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Observationally based assessment of polar amplification of global warming

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[1] Arctic variability is dominated by multi-decadal fluctuations. Incomplete sampling of these fluctuations results in highly variable arctic surface-air temperature (SAT) trends. Modulated by multi-decadal variability, SAT trends are often amplified relative to northern-hemispheric trends, but over the 125-year record we identify periods when arctic SAT trends were smaller or of opposite sign than northern-hemispheric trends. Arctic and northern-hemispheric air-temperature trends during the 20th century (when multi-decadal variablity had little net effect on computed trends) are similar, and do not support the predicted polar amplification of global warming. The possible moderating role of sea ice cannot be conclusively identified with existing data. If long-term trends are accepted as a valid measure of climate change, then the SAT and ice data do not support the proposed polar amplification of global warming. Intrinsic arctic variability obscures long-term changes, limiting our ability to identify complex feedbacks in the arctic climate system. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309).
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1. Introduction

[2] An analysis of observational records shows that global SAT has increased by 0.6°C since 1861, with a slightly greater rate of warming in the 20th century [*Jones et al.*, 1999]. During that period, the 1990s were the warmest decade in the Northern Hemisphere. This warming was associated with an increase in land-surface precipitation rate, a decrease in snow cover and sea-ice extent, sea-level rise, and changes in atmospheric and oceanic circulation patterns [*IPCC*, 1996]. Positive feedbacks are believed to lead to enhanced high-latitude warming, as shown by analysis of observed SAT [*Vinnikov et al.*, 1980] and as predicted by general circulation models (GCMs). For example, in the ice-albedo feedback mechanism, warming leads to a reduction of ice and snow coverage, decreasing albedo, and resulting in further snow and sea ice retreat. Based on the polar amplification concept, one would consider high latitudes to be the area where global warming should be most pronounced.

[3] However, identification of enhanced high-latitude warming is complicated by strong intrinsic variability, dominated by multidecadal fluctuations with a timescale of 60–80 years. This low-frequency variability in various climatically important parameters (dubbed "LFO" or "low-frequency oscillation" [*Polyakov and Johnson*, 2000]) is evident in many instrumental records from the Northern Hemisphere (*Delworth and Mann* [2000] for references therein) and the Arctic [*Polyakov et al.*, 2002a, 2002b]. The LFO may obscure possible long-term tendencies in the arctic climate system.

[4] The focus of this research is to assess the concept of polar amplification of global warming via analysis of trends in the SAT records. However, we will not attempt to divine the causes for the trends and fluctuations evident in the data. We make use of newly available long-term Russian observations of SAT from coastal stations, and sea-ice extent and fast-ice thickness from the Kara, Laptev, East Siberian, and Chukchi seas, which offer the possibility for new insights into trends and variability in the arctic environment.

2. Data

[5] A detailed description of the data used in this study is found in *Polyakov et al.* [2002a, 2002b]. Monthly surface-air temperature data sets contain measurements from land stations, Russian drifting stations, and drifting buoys obtained from the International Arctic Buoy Programme (IABP), consolidating several databases (Figure 1). The Arctic and Antarctic Research Institute produced an extensive archive of SAT observations at Russian land stations. The EOS Distributed Active Archive Center at the National Snow and Ice Data Center (NSIDC), University of Colorado, Boulder, Meteorological Service of Canada, and NASA Goddard Institute for Space Studies provided monthly air temperatures for Europe, Greenland, the Canadian Northwest Territories, and Alaska. The National Climatic Data Center database updated the records for the latter datasets to the end of 2000–beginning of 2001. SAT data from Russian drifting stations are available on CD-ROM from the NSIDC. Monthly gridded drifting-buoy data for 1979–98 were obtained from the Polar Science Center of the University of Washington. Spatial coverage is relatively uniform except at the end of the 19th century, when only a few time records (mostly from Scandinavia) are available (Figures 1 and 2). Fortunately, this geographical bias in the early part of the composite SAT time series is relatively small (compare blue and light green lines in Figure 2). Note also that computed trends are somewhat sensitive to the

