Early 20th-century Arctic warming intensified by Pacific and Atlantic multidecadal variability

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With amplified warming and record sea ice loss, the Arctic is the canary of global warming. The historical Arctic warming is poorly understood, limiting our confidence in model projections. Specifically, Arctic surface air temperature increased rapidly over the early 20th century, at rates comparable to those of recent decades despite much weaker greenhouse gas forcing. Here, we show that the concurrent phase shift of Pacific and Atlantic interdecadal variability modes is the major driver for the rapid early 20th-century Arctic warming. Atmospheric model simulations successfully reproduce the early Arctic warming when the interdecadal variability of sea surface temperature (SST) is properly prescribed. The early 20th-century Arctic warming is associated with positive SST anomalies over the tropical and North Atlantic and a Pacific SST pattern reminiscent of the positive phase of the Pacific decadal oscillation. Atmospheric circulation changes are important for the early 20th-century Arctic warming. The equatorial Pacific warming deepens the Aleutian low, advecting warm air into the North American Arctic. The extratropical North Atlantic and North Pacific SST warming strengthens surface westerly winds over northern Eurasia, intensifying the warming there. Coupled ocean–atmosphere simulations support the constructive intensification of Arctic warming by a concurrent, negative-to-positive phase shift of the Pacific and Atlantic interdecadal modes. Our results aid attributing the historical Arctic warming and thereby constrain the amplified warming projected for this important region.

early 20th-century Arctic warming | Pacific decadal variability | Atlantic multidecadal variability | ocean–atmosphere interaction | climate variability

The Arctic has warmed faster than the global average by a factor of 2 or more since the mid-20th century, a phenomenon known as the Arctic amplification. The recent temperature warming over the Arctic is strongly linked to a drastic reduction in sea ice extent since the 1970s, contributing to the Arctic amplification through positive ice–albedo feedbacks (1–3). A similar rapid warming occurred in the Arctic during the early 20th century (4–8). Compared with the recent warming, the early 20th-century Arctic warming (hereafter referred to as the early Arctic warming) is mysterious as greenhouse gas (GHG) radiative forcing was three to four times weaker than at present (9) and changes in sea ice extent were small (10). The comparison of these two warming epochs suggests that mechanisms other than GHG forcing are important for the early Arctic warming.

Several hypotheses have been proposed for the early Arctic warming, including intensified natural forcing due to decreased volcanic aerosols and increased solar radiation (11, 12); increased cloud long-wave emissivity due to sulfate aerosols transported from Central Europe (6, 13); uncertain but possible reduction in the Arctic sea ice extent (4, 5, 14); variability of the North Atlantic ocean–ice–atmosphere system (15); and atmospheric internal variability (16). Neither coupled ocean–atmosphere models nor atmospheric models driven by historical radiative forcing and observed sea surface temperature (SST)/sea ice are yet able to simulate the observed early Arctic warming (5, 14, 16, 17), hampering the study of this important phenomenon. Overlooked is the possibility that interdecadal SST variations may be underestimated in reconstructed datasets (18), especially before 1950 when observations

were sparse. In other words, the contribution of oceanic variability to the early Arctic warming could have been underestimated. We show that it is indeed the case; atmospheric model simulations capture the early 20th-century Arctic warming when interdecadal SST variations are properly prescribed. Our objective is to investigate the influence of oceanic internal variability on the early Arctic warming, with a particular focus on the Pacific and Atlantic interdecadal variability, and atmospheric circulations.

Results

Observed and Simulated Arctic Warming During the Early 20th Century. The Pacific decadal variability (PDV) and Atlantic multidecadal variability (AMV) are characterized by warm and cold anomalies of the Pacific and North Atlantic SST. Their dominant patterns are known as the Pacific Decadal Oscillation (PDO) (19) and Atlantic Multidecadal Oscillation (AMO) (20). We define the PDV index as the principal component of the first empirical orthogonal function (EOF) for detrended SST anomalies over the Pacific (120°E–70°W, 50°S–60°N) by taking account of its extension to the tropical and South Pacific (19, 21). The AMV index is defined as the SST anomaly averaged over the North Atlantic (60°W–0°, equator–70°N) (22). Supported by reconstructed SSTs and climate proxies (23–27), these two interdecadal modes shifted from the cold to warm phase about the same time in the mid-1920s, in sync with the Arctic warming (Fig. S1). This concurrent shift provides a unique opportunity to explore the combined influence of PDV and AMV on the Arctic climate. This section presents 35-y trend patterns for 1908–1942, a period when the Pacific, Atlantic, and Arctic mean land surface air temperature (LSAT) all drastically warmed (Fig. S1).

