second half of the 20th century, in spite of high equilibrium polar amplification in these models. According to ECV, reliable observations from at least the beginning of the 19th century are needed to detect significant TPA. Alternatively, CCSM3 indicates that TPA should be significant already using observations since about 1945. This discrepancy with the observations stems from too little internal variability and/or too high TPA in CCSM3, or possibly warming like that which occurred from 1930–1950 is indeed very rare — outside the 95% frequency interval for internal variability.

Future climate scenarios from CCSM3 were used to estimate when TPA is significantly greater than one in the model. Because the ratio of TPA to internal variability is biased high in CCSM3, the estimate should be viewed as the earliest possible date when observations could yield significant TPA. Assuming good data are available averaged over sea ice, ocean, and land in the Arctic beginning in 1980, we predict significantly amplified warming in the Arctic will not be detected until at least 2020.

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Auxiliary Materials

Description of Uncertainty Estimates

The uncertainty in the timeseries in Fig 1a is from uneven data coverage (i.e., sampling error), taken as the sum of random (error in capturing internal variability) and systematic (error in capturing trends) errors. Instrumental error is assumed negligible by comparison. The sampling error is estimate with the assistance of CCSM3. "Pseudo-timeseries" [after *von Storch et al.*, 2004] are constructed by subsampling surface temperatures at model gridpoints that are closest to non-missing gridcells in the Jones et al. data (or Arctic station locations) in the observations and then averaging the reduced set of points over the northern hemisphere (or Arctic). Finally we subtract averages over a complete set of land gridpoints in a given region from the pseudo-timeseries to obtain an error.

The random error is derived from the error in pseudo-timeseries constructed from the 500-yr CCSM3 control run. It is estimated in five intervals, 1855–1879, 1880–1919, 1920–1949, 1950-1989, and 1990-2004, by subsampling the model at locations where no more than 5% of the monthly observations are missing in a given time period. The random error for each period is 1.96 times the standard deviation (for the 95% confidence interval) of the error binned into pentads.

The systematic error is derived from the error in pseudo-timeseries constructed from CCSM3's nine historical runs (see example in Fig. A). This gives a measure of the systematic error in CCSM3 that would result if the model's surface temperature was sampled unevenly, like the observations. We estimate that the systematic error of the observed timeseries has the same magnitude, but could have the opposite sign. CCSM3 historical runs begin in 1870, so we extrapolate the error back in time using a 4 degree polynomial fit to obtain estimates back to 1855.

The uncertainty in the observed trends is computed from adding in quadrature the sampling error and the uncertainty from natural variability (1.96 times the standard deviation of the timeseries in Fig. 1a). The uncertainty in TPA derives from the uncertainty in the trends for the Arctic and the northern hemisphere timeseries and accounts for covariance between the two regions.

Description of Climate Models

CCSM3 and ECV are both global coupled atmosphere, ocean, sea ice, and land model. CCSM3 has an atmosphere component with spectral triangular truncation at wavenumber 85 (T85), which is equivalent to 1.4° in the horizontal (for land as well). The atmosphere has 26 vertical levels. The ocean and sea ice have zonal resolution of 1.125° and the meridional resolution of 0.54°, except in the subtropics and tropics where the resolution is finer. CCSM3 is well documented and may be downloaded freely from http://www.ccsm.ucar.edu .

ECV has a quasi-geostrophic atmosphere component with T21 horizontal resolution and 3 vertical levels. The ocean component is based on the primitive equations and has 3° resolution. The sea ice component includes thermodynamics and dynamics on the same grid as the ocean. More information about the model and a list of references is available at http://www.knmi.nl/onderzk/CKO/ecbilt-papers.html.

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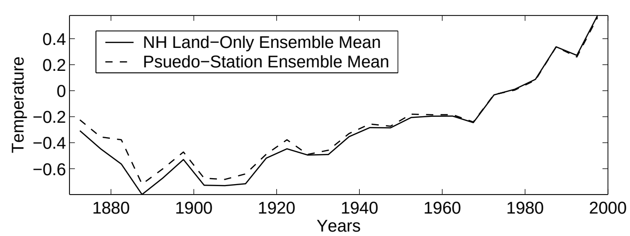

Figure A. (Auxiliary Figure) Pseudo-timeseries from subsampling and timeseries from complete sampling for northern hemisphere in CCSM3. The anomalies were computed relative to the 1961-1990 mean, so the error is zero on average during this time interval.