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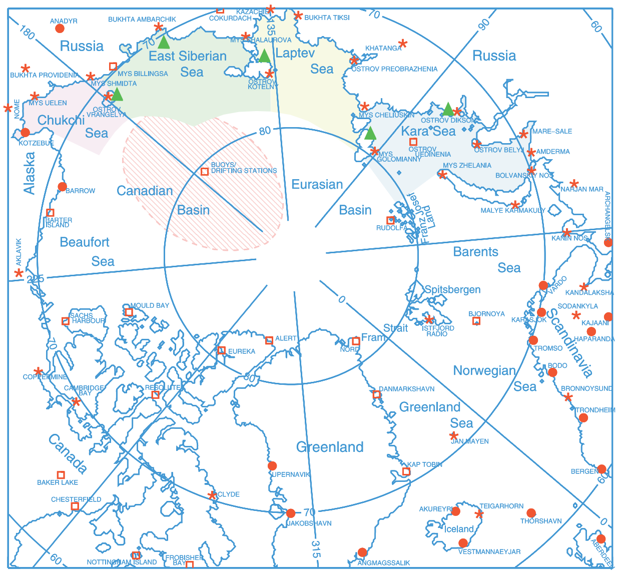

Figure 1. Locations of surface-air temperature and ice observations. Red circles show stations with length of observations L ≥ 100 years, red stars represent stations with 65 ≤ L < 100, and red squares indicate stations with L < 65. The red cross-hatched oval denotes the region represented by data from the manned drifting stations and IABP drifting buoys. Colors denote regions used for analysis of observed ice extent. Green triangles denote stations where the fast-ice thickness data were collected.

reference period used for calculation of anomalies. Following *Jones et al.* [1999], data from each station were reduced to monthly anomalies relative to 1961–90.

[6] Russian historical records of arctic sea-ice extent and thickness extend back to the beginning of the 20th century. In this study, we use August ice extent for the four arctic marginal seas (the regions where the data were collected are denoted by color in Figure 1). Five locations where measurements of fast-ice thickness (motionless sea ice anchored to the sea floor and/or the shore) extending back to 1936 were made are shown in Figure 1 by triangles. Measurements of fast-ice thickness are particularly valuable because they provide an opportunity to separate, to some extent, the contribution of thermodynamical and dynamical factors to the formation of arctic ice, since they measure "pure" thermodynamical ice growth. While these data may have substantial errors, they are unique and important in indicating changes in the arctic environment since the dawn of the industrial era.

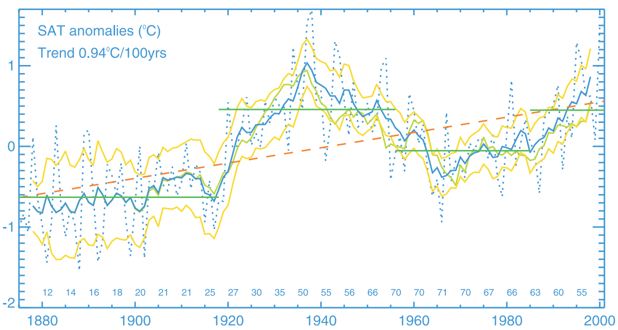

Figure 2. Composite time series of surface air temperature anomalies (°C) relative to 1961–90 for the region poleward of 62°N. The plot displays the annual means (dashed blue), six-year running means (solid blue), 95% significance level (yellow), trend (dashed red), means for positive and negative LFO phases (horizontal green), and six-year running means using the 24 longest (century plus) records. Numbers at the bottom of the panel denote the number of stations used for averaging.