Significance

Arctic amplification is a robust feature of climate response to global warming, with large impacts on ecosystems and societies. A long-standing mystery is that a pronounced Arctic warming occurred during the early 20th century when the rate of interdecadal change in radiative forcing was much weaker than at present. Here, using observations and model experiments, we show that the combined effect of internally generated Pacific and Atlantic interdecadal variabilities intensified the Arctic land warming in the early 20th century. The synchronized Pacific–Atlantic warming drastically alters planetary-scale atmospheric circulations over the Northern Hemisphere that transport warm air into the Arctic. Our results highlight the importance of regional sea surface temperature changes for Arctic climate and constrain model projections in this important region.

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We first compare SST trend patterns from two different datasets: the European Centre for Medium-Range Weather Forecast 20th-Century Reanalysis (ERA-20C) (28) and the UK Met Office Hadley Centre Sea Ice and SST (HadISST), version 1 (29). The former is also known as the HadISST, version 2.1 (28, 30) (hereafter referred to as HadISST2), which incorporates several million more in situ observations than HadISST1, applies more comprehensive bias adjustments, and uses reconstruction methods that make use of every single observation (30). The HadISST2 trend pattern for 1908–1942 clearly exhibits the cold-to-warm phase shifts of PDO and AMO, with significant warming in the equatorial Pacific, the Bering Sea, the Gulf of Alaska, and the North Atlantic (Fig. 1A). Although the timing of phase shift and basin-scale patterns are similar, HadISST1 does not capture the amplitudes of zonally elongated equatorial Pacific warming and North Atlantic warming (Fig. 1B). Overall, larger warming trends of HadISST2 closely follow the patterns of positive SST anomalies associated with warm PDO and AMO (Fig. S2), contributing to a larger increase in the global mean SST. Furthermore, the HadISST2 trends show a basin-scale weakening of zonal gradient over the equatorial Pacific (130°E–130°W), physically consistent with that of observed sea level pressure (SLP) trends featuring a Walker circulation slowdown (Fig. S3A and B).

We evaluate the contribution by the concurrent phase shift of PDV and AMV modes to the early 20th-century Arctic warming by performing a set of 18-member ensemble experiments using the US National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL) AM2.1 (31) atmospheric general circulation model (AGCM). The model is forced by HadISST2 (HIST2 experiment) and HadISST1 (HIST1 experiment), in which the observed monthly SSTs are prescribed in the global oceans. We also perform the “Tropical Ocean–Global Atmosphere” (HIST2-TOGA) and “no PDV/AMV mode” (HIST2-N) experiments using HadISST2. In the HIST2-TOGA experiments, the observed monthly SSTs are prescribed only in the tropics (20°N–20°S) with climatological SSTs poleward of 30° and linearly blended SSTs over the latitude band 20°–30° in both hemispheres. In the HIST2-N experiments, SST anomalies associated with the PDV and AMV patterns are removed based on the linear regression. Each ensemble member is integrated for 1899–1950 with the same historical radiative forcing and the same monthly sea ice concentration from HadISST2 (32) but begins from a slightly different initial atmospheric condition. The prescribed sea ice extent over the Northern Hemisphere shows no significant trend during the early 20th century (32) but is presumably subject to large uncertainty (4, 5, 14). For this reason, we discuss only SST effects in the present study.

To obtain an observational mean of the Arctic LSAT time series, we use six datasets from the NOAA Merged Land Ocean

