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Tropical Indo-western Pacific forcing expedites warming in the northern Canadian-Greenland Arctic



Shuai-Lei Yao¹✉, Renguang Wu²✉, Pengfei Lin^{1,3}✉, Haosu Tang⁴✉ & Pengfei Wang¹

Since the beginning of modern satellite monitoring around 1980, near-surface and tropospheric temperatures in the northern Canadian-Greenland Arctic have substantially warmed, with magnitudes comparable to those in the pan-Arctic. However, the main causes of this marked regional warming and its magnitude in future projections remain debated because of large inter-model spread across historical and future periods. Here, using a hierarchy of pacemaker experiments in which regional sea surface temperature anomalies are nudged toward observations, we reveal that the tropical Indo-western Pacific (IOWP) forcing amplifies warming in northern Canada and Greenland through the IOWP-Arctic teleconnection. Anomalous tropical IOWP warming remotely triggers enhanced subsidence and reduced total cloud cover, increasing incoming shortwave radiation and, consequently, near-surface and tropospheric temperature warming. Further, by observationally constraining future projected warming magnitudes with recent tropical IOWP warming trends, the upper bounds (95th percentile values) of near-term (2026–2055 minus 1981–2010) warming magnitudes in the northern Canadian-Greenland Arctic and pan-Arctic decrease by ~19.8% and ~18.3%, respectively, under the high-emission scenario. Our results highlight the potential of the tropical IOWP warm pool to enable reliable Arctic warming projections.

Arctic near-surface warming has been almost four times^{1,2} faster than the global average since around 1980, as robustly shown across multiple observations within the varying analyzed periods (1980–2013 or to the present; Supplementary Fig. 1). The alarming warming signal also penetrates throughout the lower-to-upper tropospheric temperature^{3–5} (850–300 hPa; Supplementary Fig. 1). Despite the unprecedented circumpolar Arctic warming, substantial spatial heterogeneity emerges, with remarkable warming covering northern Siberia and the northern Canadian-Greenland Arctic during 1980–2013 (Fig. 1 and Supplementary Fig. 1). The observed near-surface warming in northern Siberia is strongly correlated with the in situ sea-ice retreat, with correlation coefficient of about –0.7 to –0.9 as documented in previous studies³. However, the precise factors governing near-surface and tropospheric warming over northern Canada and Greenland remain unclear because radiative forcing explains only ~40–50% of the observed regional warming magnitudes, as inferred from the Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model historical simulations³. Accurately identifying the major driver of recent pronounced warming in northern Canada and Greenland could provide

important clues for delivering proactive climate and environmental policies in Arctic communities in an overshoot world of warming exceeding 1.5 °C.

Various local positive climate feedbacks have been invoked to explain the pan-Arctic warming. One leading hypothesis highlights the role of surface ice-albedo feedback^{6–12}: sea-ice retreat in boreal summer reflects less incoming solar radiation and promotes greater oceanic heat release, suppressing subsequent cold-season sea-ice expansion and heating the tropospheric atmosphere aloft. Still, diminishing sea ice tends to facilitate more surface warming but less upper-tropospheric warming^{5,6}. Likewise, positive lapse-rate feedback^{13–18} and Planck feedback¹³ via reduced outgoing longwave radiation, water vapor feedback^{10,16,19,20}, and low cloud feedback^{21–26} through increased surface downwelling longwave radiation, effectively trap more warming at the Arctic surface than in the overlying troposphere. Conversely, enhanced moist static energy convergence²⁷ and increased poleward atmospheric heat transport^{4,28–31} into the Arctic promote greater warming in the mid- to upper-troposphere, with largely uniform patterns. Additional radiative processes, such as reduced European sulfate aerosol emissions since 1980 (ref. 32.) and increased Northern Hemisphere boreal

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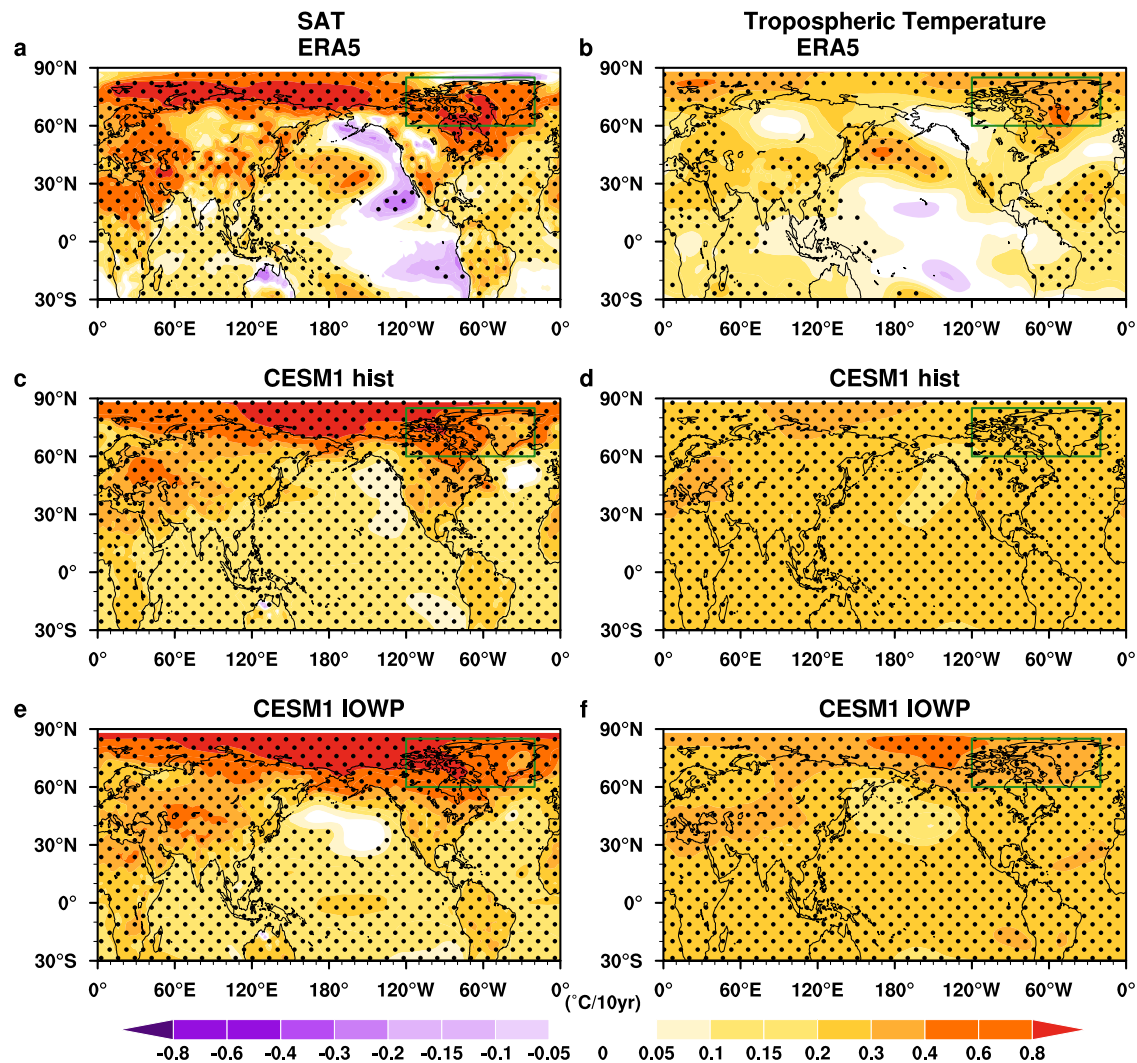


Fig. 1 | Observed and simulated annual-mean near-surface and tropospheric temperature. Linear trends of annual-mean near-surface air temperature (left panel) and tropospheric (300–850 hPa) temperature (right panel) for 1980–2013 are computed from ERA5 (a, b) the 40-member ensemble mean of CESM1 historical simulations (c, d) and the 10-member ensemble mean of tropical Indian Ocean-

western Pacific (IOWP) pacemaker experiments with CESM1 (e, f). Stippling denotes regions where trends are statistically significant at the 95% confidence level according to a two-sided Student's *t* test. Green boxes represent the northern Canada and Greenland sector of the Arctic.

biomass-burning aerosols³³, also contribute to a significant fraction of Arctic surface warming. While these interconnected local climate feedbacks and processes contribute to pan-Arctic warming^{34,35}, they cannot unequivocally account for the stark regional characteristics of Arctic warming, particularly the recent pronounced warming in northern Canada and Greenland.