3. Air Temperature Analysis

[7] Composite time series of air-temperature anomalies for the Arctic and sub-Arctic region northward of 62°N are shown in Figure 2. LFO dominates SAT fluctuations, with two distinct warming periods (in the 1920–50s and from the mid-1970s to the present) and two cooling periods (prior to the 1920s and in the 1960–70s). Arctic warming in the 1930–40s was exceptionally strong, reaching 1.7°C, compared with the 2000 maximum of 1.5°C. The multidecadal LFO is stronger in the Arctic than in the Northern Hemisphere (compare Figure 2 from this study and Figure 2 from [*Jones et al.*, 1999]). This may be attributed to the proximity of the Arctic to the North Atlantic, believed to be the origin of the LFO [e.g., *Delworth and Mann*, 2000].

[8] Strong multidecadal variability results in oscillatory SAT trends (Figure 3, green). For example, during the previous 60 years (since the 1940s) arctic SAT trends are positive and are very large in the 1990s. However, arctic temperatures in the 1930–40s were exceptionally high, so that from the 1920s forward the data show a small but statistically significant cooling tendency. Extending the time series further back into the nineteenth century, the temperature trend again changes sign, signifying a general warming tendency over the entire record. Moreover, over the 125-year record we can identify periods when arctic trends were actually smaller or of different sign than Northern Hemisphere trends calculated using *Jones et al.* [1999] SAT data (Figure 3, red). This analysis underscores the inherent difficulty in differentiating between trends and long-term fluctuations. Computed arctic SAT trends depend on the phases and intensity of the LFO in addition to any underlying trend, whereas Northern Hemisphere trends do not

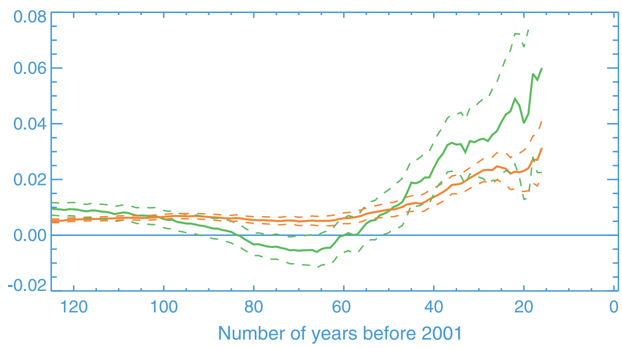

Figure 3. Arctic (green) and northern-hemispheric ([*Jones et al.*, 1999], red) SAT trends (°C/year) (solid lines) and their 95% significance levels (dashed lines) computed from SAT time series, ranging from a 17 year (1985–2001) to the full record length (1875–2001), with 1 year increments.

Table 1. Trends of Air Temperature (°C/decade) from Various Sources

Source	Region	Period	Trend	Trend from this study
Vinnikov et al. [1980]	17.5–87.5°N	1891–1978	+0.04	
	72.5–87.5°N	1891–1978	+0.07	+0.09 ± 0.05
Chapman and Walsh [1993]	Land stations	1961–1990	+0.19	+0.17 ± 0.18
Kahl et al. [1993]	Arctic Ocean	1950–1990	−0.37	−0.05 ± 0.13
Martin et al. [1997]	Central Arctic Ocean	1961–1990	+0.14	+0.17 ± 0.18
Jones et al. [1999]	Northern Hemisphere	1861–1997	+0.04	
	Northern Hemisphere	1901–1997	+0.06	+0.05 ± 0.04
Rigor et al. [2000]	Eastern Arctic Ocean	1979–1997	+1.00	
	Western Arctic Ocean	1979–1997	+0.00	
Present study	Poleward of 62°N	1875–2001	+0.09 ± 0.03	

show such a strong dependence on the LFO. Because the LFO is stronger there, it is reasonable to expect a stronger LFO-driven modulation of trends in higher latitudes.