Global Surface Temperature (NOAAGlobalTemp), version 4.0.1 (33); the US National Aeronautics and Space Administration/Goddard Institute for Space Studies surface temperature analysis (GISTEMP) with 250-km smoothing (34); the Climatic Research Unit (CRU) Temperature, version 4.4 (CRUTEM4.4) (35); the CRU time series, version 3.23 (CRU-TS v3.23) (36); ERA-20C (28); and the NOAA 20th-Century Reanalysis, version 2c (20CRv2c) (37). We also use the bias-corrected station data of the Global Historical Climatology Network-Monthly, version 3 (GHCN-M) (38), to capture the actual spatial distributions of LSAT trends. Figs. 2 and 3 compare observed and simulated Arctic LSAT trends in boreal winter (November–March), a season when the early Arctic warming was most pronounced (4, 39) (hereafter all figures show the same seasonal mean). The observed early Arctic warming is apparent in all LSAT datasets, with a rapid warming trend during the 1920s (Fig. 2A). Significant warming trends are detected at weather stations north of 60°N (Fig. 3A). Despite no significant trend in the prescribed sea ice extent (32), the HIST2 run successfully reproduces the temporal and spatial variations of the early Arctic warming (Figs. 2B and 3B and C). It captures the seasonality as well, with a maximum warming in boreal winter and minimum in summer (Fig. S4). The HIST1 run also simulates the early Arctic warming within the range of observational uncertainty (Figs. 2C and 3D). However, it underestimates the warming trend with a magnitude 53% weaker than observations (Table S1), consistent with other AGCM simulations forced with earlier SST datasets (5, 14). The HIST2-N run reproduces only 57% of the observed Arctic warming (Fig. S5A and Table S1), suggesting that the intense early Arctic warming cannot be fully explained without the influence of PDV and AMV.

The near-surface atmospheric circulation change is important for the early Arctic warming. Characteristic of the cold-to-warm PDO shift (19, 40, 41), a Pacific/North America (PNA) pattern develops in response to enhanced atmospheric convection over the tropical western to central Pacific (Fig. S6A), with a deepened Aleutian low, increased SLPs over North America, and intensified cyclonic surface winds over the North Pacific (Fig. 3A). Intensified southeasterly winds along the coast of the Gulf of Alaska advect warm air from the Pacific into the North American Arctic. Over the North Atlantic, a northeast–southwest dipole pattern was observed in SLP. These SLP trend patterns are also captured by 20CRv2c with larger amplitudes (Fig. S5B). In the winter climatology, strong temperature gradients are generated between the warmer ice-free North Atlantic and colder adjacent land. Easterly-to-southeasterly wind trends around 60°N enhance warm advection of this climatological temperature gradient, warming Greenland and Iceland. A similar effect works for Eurasian Arctic warming. North of the

Fig. 1. Comparison of November–March mean SST trends for 1908–1942. (A) The UK Met Office Hadley Centre sea ice and SST, version 2 (HadISST2), and (B) version 1 (HadISST1). Stippling indicates trends exceeding the 90% confidence level.

Fig. 3. Observed and simulated trend patterns in LSAT and near-surface atmospheric circulation. Trends of LSAT (filled circles for A, shading for B–D), SLP (contour interval 0.6 hPa per 35 y), and marine surface wind (vectors; in meters per second per 35 y) for 1908–1942, based on (A) observations from GHCN-M (38) and the International Surface Pressure Databank (59)/International Comprehensive Ocean–Atmosphere Data Set (60), and simulations from (B) full HIST2, (C) four-member HIST2, (D) full HIST1, and (E) full HIST2-TOGA ensemble means. (F) HIST2 minus HIST2-TOGA difference. Larger circles in A and stippling in B–F indicate LSAT trends exceeding the 90% confidence level. Positive (negative) SLP trends are indicated by solid (dashed) contours, and zero contours thickened.

the North Atlantic shows signs of ocean-to-atmosphere feedback. The North Atlantic warms despite upward surface heat flux anomalies that occupy much of the extratropical basin (Fig. 4C), suggesting an ocean dynamical origin of the warming (e.g., the intensified Gulf stream and AMOC) (48). This is corroborated by precipitation increases along the Gulf stream to the Barents/Kara

Sea (Fig. 4D). The oceanic forcing presumably intensifies the meridional SLP gradient over northern Eurasia, contributing to the Eurasian Arctic warming.

Fig. 5 shows the November–March mean composite anomalies of Arctic LSAT as a function of the normalized PDV and AMV indices. Strong positive and negative anomalies of Arctic LSAT

Fig. 4. Composite anomalies regressed onto the normalized Arctic mean LSAT anomaly, based on 37 CMIP5 piControl simulations. (A) LSAT (shading; in degrees Celsius) and SLP (contour interval, 0.15 hPa; zero contours thickened, positive solid, and negative dashed), (B) SST (in degrees Celsius), (C) upward latent and sensible heat fluxes (in watts per square meter), and (D) precipitation (in millimeters per month). Stippling indicates the composite regression anomalies exceeding the 95% confidence level.

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