By comparison, remote sea surface temperature (SST) anomalies play an indispensable role in modulating regional variations in Arctic warming by altering atmospheric and oceanic circulations. Previous studies³ employing an atmospheric-slab ocean model report that tropical Pacific cooling produces recent rapid warming in northeastern Canada and Greenland via Rossby wave-train activity, somewhat contrary to the fact that tropical Pacific cooling partly offsets greenhouse gas-induced warming^{36–38}. Additionally, earlier atmospheric reanalysis diagnostic studies³⁹ link tropical Indo-western Pacific (IOWP) convective heating to pan-Arctic warming via anomalous planetary-scale waves. Moreover, instrumental records⁴⁰, paleoclimate proxy datasets⁴¹, and climate models⁴² indicate that a warm-phase Atlantic Multi-decadal Variability (AMV) may accelerate Arctic warming by adjusting the Atlantic thermohaline circulation on multi-decadal timescales⁴³. Despite these insights, it remains unclear which ocean basin drives rapid warming across northern Canada and Greenland during

1980–2013 (Fig. 1 and Supplementary Fig. 1), largely because of trans-basin interactions^{44–47}.

In addition, current coupled climate models participating in CMIP6 exhibit wide model diversity in simulating warming magnitudes in northern Canada and Greenland for 1980–2013 (Supplementary Fig. 2). Due to, on average, biased higher equilibrium climate sensitivity and transient climate response estimated from CMIP6 than CMIP5 (ref. 48.), large inter-model spreads could persist into future projections of warming magnitudes in northern Canada and Greenland, rendering low confidence in effective preparedness for more severe climate consequences related to a warmer Arctic in an overshoot age of 1.5 °C. Thus, a more faithful understanding of the major drivers of recent Arctic regional warming is vital not only for deciphering inter-model spreads but also for reducing uncertainty in future projections through an observational emergent constraint.

Here, by diagnosing a hierarchy of time-evolving and idealized pacemaker experiments conducted with the same experimental protocol using the Community Earth System Model version 1 (CESM1)⁴⁹, we systematically quantify, in a more realistic fashion, the extent to which SST variability in individual ocean basins drives recent warming in the northern Canadian-Greenland Arctic. In time-evolving pacemaker simulations, SST

anomalies over the tropical IOWP, tropical eastern Pacific, and North Atlantic are nudged separately to observations (see “Methods” and Supplementary Fig. 3). In idealized pacemaker experiments, the Inter-decadal Pacific Oscillation (IPO) and AMV warm-polarity and cold-polarity SST anomalies are individually restored to the observed SST patterns (see “Methods”). The hierarchical pacemaker experimental framework uncovers that the tropical IOWP warm pool drives prominent warming in northern Canada and Greenland through a quasi-stationary Rossby wave train. Importantly, constraining future projections with observed historical tropical IOWP SST warming greatly reduces uncertainty in future projected warming magnitudes in the northern Canadian-Greenland Arctic and even the pan-Arctic under the low-, ambitious-, and high-emission scenarios.

Results

Tropical IOWP dominance

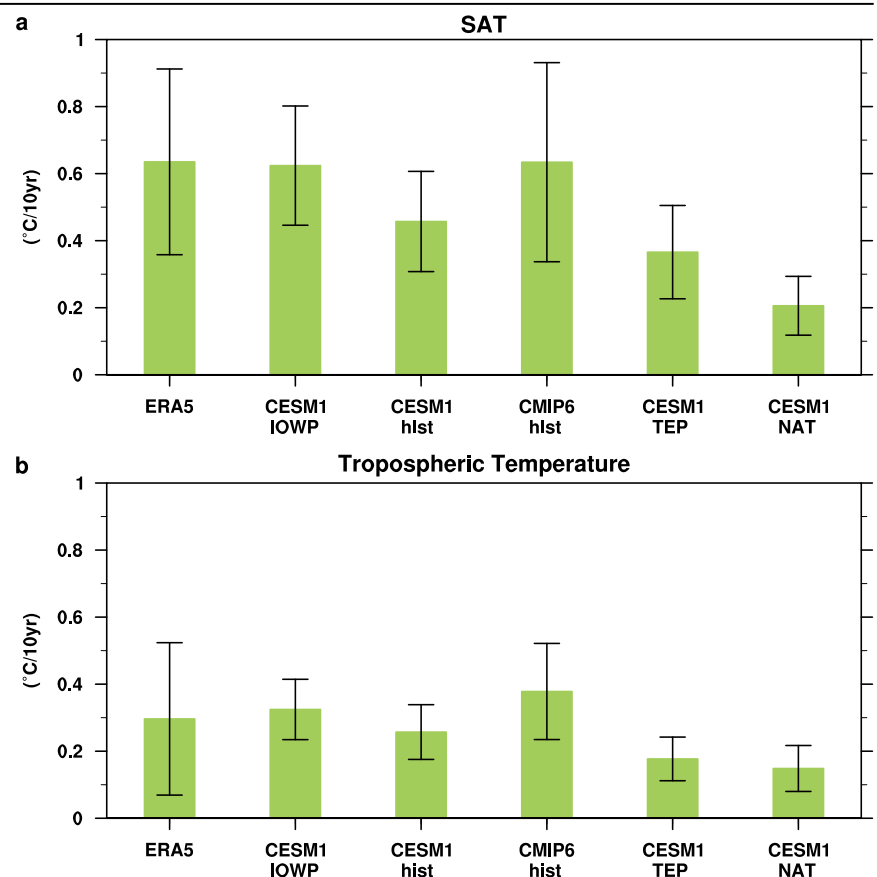
We begin by exploring the role of tropical IOWP SST anomalies in generating warming over northern Canada and Greenland during 1980–2013 using tropical IOWP pacemaker experiments (“Methods”). Tropical IOWP restoring simulations reproduce the observed regional variations in pan-Arctic warming, characterized by salient warming extending from near-surface through the upper troposphere in northern Canada and Greenland (cf. Fig. 1a, b and e, f), though with reduced near-surface warming magnitude across Greenland. Tropical IOWP-forced near-surface and tropospheric temperature warming magnitudes in northern Canada and Greenland are ~ 0.62 °C/10 yr and ~ 0.32 °C/10 yr, closely matching the observed trends of ~ 0.64 °C/10 yr and ~ 0.3 °C/10 yr (see Fig. 2). The tropical IOWP-induced spatially varying warming pattern is fundamentally distinct from the radiatively forced, nearly uniform warming pattern, illustrated by CESM large ensemble historical simulations (Fig. 1c, d) and CMIP6 multi-model historical simulations (Supplementary Fig. 2). The radiatively-forced regional warming from CESM1 (~ 0.4 °C/10 yr and ~ 0.26 °C/10 yr) accounts for $\sim 60\%$ and $\sim 86\%$ of the observed near-surface and tropospheric

warming, larger than that estimated from CMIP5 historical simulations³ (~ 40 – 50%). However, regional warming magnitudes show considerable inter-model spread across CMIP6 (Supplementary Fig. 2), suggesting strong model dependence in the regional Arctic response to radiative forcing. A quantitative comparison of tropical IOWP and historical simulations demonstrates that tropical IOWP expedites warming over northern Canada and Greenland. Additionally, the IOWP nudging experiments (Supplementary Fig. 3) successfully capture the distinctive seasonality of near-surface and tropospheric warming in northern Canada and Greenland, with greater magnitudes and extent throughout the boreal autumn and winter (Supplementary Figs. 4–5).

To fully clarify the potential drivers of recent rapid warming in northern Canada and Greenland, we also quantify the influence of tropical Pacific cooling and North Atlantic warming by analyzing the tropical eastern Pacific and North Atlantic pacemaker runs alike. Tropical Pacific cooling pacemaker simulations replicate near-surface and tropospheric warming patterns (Supplementary Fig. 6a–b), but with reduced magnitudes of ~ 0.37 °C/10 yr and ~ 0.18 °C/10 yr during 1980–2013 compared to historical simulations (Fig. 2), reinforcing the previous notion that recent tropical Pacific cooling partially counteracts greenhouse gas-forced warming^{36–38}. North Atlantic warming-restoring simulations, on the other hand, intensify tropical eastern Pacific cooling via trans-basin interactions^{44–46} and therefore generate relatively weaker near-surface and tropospheric warming trends of ~ 0.21 °C/10 yr and ~ 0.15 °C/10 yr (Fig. 2 and Supplementary Fig. 6c–d) compared with historical simulations.