[9] Comparing SAT trends for 1901–97 (potentially years with the most pronounced human impact) the difference between the *Jones et al.* [1999] northern hemisphere data and arctic data is only 0.01°C/decade, a statistically indistinguishable 20% difference (Table 1). The similarity of arctic and Northern Hemisphere air-temperature trends for this period may result from near-cancellation of positive/negative LFO phases and does not support amplified warming in polar regions predicted by GCMs [*IPCC*, 1996]. *Przybylak* [2000], analyzing arctic SAT, also underlined this inconsistency. The apparent lack of amplification in the century-long arctic SAT time series may be due to the moderating role of sea ice. Extending our SAT time series by 25 years back to 1875 (years associated with an extended and cold negative LFO phase) leads to a two-fold increase of the arctic trend compared with the Northern Hemispheric trend (Table 1, Figure 3). While this appears consistent with polar amplification, we believe it is more appropriately described as a statistical artefact resulting from biased sampling of the LFO. In an analysis of long-term air temperature changes *Vinnikov et al.* [1980] used gridded northern-hemispheric SAT for 1891–1978, the first half of which was dominated by the negative, cold LFO phase prior to the 1920s, and the second by the positive, warm LFO phase of the 1930–40s. Averaging these data within zonal bands they also found a two-fold polar amplification of SAT trends (Table 1).

[10] Trends in Arctic SAT for recent decades have been discussed in several studies, and vary from −0.37 to +0.19°C/decade (Table 1). *Chapman and Walsh* [1993] and *Martin et al.* [1997] estimates are relatively close, showing warming trends of 0.19 and 0.14°C/decade, respectively, and are consistent with our trend of 0.17 ± 0.18°C/decade, calculated for the same period of time. *Kahl et al.* [1993] analyzed temperatures measured over the central Arctic Ocean in the 1950–90s, and detected strong cooling trends. We find negative SAT trends in our record for the period 1950–90 as well (see Table 1). The above inconsistencies in arctic SAT trends may be explained in the context of the mid-1960s shift from negative to positive LFO phase.

4. Ice Extent and Fast-Ice Thickness Analysis

[11] The ice-extent time series display a combination of decadal and multidecadal variability, with lower values prior to the 1920s, in the late 1930s–40s, and in recent decades, and higher values in the 1920s–early 1930s, and in the 1960–70s (Figure 4, left). This is consistent with multi-year variability (LFO) evident in SAT records (Figure 2) and ice variability in the Barents Sea [*Vinje*, 2002]. In the entire Siberian marginal ice zone the century-long trend of ice extent is only −0.5 ± 0.7% per decade (percentages are relative to total surface area). In the Kara, Laptev, East Siberian, and Chukchi seas ice extent trends are not substantial either: −1.1 ± 1.2, −0.4 ± 1.2, 0.3 ± 1.0, and −1.0 ± 0.9% per decade, respectively. Statistical analysis based on the bootstrap technique shows that these trends, except for the small area of the Chukchi Sea, are not statistically significant. Trends for recent decades seem to be larger [e.g., *Parkinson et al.*, 1999], but because of the fewer degrees of freedom in these shorter time records they are not statistically significant either.

[12] Ice dynamics makes detection of climate change using ice data most difficult. The simplest effect of warming may be seen in the thinning of fast ice. Figure 4, right shows five 65-year-long time series of fast-ice thickness measurements from the four arctic marginal seas. Consistent with variations of arctic SAT and ice extent, fast-ice thickness variability is modulated by multidecadal LFO and decadal fluctuations. The fast-ice records do not show any steady tendency: their trends are relatively small, positive or negative in sign at different locations, and not statistically significant at the 95% level. This appears inconsistent with a hypothesis that sea ice has moderated arctic SAT in the last century, reducing atmospheric warming through ice melt [*Vinje*, 2001]. This hypothesis is based on the observation that 20th century SAT trends in the maritime Arctic and Northern Hemisphere are similar, whereas GCMs predict a two-fold polar amplification. This amplification implies a 0.1°C/decade arctic SAT trend, half of which (0.05°C/decade), one might assume, went toward ice decline. Thus, if the hypothesis of the ice-moderating role is correct, warming in the Arctic may have been reduced by 0.5°C over the last century due to ice melt (in other words, because of ice reduction, 2000 may have been 0.5°C colder than it would otherwise have been). To evaluate the fast-ice thickness change required to compensate this SAT increase, we used an empirical formula which relates freezing rate to the number of "freezing degree-days" [*Zubov*, 1943]. This formula has been widely used in Russian arctic research and its thermodynamical justification is presented by *Doronin* [1971]. According to Zubov's formula, a SAT increase of 0.5°C for each month over the freezing period (October–May) would yield a 2.5 cm decrease in maximum ice thickness in 2000 compared with 1901, or a downward trend of fast-ice thickness of 0.25 cm/decade. This trend is statisti-