Given a warm-to-cold phase shift of the IPO and a cold-to-warm phase transition of the AMV between 1980 and 2013 (ref. 46.), we further investigate the impact of the IPO and AMV phase transitions on recent warming in northern Canada and Greenland by individually nudging the IPO and AMV cold-phase and warm-phase SST anomalies towards observed patterns in idealized pacemaker experiments (see “Methods”). We estimate a cold-phase IPO-forced Arctic climate response as the 10-year mean of the

Fig. 2 | Observed and simulated near-surface and tropospheric temperature trends in northern Canada and Greenland. Linear trends of annual-mean near-surface air temperature (a) and tropospheric (300–850 hPa) temperature (b) averaged over northern Canada and Greenland are estimated from ERA5, the ensemble mean of 40 CESM1 historical runs (hist), the 10-member ensemble mean of tropical Indian Ocean-western Pacific (IOWP), tropical eastern Pacific (TEP), and North Atlantic (NAT) pacemaker runs with CESM1, as well as 30 CMIP6 model historical simulations (hist). Error bars denote the 95% confidence interval based on a two-sided Student’s *t* test, except for historical simulations where plus/minus one standard deviation of 40 members (CESM1 hist) and 30 models (CMIP6 hist) trends are shown, respectively.



cold-phase IPO pacemaker runs minus the warm-phase counterpart. Similarly, we calculate a warm-polarity AMV-induced response by subtracting the 10-year average of the cold-polarity AMV pacemaker runs from the warm-polarity AMV counterpart. The idealized pacemaker framework allows us to assess the relative importance of IPO and AMV phase shifts in regional Arctic warming in the absence of anthropogenic warming.

It is worth noting that a cold-phase IPO-SST anomaly favors significant cooling across a large swath of the pan-Arctic, especially northern Canada and Greenland (Supplementary Fig. 7a), qualitatively consistent with reduced warming magnitudes in the tropical Pacific cooling restoring simulations (Supplementary Fig. 6a–b) and earlier studies that a warm-phase IPO leads to early twentieth-century Arctic warming^{50,51}. In contrast, the warm-polarity AMV-SST forcing heats northern Canada and Greenland (Supplementary Fig. 7b) through competing effects of two different dynamic pathways as explained below, with near-surface warming of $\sim 0.26^\circ\text{C}/10\text{ yr}$ in a comparable magnitude to that shown in the North Atlantic warming restoring simulations ($\sim 0.21^\circ\text{C}/10\text{ yr}$ in Fig. 2a and Supplementary Fig. 6c). For a warm-polarity AMV case, increased northward ocean heat transport^{52–54} into the Arctic basin from the Atlantic sector facilitates sea-ice loss and directly increases near-surface air temperature in northern Canada and Greenland. Alternatively, a warm-phase AMV-SST anomaly amplifies tropical Pacific cooling through an intensified Pacific Walker circulation^{55–58} and, to some degree, indirectly suppresses warming in northern Canada and Greenland. Taken together, the time-varying and idealized pacemaker simulations identify that the tropical IOWP is a dominant contributor to the recent prominent warming in northern Canada and Greenland.

Key physical mechanisms

Next, we untangle the key dynamic pathway by which the tropical IOWP enhances Arctic warming over northern Canada and Greenland. The IOWP pacemaker experiments enable us to rigorously quantify large-scale adjustments in atmospheric circulation in response to the tropical IOWP warm pool. A relatively warmer tropical western Pacific than the tropical Indian Ocean appears in the observed and tropical IOWP-pacemaker simulations, unlike the radiatively forced almost even warming pattern (Supplementary Fig. 8). The warmer tropical western Pacific relative to surrounding domains induces increased precipitation there (Fig. 3a), following the warmer-get-wetter paradigm⁵⁹. Correspondingly, enhanced atmospheric deep convection, indicated by negative outgoing longwave radiation (Fig. 3a), prevails across the entire western Pacific basin.

The resultant convective heating initiates the establishment of a quasi-stationary Rossby wave train along a great-arc route that emanates from the tropical western Pacific, propagates poleward and curves eastward, eventually traversing the North Pacific and reaching the North America and Greenland sectors of the Arctic (Fig. 3b). Note that warm SST anomalies in the tropical western Pacific may cause anomalous convection under high background mean SST that then induces the Rossby wave response in two distinctive ways. One directly excites a Rossby wave train that follows a great arc-shaped trajectory, extending from the tropical western Pacific toward the Arctic. The other is by first mediating warm SST anomalies in the tropical central Pacific, and then generating the tropical central Pacific–Arctic teleconnection. The anomalous Rossby wave-train activity spreading from the tropical central Pacific toward the Arctic is also forced in a standalone atmospheric circulation model experiment through imposing an idealized heating in the tropical Pacific⁶⁰. Therefore, the quasi-stationary

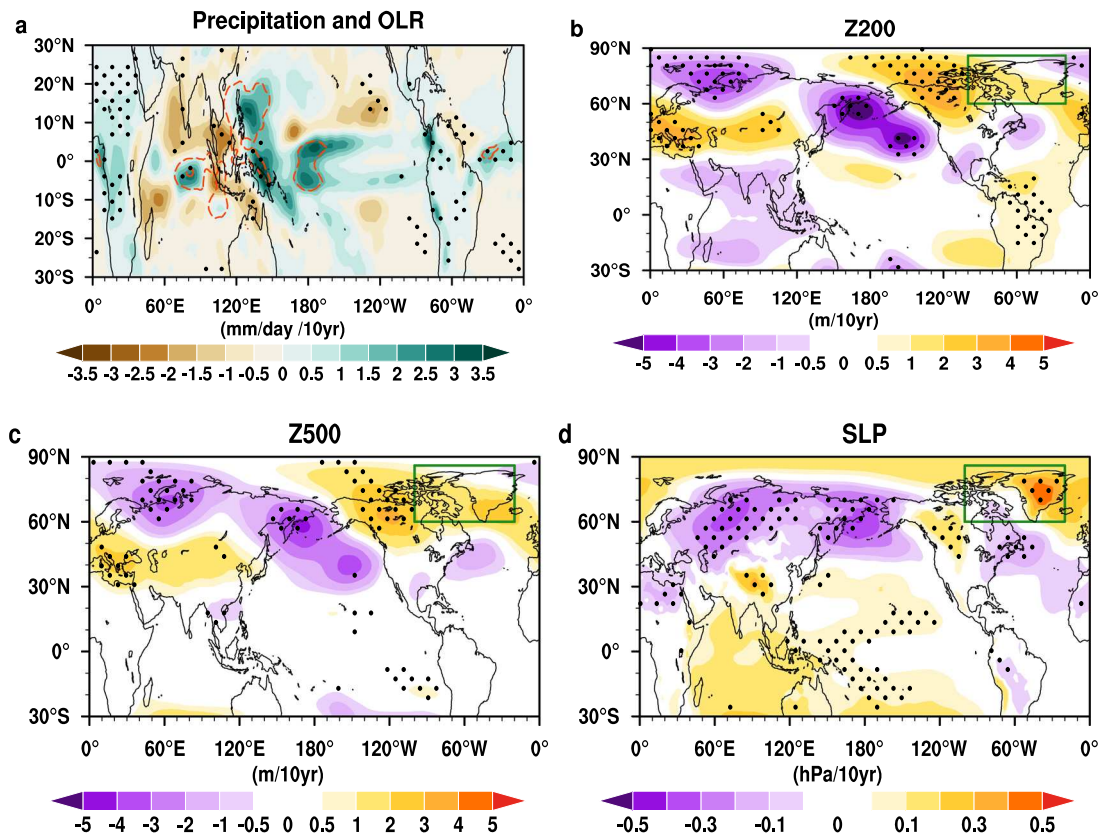
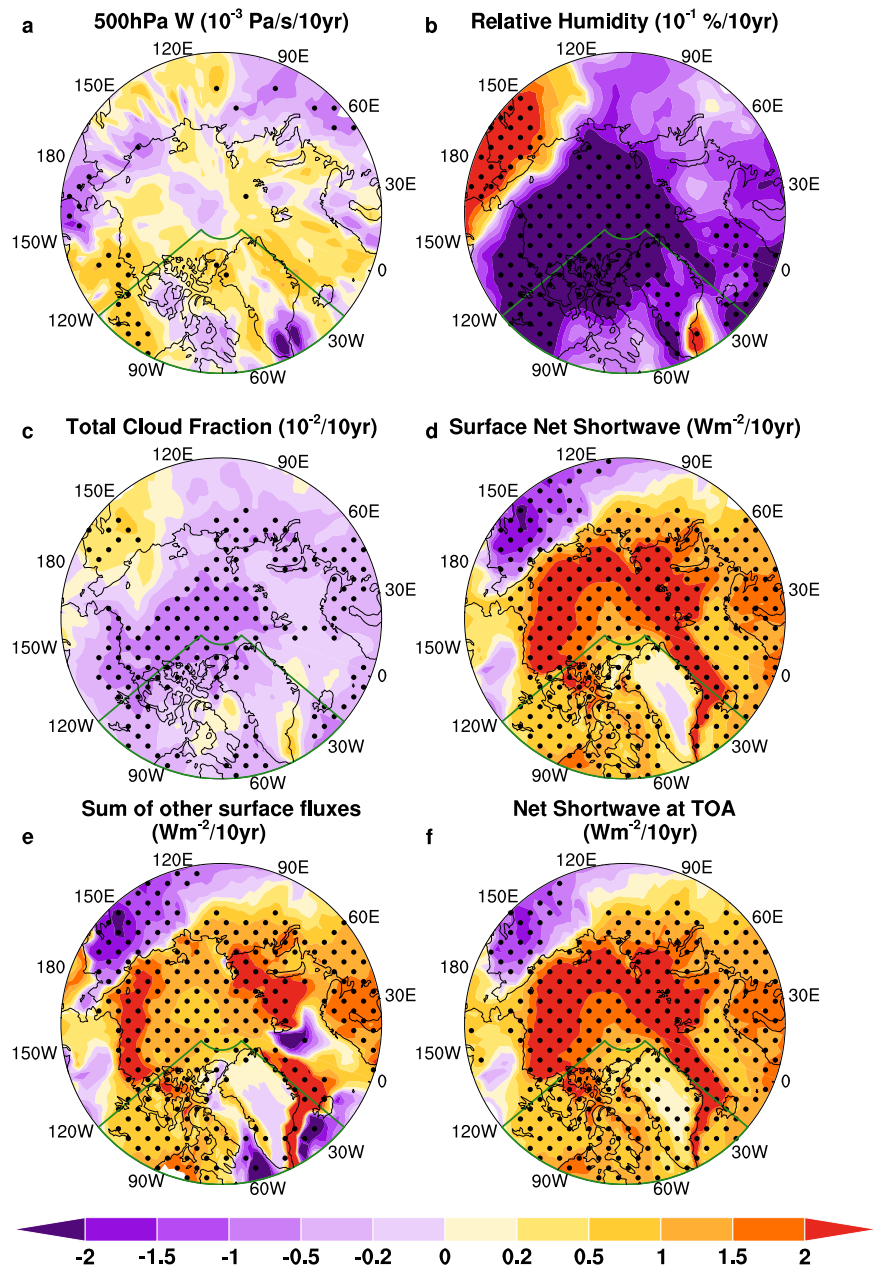