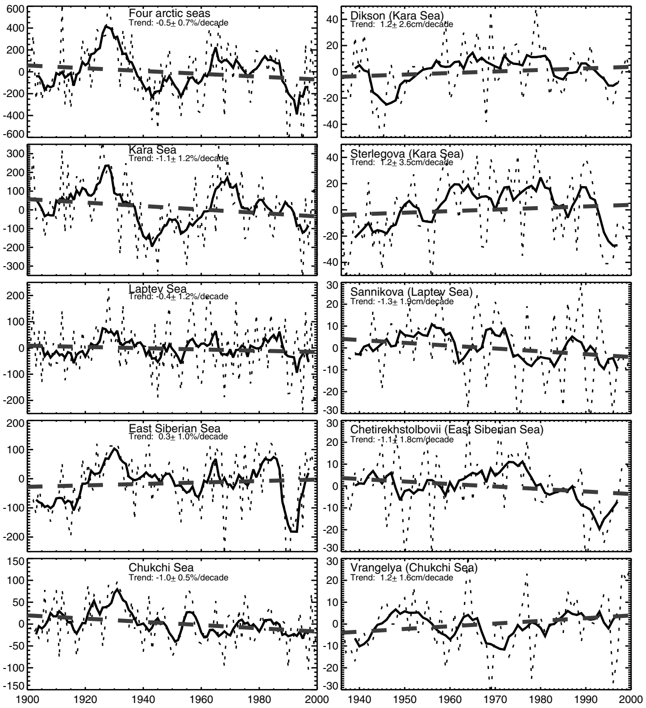

Figure 4. (Left) Time series of August ice-extent anomalies ($\times 1000$ km^2) in four arctic seas. (Right) Time series of annual maximum fast-ice thickness anomalies (cm) at five locations. The plot shows annual means (dotted), six-year running means (solid), and linear trends at the quoted 95% level (dashed).

cally indistinguishable from zero, implying we cannot conclusively identify the moderating role of sea ice in polar amplification of global warming from existing ice-thickness time series. Therefore, the proposed moderation of high-latitude warming by sea-ice may be an untestable hypothesis.

5. Conclusions

[13] We examine arctic variability using long-term records of SAT from the maritime Arctic poleward of 62°N, fast-ice thickness from five locations off the Siberian coast, and ice extent in arctic marginal seas. Arctic atmosphere and ice variability is dominated by multi-decadal variability, which is exceptionally strong in the northern polar region, probably because of its proximity to the North Atlantic, which is believed to be the origin of the LFO. The highly variable behavior of arctic trends results from incomplete sampling of large-amplitude multidecadal fluctuations. Trends for LFO-modulated arctic air-temperatures are generally larger than northern-hemispheric trends, but over the 125 year record we can identify periods when arctic SAT trends were actually smaller or of different sign than northern-hemispheric trends. Arctic and northern-hemispheric air-temperature trends over the 20th century, when multidecadal variability had little net effect on computed trends, are similar and do not support the hypothesis of the polar amplification of global warming simulated by GCMs. It has been hypothesized that this may be due to the moderating role of arctic ice. Evaluation of fast-ice melt required to compensate for the two-fold enhancement of polar warming simulated by GCMs shows that the required ice-decay rate would be statistically indistinguishable from zero, given the substantial intrinsic variability observed in the data. Observed long-term trends in arctic air temperature and ice cover are actually smaller than expected, and may be indicative of complex positive and negative feedbacks in the arctic climate system. In summary, if we accept that long-term SAT trends are a reasonable measure of climate change, then we conclude that the data do not support the hypothesized polar amplification of global warming.

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