Fig. 3 | Physical pathways for tropical Indo-Western Pacific connections to the Arctic. Linear trends of annual-mean precipitation (color shading) and outgoing longwave radiation (red contours with intervals at $-2, -1, 1, 2\text{ Wm}^{-2}/10\text{ yr}$; dashed contours indicate negative values and represent strengthened convection) (a) 200-hPa geopotential height (b Z200), 500-hPa geopotential height (c Z500), and sea level pressure (d SLP) for 1980–2013 are estimated from the ensemble mean of 10

tropical Indo-Western Pacific (IOWP) pacemaker runs. Note that the zonal mean of Z200 and Z500 has been removed before calculating linear trends. Stippling denotes regions where trends are statistically significant at the 95% confidence level based on a two-sided Student's t test. Green boxes demarcate the northern Canada and Greenland domain.

Fig. 4 | Dynamic processes for tropical Indo-Western Pacific driving pan-Arctic climate changes. Linear trends of 500-hPa vertical velocity (a) 300–850 hPa relative humidity (b) total cloud fraction (c) net surface shortwave radiation (d) a combination of net surface longwave radiation, sensible heat flux, and latent heat flux (e) and net shortwave radiation at the top of the atmosphere (f) for 1980–2013 are estimated from the ensemble mean of 10 tropical Indo-Western Pacific (IOWP) pace-maker runs. Positive downward denotes diabatic heating. Stippling denotes the statistically significant trends at the 95% confidence level based on a two-sided Student's *t* test. Green boxes demarcate northern Canada and Greenland.



Rossby wave acts as a collective response to warm SST anomalies in the tropical western-central Pacific in the tropical Indo-western Pacific pace-maker experiments (Fig. 3a).

The Rossby wave train features a quasi-barotropic structure extending from the surface to the upper troposphere (Fig. 3b–d), with alternating low- and high-pressure anomaly centers of action. In the upper troposphere (Fig. 3b), the large-scale atmospheric circulation adjustment manifests an anomalous high-pressure center in the subtropical western North Pacific spanning from the Japan Sea to Hawaii Island and an anomalous low-pressure center across northeast Asia and the North Pacific, culminating in an anomalous anticyclone occupying the North America and Greenland domain of the Arctic.

As a consequence, the anticyclonic circulation anomalies covering the North America and Greenland sector of the Arctic induce anomalous descending motion and reduce relative humidity in the lower-to-upper troposphere (Fig. 4a, b), except for some patches of opposite-sign changes over southeastern Greenland. The simulated tropospheric drying broadly aligns with the observed muted precipitation changes over the North

American Arctic⁵⁴ during 1980–2013. Moreover, the total cloud fraction, especially the low-level cloud fraction (Supplementary Fig. 9c), decreases considerably across northern Canada and Greenland (Fig. 4c). These anomalous atmospheric conditions favor the increase in surface net shortwave radiation flux (Fig. 4d), whose contribution is overall larger than the combined influence of other components (cf. Fig. 4d, e), including surface net longwave radiation flux, sensible heat flux, and latent heat flux. Compared with net shortwave radiation flux, the individual magnitude of the other three components is rather smaller (Supplementary Fig. 9). Although all the other three components partially boost near-surface air temperature in northern Canada, they instead lead to non-negligible cooling off the southwestern and southeastern flanks of the Greenland continent, with a spatial pattern opposite to that of surface net shortwave radiation, partly counterbalancing its warming effects (cf. Fig. 4d, e and Supplementary Fig. 9).

Remarkably, a narrow strip of reduced surface net shortwave radiation flux occurs in the Greenland continent, mainly due to an increase in low-level cloud fraction (Supplementary Fig. 9c) linked to surface processes

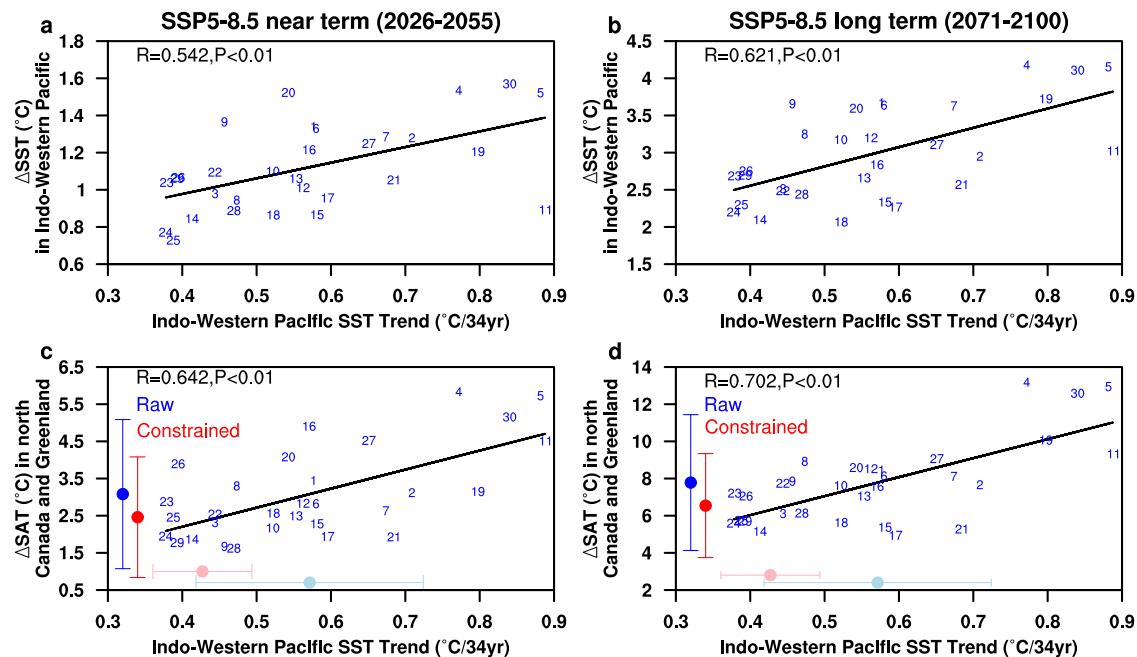


Fig. 5 | Observational constraints on the future changes in near-surface air temperature over northern Canada and Greenland. Inter-model relationship between 1980 and 2013 trends of tropical Indo-Western Pacific (IOWP: 20°S–20°N, African coast to 180°E) SST and future projected changes in tropical IOWP SSTs for the near term (**a** 2026–2055 minus 1981–2010) and the long term (**b** 2071–2100 minus 1981–2010) from 30 CMIP6 models under SSP5-8.5 scenarios. **c, d** Same as **a, b** but for future projected changes in near-surface air temperature (Δ SAT) averaged over northern Canada and Greenland. The vertical bars show the average (dots) and 5–95%

ranges of the raw (blue) Δ SAT and the constrained (red) Δ SAT using observations. The horizontal bars display the average (dots) and two standard deviations of the observed (pink) and CMIP6-modeled tropical IOWP SST trends (light blue) for 1980–2013. The solid lines denote the least-squares linear fits. Shown are Pearson's correlation coefficients (R), together with the statistical significance ($P < 0.01$) based on a two-sided Student's t -test. Numbers (blue) ranging from 1 to 30 correspond to the 30 CMIP6 models shown in Supplementary Table 1.

induced by topographical effects. Despite these regional variations, the spatial distribution of surface net shortwave radiation flux is broadly consistent with that of net shortwave radiation at the top of the atmosphere (cf. Fig. 4d, f), with high uncentered pattern correlation coefficients of ~ 0.995 in northern Canada and Greenland and ~ 0.994 across the pan-Arctic. The physical consistency implies a trifling impact of shortwave-cloud feedback on regional Arctic warming in the tropical Indo-western Pacific pacemaker experiments. Overall, the qualitative agreement supports our hypothesis that increased incoming solar radiation at the surface plays a vital role in generating widespread warming across northern Canada and the Greenland sector of the Arctic.

Previous modeling studies have linked tropical eastern Pacific or North Atlantic SST variability to Arctic climate changes via atmospheric bridges on multi-decadal timescales. Considering the active two-way interactions among the trans-ocean basins^{44–46,55}, we further shed light on the specific physical pathways by which tropical eastern Pacific cooling or North Atlantic warming separately govern regional climate variations in northern Canada and Greenland during 1980–2013 in the time-evolving pacemaker experiments. Tropical eastern Pacific cooling excites an equivalent barotropic Rossby wave response spreading from the subtropical North Pacific toward the Arctic, characterized by an anomalous low-pressure center covering the North American Arctic and an anomalous high-pressure center over Greenland (Supplementary Fig. 10a, c, e). By contrast, North Atlantic warming excites the two-pronged atmospheric teleconnections to northern Canada and Greenland. Anomalous North Atlantic warming not only directly produces an extratropical wave train⁵⁵ extending from the extratropical North Atlantic, crossing Eurasia, to northern Canada and Greenland, but it also indirectly forces a Rossby wave-train activity propagating from the subtropical North Pacific towards northern Canada and Greenland, mediated by tropical eastern Pacific cooling (Supplementary Fig. 10b, d). These two distinct Rossby wave trains work together to shape anomalous cyclonic circulation occupying North America and

southwestern Canada, and anomalous anticyclonic circulation across northeastern Canada and Greenland. The atmospheric circulation pattern is mainly confined to the mid-to-upper troposphere (Supplementary Fig. 10b, d, f) and shifts noticeably westward relative to the direct response to the tropical Pacific cooling-only forcing (Supplementary Fig. 10).

Unlike the tropical eastern Pacific cooling-only forced and North Atlantic warming-mediated atmospheric circulation pattern across northern Canada and Greenland (Supplementary Fig. 10), tropical IOWP warming drives an anomalous high-pressure center indicative of a monopolar pattern occupying northern Canada and Greenland (recall Fig. 3). The resultant subsidence enhancement also generates adiabatic warming^{39,50} there, in addition to diabatic warming related to increased incoming shortwave radiative flux (Fig. 4). As such, supported by the earlier atmosphere reanalysis diagnosis³⁹, these hierarchical pacemaker experiments provide strong modeling evidence that tropical IOWP warm pool is more influential in producing remarkable warming in northern Canada and Greenland on multi-decadal timescales via the tropical IOWP-Arctic teleconnection.

Emergent constraints on future projected regional warming magnitudes

Our results reveal that the tropical IOWP SST has substantially warmed near-surface air temperature and tropospheric temperature in northern Canada and Greenland during 1980–2013, a period when global mean anthropogenic aerosol emissions remained almost steady^{61–63}. Particularly after 1980, the fairly constant global-mean aerosol emissions exert little influence on the enhanced pan-Arctic warming. As recent (1980–2013) trend of and future projected change in tropical IOWP SSTs are dominated by the responses to increasing greenhouse gas concentrations^{64–66} (Fig. 5a, b), significant positive correlations between the two climate metrics exist for the near term (2026–2055 minus 1981–2010; $R \sim 0.542$, $P < 0.01$) and the long term (2071–2100 minus 1981–2010; $R \sim 0.621$, $P < 0.01$)

under the high-emission scenario (SSP5-8.5 in Fig. 5). The statistically significant relationship also holds for both the ambitious-emission (SSP2-4.5) and low-emission (SSP1-2.6) scenarios, with positive correlation coefficients greater than 0.5 (Supplementary Figs. 11–12). The relationship implies that CMIP6 models exhibiting larger warming trends in tropical IOWP SSTs for 1980–2013 would predict greater changes in tropical IOWP SSTs in both near- and long-term projections (Fig. 5a, b and Supplementary Figs. 11–12).

Since the significant correlations between recent trends of and future projected changes in tropical IOWP SSTs, we also find strong correlations between future projected changes in near-surface air temperature warming magnitudes (Δ SAT) in northern Canada and Greenland and recent past trends of tropical IOWP SSTs under the SSP5-8.5 scenario (Fig. 5c, d), with large correlation coefficients for the near term ($R = \sim 0.642$, $P < 0.01$) and the long term ($R = \sim 0.702$, $P < 0.01$). The statistically significant connection also occurs under the SSP2-4.5 and SSP1-2.6 scenarios, with correlation coefficients exceeding 0.5 for the near- and long-term projections (Supplementary Figs. 11–12). Combining the emergent relationship between recent trends of tropical IOWP SSTs and future projected Δ SAT over northern Canada and Greenland with observations indicates that the upper bounds of future projected Δ SAT among CMIP6 models may be hardly credible and potentially diminished, mostly because CMIP6 models with the higher upper end of future projected Δ SAT typically overestimate warming trends of SAT in northern Canada and Greenland during 1980–2013 (cf. Fig. 5 and Supplementary Fig. 2). As expected, there is substantial inter-model disagreement among recent warming trends of SAT and future projected Δ SAT over northern Canada and Greenland (Supplementary Figs. 2 and 5). These statistical analyses point to the fact that historical-simulation errors in the relationship between SST over tropical IOWP and SAT in northern Canada and Greenland readily propagate into future climate responses to greenhouse gas increases under greenhouse warming, providing a plausible constraint on future warming magnitudes in northern Canada and Greenland.

To reduce potential uncertainties, we use the hierarchical emergent constraint framework⁶⁷ to estimate observationally constrained ranges of future projected Δ SAT over northern Canada and Greenland (see “Methods”). Under the SSP5-8.5 scenario, the raw ensemble mean value and its 5–95% ranges (assuming a Gaussian distribution) of Δ SAT in northern Canada and Greenland for the near-term (2026–2055 minus 1981–2010) and long-term (2071–2100 minus 1981–2010) projections are $\sim 3.08^\circ\text{C}$ (1.07–5.09 $^\circ\text{C}$) and $\sim 7.78^\circ\text{C}$ (4.12–11.44 $^\circ\text{C}$), respectively (Fig. 5c, d). By incorporating seven different observations to constrain the simulated tropical IOWP SST trends during 1980–2013 (“Methods”), the near-term and long-term projected upper bounds (95th percentile value) of Δ SAT over northern Canada and Greenland drop by $\sim 19.8\%$ from ~ 5.09 to $\sim 4.08^\circ\text{C}$ and by $\sim 18.4\%$ from ~ 11.44 to $\sim 9.34^\circ\text{C}$ (Fig. 5c, d), respectively. Consistently, the relative reductions in variance (RRVs in “Methods”) for the near-term and long-term projected Δ SAT in northern Canada and Greenland, based on seven observations, are $\sim 34.64\%$ and $\sim 41.46\%$, respectively. Our observational emergent-constraint approach, built on recent trends in tropical IOWP SSTs, also performs well for both the SSP2-4.5 and SSP1-2.6 scenarios. Under the SSP2-4.5 scenario, the upper bounds of near-term and long-term projected Δ SAT in northern Canada and Greenland decrease by $\sim 21.2\%$ from ~ 4.33 to $\sim 3.41^\circ\text{C}$ and by $\sim 20.9\%$ from ~ 7.18 to $\sim 5.68^\circ\text{C}$, respectively. Correspondingly, the variances of future projected Δ SAT over northern Canada and Greenland are reduced by $\sim 36.56\%$ for the near-term projections and by $\sim 40.37\%$ for the long-term projections (Supplementary Fig. 11c–d). Under the SSP1-2.6 scenario, the 95th percentile values of near-term and long-term projected Δ SAT in northern Canada and Greenland are lowered by $\sim 11.5\%$ (~ 7.41 to $\sim 6.56^\circ\text{C}$) and $\sim 23.9\%$ (~ 9.37 to $\sim 7.13^\circ\text{C}$), respectively. The variances of future projected Δ SAT over northern Canada and Greenland are diminished by $\sim 23.54\%$ and $\sim 31.62\%$ (Supplementary Fig. 12c–d), respectively. These results show that the observational emergent-constraint framework, using more realistic tropical IOWP SST trends in observations, substantially

lowers the upper bounds of future projected Δ SAT in northern Canada and Greenland, regardless of greenhouse gas emission trajectories. Moreover, owing to discrepancies between the observed and modeled representations of internal variability, such as changes in the magnitude and phase transitions of AMV (see Supplementary Fig. 7), reductions in the constrained upper bounds of future projected Δ SAT over northern Canada and Greenland may be partly explained by internal variability.

Implications for emergent constraints on future pan-Arctic warming

During 1980–2013, observed SAT over the northern Canadian–Greenland Arctic has warmed almost as much as the pan-Arctic, a robust feature across multiple observations (Supplementary Fig. 1). This amplified regional warming clearly reflects the fourfold Arctic amplification. In addition, the near-term (2026–2055 minus 1981–2010) and long-term (2071–2100 minus 1981–2010) projected Δ SAT in the pan-Arctic is basically proportional to recent simulated trends of tropical IOWP SSTs under both the SSP1-2.6 (Supplementary Fig. 13) and SSP2-4.5 (Fig. 6a, b) scenarios, with strong positive correlation coefficients greater than 0.55 ($P < 0.01$). Comparably, the future projected Δ SAT in the pan-Arctic under the SSP5-8.5 scenario is also well correlated with the simulated tropical IOWP SST trends during 1980–2013 (Fig. 6c, d), with high correlation coefficients of both greater than ~ 0.63 ($P < 0.01$). The statistically significant relationship between the recent past tropical IOWP SST trends and future pan-Arctic Δ SAT suggests that CMIP6 models showing greater recent warming in tropical IOWP SSTs would simulate higher warming in the pan-Arctic. Therefore, both observational and modeling evidence enable an observationally constrained relationship for future warming magnitudes across the pan-Arctic.

We further extend the hierarchical emergent constraint framework⁶⁷ to observational constraints on future projected Δ SAT across the pan-Arctic, based on recent trends in tropical IOWP SSTs. After incorporating observed estimates of tropical IOWP SST trends into constraints, the near-term and long-term projected upper bounds of pan-Arctic Δ SAT decline by $\sim 20.8\%$ (~ 5.23 to $\sim 4.14^\circ\text{C}$) and $\sim 23.2\%$ (~ 6.47 to $\sim 4.97^\circ\text{C}$) under the SSP1-2.6 scenario (Supplementary Fig. 13), and by $\sim 19.4\%$ (~ 4.65 to $\sim 3.75^\circ\text{C}$) and $\sim 19.6\%$ (~ 7.51 to $\sim 6.04^\circ\text{C}$) under the SSP2-4.5 scenario (Fig. 6a, b). The variances of future projected Δ SAT in the pan-Arctic are reduced by ~ 20.8 to $\sim 23.2\%$ and ~ 33.52 to $\sim 40.16\%$, respectively. Our observational constraints based on recent tropical IOWP SST trends also work well for the SSP5-8.5 scenario (Fig. 6c, d). The upper bounds of the near-term and long-term projected Δ SAT decrease significantly across the pan-Arctic, reaching $\sim 18.3\%$ (~ 5.4 to $\sim 4.41^\circ\text{C}$) and $\sim 16.9\%$ (~ 11.68 to $\sim 9.71^\circ\text{C}$), respectively. The variances of future projected Δ SAT in the pan-Arctic decrease by $\sim 32.91\%$ and $\sim 41.22\%$, respectively. Altogether, the 95th percentile values (the upper bounds) of future projected Δ SAT in the northern Canadian–Greenland Arctic and the pan-Arctic are lowered more under both the SSP1-2.6 and SSP2-4.5 scenarios than under the SSP5-8.5 scenario (cf. Supplementary Fig. 13 and Figs. 5–6). In contrast, the 5th percentile values (the lower bounds) are negligible across all scenarios (Supplementary Fig. 13 and Figs. 5–6). Additionally, the 5%–95% ranges of constrained Δ SAT in the northern Canadian–Greenland Arctic and the pan-Arctic are not sensitive to the choice of seven observed SSTs. When one observed SST is subtracted from seven observations, the 5–95% ranges of constrained Δ SAT in the regional Arctic and the pan-Arctic are largely unchanged (Supplementary Figs. 14–15), verifying the robustness of the proposed emergent constraint.

Discussion

We present clear modeling evidence from hierarchical pacemaker experiments that the tropical IOWP warm pool is crucial for pronounced near-surface and tropospheric warming over the northern Canadian–Greenland Arctic during 1980–2013. Anomalous tropical IOWP SST warming initiates a Rossby wave train towards the Arctic, forming the anomalous anticyclonic circulation covering northern Canada and Greenland. The resulting large-scale atmospheric circulation adjustment induces near-surface and

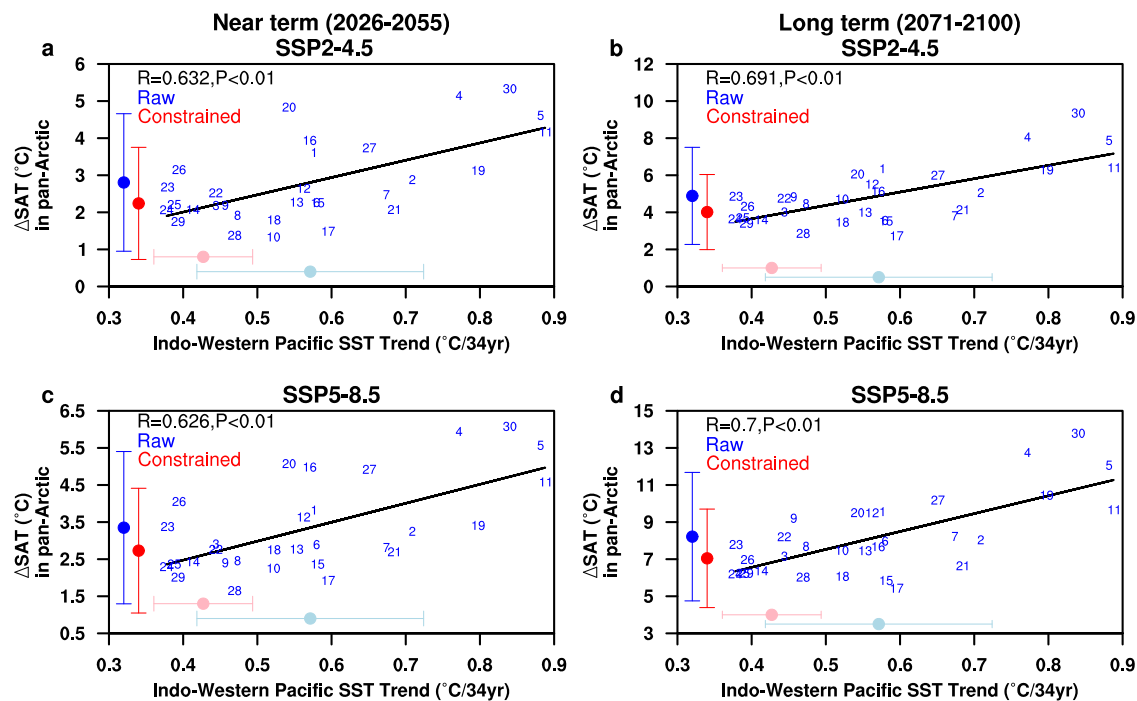


Fig. 6 | Observational constraints on future projected changes in near-surface air temperature in the pan-Arctic. Inter-model relationship between 1980–2013 trends of tropical Indo-Western Pacific (IOWP: 20°S–20°N, African coast to 180°E) SST and future projected changes in near-surface air temperature (Δ SAT) averaged in pan-Arctic for the near term (a and c 2026–2055 minus 1981–2010) and the long term (b and d 2071–2100 minus 1981–2010) from 30 CMIP6 models under SSP2-4.5 (a, b) and SSP5-8.5 (c, d) scenarios. The vertical bars depict the average (dots) and 5–95% ranges of the raw 30 CMIP6 (blue) Δ SAT and the constrained (red) Δ SAT

using seven different observations. The horizontal bars portray the average (dots) and two standard deviations of the observed (pink) and CMIP6-modeled tropical IOWP SST trends (light blue) for 1980–2013. The solid lines denote the least-squares linear fits. Shown are Pearson's correlation coefficients (R), together with the statistical significance ($P < 0.01$) based on a two-sided Student's t test. Numbers (blue) ranging from 1 to 30 correspond to the 30 available CMIP6 models shown in Supplementary Table 1.

tropospheric warming anomalies over northern Canada and Greenland, driven primarily by increased incoming shortwave radiation owing to enhanced subsidence and reduced low-level cloud cover. The tropical IOWP convective heating accounts for ~40% of the observed near-surface warming, with an additional 50–60% warming arising from greenhouse gas increases³ (see Fig. 2). Based on recent past trends of tropical IOWP SSTs, we establish observational constraints on future projected warming magnitudes in the northern Canadian-Greenland Arctic and the pan-Arctic to reduce potential uncertainty. The 95th percentile values of near-term (2026–2055) and long-term (2071–2100) projected warming magnitudes in the northern Canadian-Greenland Arctic are reduced by ~11.5% to ~23.9%, ~20.9% to ~21.2%, and ~18.4% to ~19.8% under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively. For the pan-Arctic, the upper bounds of near-term and long-term projected warming magnitudes are reduced by ~20.8% to ~23.2%, ~19.4% to ~19.6%, and ~16.9% to ~18.3%, respectively, under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios.

Recognizing the importance of tropical IOWP-Arctic trans-hemispheric teleconnections could have profound implications for future projections of Arctic warming, despite the same greenhouse gas concentrations in each scenario, CMIP6 models with overestimated tropical IOWP SST warming tend to produce larger increases in SAT warming magnitudes over the northern Canadian-Greenland Arctic and the pan-Arctic for both historical and future periods (see Figs. 4–5 and Supplementary Fig. 2). Some CMIP6 models simulating greater recent trends in tropical IOWP SSTs than observations even produce larger recent trends in SAT over the northern Canadian-Greenland Arctic and the entire Arctic than observations. Thus, these biased models should be considered low credibility for future projected Arctic amplification. We may further disentangle the primary factors underlying the consistently too-high simulated Arctic warming and the typically associated too-strong simulated Arctic sea-ice loss in these outlier

models. A reliable estimate of Arctic amplification and sea-ice loss, particularly the timing of a summer ice-free Arctic⁶⁸, could enhance our confidence in viable planning and mitigation measures to avoid adverse economic and societal impacts arising from the Arctic-relevant high susceptibility⁶⁹ to an overshoot world of warming greater than 1.5°C.

Validating the tropical-Arctic teleconnections in climate models against observations is essential to ameliorate the credibility of future Arctic climate projections. The background state may mediate the atmospheric teleconnection at mid- and high latitudes. For instance, the Arctic warming may weaken the meridional tropospheric potential vorticity^{70,71} and alter the energy dispersion and nonlinearity of large-scale Rossby wave trains. Furthermore, the winter Arctic sea-ice decline linked to the long-lived Ural blocking⁷² and/or La Niña-like SST cooling favors a positive-phase North Atlantic Oscillation-like circulation pattern⁷³, promoting surface warming in northern Canada and Greenland. Additionally, the tropical-Arctic teleconnection may be non-stationary on multi-decadal timescales⁷⁴. However, current climate models cannot simulate the observed tropical SST variability, especially in the tropical eastern Pacific and tropical Indo-western Pacific identified in this study, raising concerns about the robustness and non-stationarity of the tropical Pacific-Arctic teleconnection⁷⁴. Thus, the simulated tropical-Arctic teleconnection depends heavily on realistic representations of tropical SST variability and the mid- to high-latitude background state, warranting further systematic study through dedicated model experiments, such as a hierarchy of pacemaker experiments proposed in this study.

Our hierarchical pacemaker framework operates more realistically than the previous diagnosis based on atmospheric reanalysis³⁹, a low-resolution atmosphere-standalone model⁷⁵, and a slab ocean-atmosphere model³, which underrepresent the full extent of ocean dynamics, ocean-air coupling, and trans-basin interactions. The innovative experimental design

enables us to clarify the active role of the tropical IOWP in promoting climatic impacts in northern Canada and Greenland through the tropical IOWP-Arctic teleconnections on multi-decadal timescales. Although earlier studies argue the potential influence of the tropical eastern Pacific cooling³ and North Atlantic warming^{40–42}, the tropical eastern Pacific-dominated cooling effects on northern Canada and Greenland are largely underestimated by nearly all the coupled climate models in the CMIP5 and CMIP6 archive: directly via the tropical Pacific-North American teleconnection^{76–78} and indirectly through North Atlantic warming-induced trans-basin interactions^{44–46,55,56,58} (see Supplementary Figs. 6 and 7). Our study identifies the previously overlooked roles of tropical eastern Pacific cooling and North Atlantic warming in suppressing the regional and pan-Arctic warming through trans-basin interactions^{44,45,55,56}.

The hierarchical pacemaker framework also offers new insights into the observed fourfold warming rate across the pan-Arctic since around 1980, which is underrepresented in both CMIP5 and CMIP6 (refs. 1, 2.). Our ongoing study indicates that the simulated Arctic amplification in the tropical IOWP pacemaker simulations is closer to observations than the tropical eastern Pacific and North Atlantic pacemaker experiments. The model-observation disparity probably stems from common model biases in simulating the tropical-Arctic teleconnection, the present-day climatological Arctic sea-ice area^{68,79}, and the sensitivity of Arctic sea-ice formation to the atmospheric circulation^{53,80} because of the ensemble-averaged responses in pacemaker simulations as a combination of the remote SST forcing and local intensification related to sea-ice decline. The Tropical Basin Interaction Model Intercomparison Project⁸¹ may help ameliorate these model limitations and gain deeper insight into the tropical IOWP-Arctic teleconnections by adopting a new pacemaker experimental protocol based on the observed climatology rather than the model mean state, albeit at the cost of introducing observational uncertainties.

Methods

Observations and reanalyses

Four different datasets are used to illustrate the consistent near-surface prominent warming over northern Canada and Greenland (Fig. 1 and Supplementary Fig. 1), including the European Center for Medium-Range Weather Forecasts fifth-generation atmospheric reanalysis (ERA5)⁸² on a $1^\circ \times 1^\circ$ horizontal resolution for 1950–2013, the Met Office Hadley Center/Climatic Research Unit version 5 (HadCRUT5)⁸³ by blending land surface air temperature (CRUTEM5) and sea surface temperature (HadSST4) with a $5^\circ \times 5^\circ$ grid for 1950–2013, the NASA Goddard Institute for Space Studies Surface Temperature version 4 (GISTEMP4)⁸⁴ by merging land surface air temperature (GHCN v4) and sea surface temperature (ERSST v5) with a $5^\circ \times 5^\circ$ grid for 1950–2013, and the Berkeley Earth Surface Temperature (Berkeley)⁸⁵ by combining land temperature records with an interpolated version of HadSST3 with a $1^\circ \times 1^\circ$ grid for 1950–2013. Since ERA5 shows fairly realistic Arctic tropospheric temperature distributions and fewer spurious trends^{6,82} than previous ERA-40 reanalysis datasets, as well as longer periods than ERA-interim reanalysis product and larger coverage than meteorological station datasets, we use ERA5 alone to compute the tropospheric temperature warming in northern Canada and Greenland (Fig. 1 and Supplementary Fig. 1). Seven different SST products are utilized to estimate the tropical Indo-western Pacific (IOWP: 20°S – 20°N and the African coast to 180°E) warming trends of 1980–2013, including Extended Reconstructed Sea Surface Temperature version 3b, 4, and 5 (ERSST v3b, ERSST v4, and ERSST v5)⁸⁶, Centennial in situ Observation-Based Estimates of Sea Surface Temperature (COBE-SST and COBE-SST2)⁸⁷, Hadley Center Sea Ice and SST dataset (HadISST)⁸⁸, and the merged Hadley-NOAA/OI sea surface temperature (Hurrell)⁸⁹. Unless otherwise specified, we use least-squares linear regression to estimate linear trends, with a 95% significance level based on a two-sided Student's *t*-test. Slight changes to the definition of the northern Canadian-Greenland Arctic domain do not alter our main conclusions.

CMIP6 and CESM1 ensemble simulations

To evaluate the contribution of radiative forcing to near-surface and tropospheric warming over the northern Canada and Greenland sector of the Arctic (Supplementary Fig. 2), we mainly use the historical (1980–2013) and Shared Socioeconomic Pathway 2-Representative Concentration Pathway 4.5 (SSP2-4.5) and SSP5-8.5 simulations (2015–2100) of 30 available models participating in the Coupled Model Intercomparison Project phase six (CMIP6) (Supplementary Table 1). We analyze only the first realization for each model. These multi-model simulations provide a comprehensive assessment of warming magnitudes over northern Canada and Greenland for historical periods and future projections. We also employ CESM1 large ensemble simulations⁴⁹ with different initial atmospheric conditions to quantify the role of radiative forcing in driving warming over northern Canada and Greenland during 1980–2013. Following the CMIP5 experimental protocol, the CESM1 simulations are forced by historical radiative forcing for 1920–2005 and by RCP8.5 for 2006–2100 (Supplementary Table 2).

Time-evolving and idealized pacemaker experiments

To quantify how SST variability in individual ocean basins, through trans-basin interactions, contributes to warming over northern Canada and Greenland during 1980–2013, we diagnose three 10-member ensemble time-evolving pacemaker experiments with the fully coupled climate model CESM1, following the previously proposed method^{57,90}. In these simulations (Supplementary Table 2 and Supplementary Fig. 3), SSTs in the tropical Indian Ocean-Western Pacific (IOWP: 15°S – 15°N , African coast to 174°E with 5° buffer zones), tropical eastern Pacific (TEP: 15°S – 15°N , 180° to the American coast with 5° buffer zones), and North Atlantic Ocean (NAT: 5° – 55°N , the American coast to Africa/Europe with 5° tapering buffer zones) are separately nudged toward the model climatology plus observed anomaly (ERSST v3b). Outside the restoring regions, the ocean-atmosphere system is fully coupled and evolves freely. Each experiment spans 1920 to 2013 and consists of 10 members generated by introducing micro-perturbations in atmospheric initial conditions. All simulations follow historical radiative forcing until 2005 and the RCP8.5 scenario thereafter. These time-evolving pacemaker experiments have successfully captured a strengthening of Pacific Walker circulation⁴⁶, tropical-Southern Ocean trans-hemispheric teleconnections⁹¹, and recent inter-tropical Africa drying conditions⁹², increasing our confidence in evaluating the roles of SST variability in individual ocean basins and trans-basin interactions in shaping rapid warming over northern Canada and Greenland during 1980–2013.

Because the IPO switches phase from positive to negative and the AMV translates into a warm phase from cold during 1980–2013, we also examine the respective roles of the IPO and AMV phase shifts in generating Arctic near-surface temperature anomalies by analyzing two sets of idealized pacemaker experiments wherein the warm-phase and cold-phase IPO-SST anomaly (40°S – 60°N , from Indonesia to the American coast) and the warm-polarity and cold-polarity AMV-SST anomaly (8° – 65°N , from the American coast to Africa/Europe) are prescribed, respectively (Supplementary Table 2). Note that the idealized IPO and AMV configurations correspond to the internal components of observed IPO-SST and AMV-SST patterns and are obtained by regressing the internally generated SST components at each grid point against the respective IPO and AMV indices. The internally-driven SST components are calculated as the residual of the observed SST after removing the externally forced component derived from CMIP5 multi-model historical simulations using a signal-to-noise-maximizing empirical orthogonal function method^{58,93}.

The cold-phase and warm-phase IPO experiments (termed –IPO and +IPO) each consist of 10 members. The warm-polarity and cold-polarity AMV experiments (denoted +AMV and –AMV) each comprise 30 members. Each run is integrated for 10 years, with all external forcings kept constant at pre-industrial levels. We estimate the simulated Arctic climate response to a warm-to-cold IPO phase shift as the 10-year mean difference between –IPO and +IPO, averaged across 10 members. Similarly, we calculate the impact of a cold-to-warm AMV phase transition by subtracting

–AMV from +AMV, averaged across 30 members and 10 years. When randomly selecting 10 members from +AMV and –AMV to estimate the ensemble-mean responses, our main results are qualitatively similar.

Estimation of uncertainty range

Given the large uncertainty in future projected warming magnitudes across the northern Canadian–Greenland Arctic and the pan-Arctic, we calculate raw 5–95% uncertainty ranges by assuming a Gaussian distribution of the 30 available CMIP6 model spreads. Specifically, we estimate the observationally constrained ranges of future projected warming magnitudes using the hierarchical emergent constraint framework⁶⁷. In this study, Z and X are future changes in and recent past trends of 30 models, respectively. μ_z and δ_z are the ensemble mean and standard deviation of future changes in warming magnitude (z), respectively. μ_x and δ_x are the ensemble mean and standard deviation of the 1980–2013 trends of SSTs in the tropical IOWP (20°S–20°N, African coast to 180°E) (x), respectively. R denotes the correlation coefficient between Z and X . Y is the 1980–2013 trend of tropical IOWP SST from seven different observations. μ_y and δ_y are the ensemble mean and standard deviation of the observed trends of tropical IOWP SST, respectively. Given the recent past and long-term warming trends in the tropical IOWP SST, which are mainly forced by greenhouse gases and less affected by internal climate variability and aerosols, we focus on uncertainties in these trends across seven observational datasets.

We measure the mean ($E(z|y)$) and standard deviation ($\delta(z|y)$) of the constrained future projections of warming magnitudes following the equations:

$$E(z|y) = \mu_z + \frac{R\delta_z\delta_x}{\delta_x^2 + \delta_y^2} (\mu_y - \mu_x) \quad (1)$$

$$\delta(z|y) = \delta_z \sqrt{1 - \frac{R^2}{1 + (\delta_y^2/\delta_x^2)}} \quad (2)$$

The constrained 5–95% ranges of future projected warming magnitudes are calculated by assuming a Gaussian distribution of $E(z|y)$ and $\delta(z|y)$. The relative reduction of variance (RRV) is estimated as follows:

$$RRV = \left(1 - \frac{\delta(z|y)^2}{\delta_z^2}\right) \times 100\% \quad (3)$$

Data availability

Observations and model outputs used here are publicly available from the following websites: ERA5 (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=download>); HadCRUT5 (<https://www.metoffice.gov.uk/hadobs/hadcrut5/>); NOAA GISTEMP4 (<https://psl.noaa.gov/data/gridded/data.noaa.globaltemp.html>); Berkeley (<https://berkeleyearth.org/data/>); ERSST v3b, v4, and v5 (<https://www.ncei.noaa.gov/products/extended-reconstructed-sst>); HadISST (<https://www.metoffice.gov.uk/hadobs/hadisst/>); COBE-SST and COBE-SST2 (<https://climatedataguide.ucar.edu/climate-data/sst-data-cobe-centennial-situ-observation-based-estimates/>); Hurrell (<https://climatedataguide.ucar.edu/climate-data/merged-hadley-noaa-i-sea-surface-temperature-sea-ice-concentration-hurrell-et-al-2008>); All the CMIP6 model outputs are available at <https://esgf-metagrid.cloud.dkrz.de/search>. The CESM1 datasets generated and/or analyzed during the current study are not publicly available due to their large size but are available from the corresponding author (S.L.Y.) upon reasonable request.

Code availability

The codes generated and/or analyzed during the current study are not publicly available because they require a Unix compiling and execution environment to run the NCAR Command Language (NCL; <https://www.ncl.ucar.edu/>), but are available from the corresponding author (S.L.Y.) upon reasonable request.

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Author contributions

S.L.Y. conceived the study, conducted all the analyses, generated all the figures, and wrote the manuscript. R.W., P.L., and H.T. provided comments on and revised the manuscript. P.W. helped process datasets. All the authors contributed to refining the results.

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Competing interests

The authors declare no competing interests.

Additional information

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