

Slowdown of wintertime Arctic amplification since 2012

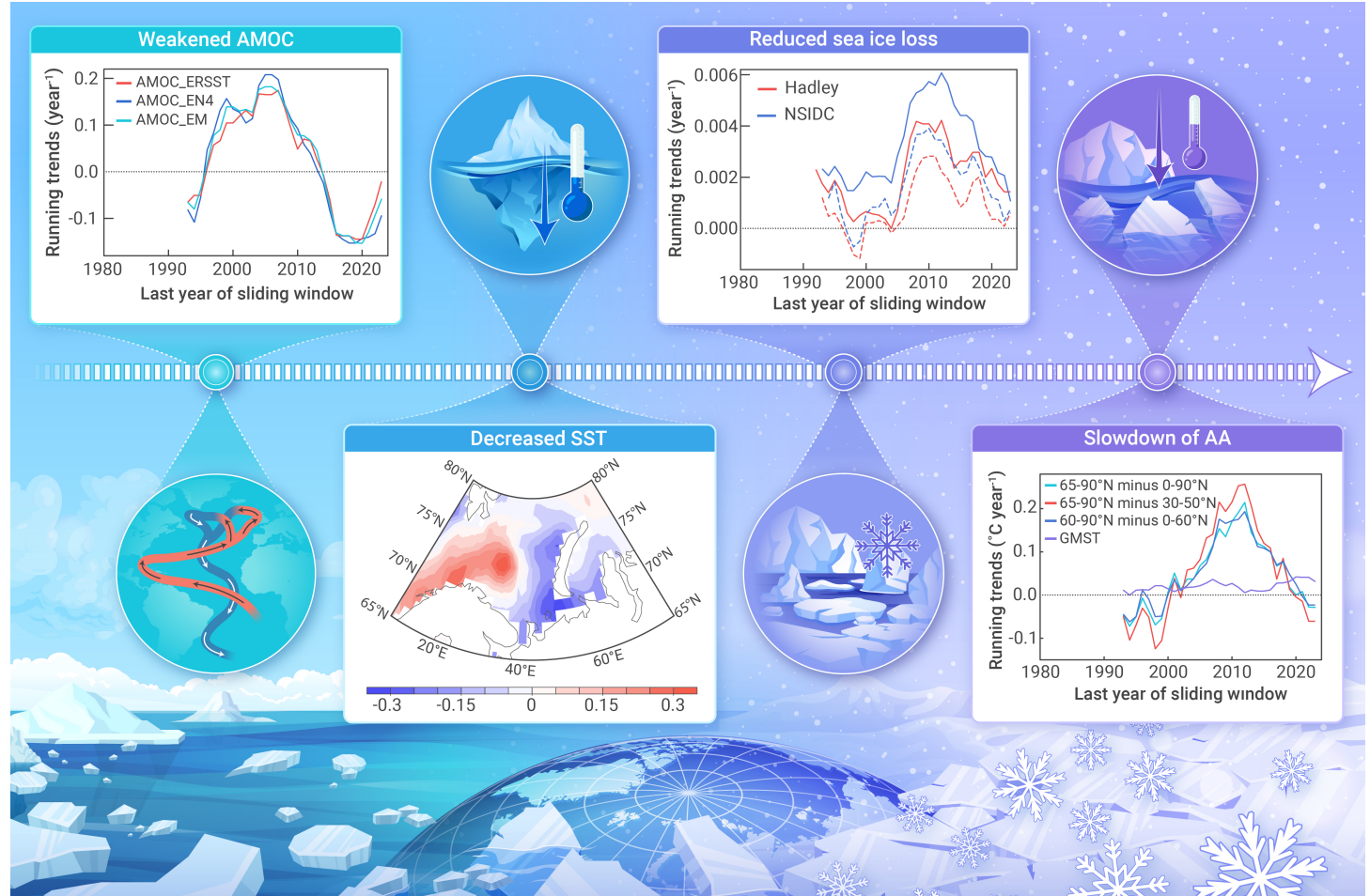
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Received: October 25, 2024; Accepted: March 4, 2025; Published Online: March 13, 2025; <https://doi.org/10.59717/j.xinn-geo.2024.100130>

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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- The rate of wintertime Arctic amplification shows a slowdown in recent decades.
- The rate of wintertime Arctic sea ice loss exhibits a deceleration in recent decades.
- The attenuation of the Atlantic Meridional Overturning Circulation decelerates winter Arctic sea ice loss.
- The Barents and Kara Seas play an important role in the slowed rate of wintertime Arctic amplification.

Slowdown of wintertime Arctic amplification since 2012

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Received: October 25, 2024; Accepted: March 4, 2025; Published Online: March 13, 2025; <https://doi.org/10.59717/j.xinn-geo.2024.100130>

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Citation: Luo N., Li J., Xiao C., et al. (2025). Slowdown of wintertime Arctic amplification since 2012. *The Innovation Geoscience* 3:100130.

A significant climate phenomenon “Arctic amplification” emerged during the late twentieth century, wherein the Arctic warming is faster than the rest of the world. However, recent episodes of the decreased rate of Arctic sea ice loss may bring prominent alterations to this uneven warming trend. Here, we re-evaluate the warming pattern, revealing an obvious slowdown of winter Arctic amplification since 2012, which probably contributes to the recent reversal in the winter surface wind speed in boreal midlatitudes. This slowdown may be attributed to the clearly slowed Arctic sea ice loss, especially in the Barents and Kara Seas, which is modulated by the weakened Atlantic Meridional Overturning Circulation. Our findings emphasize the urgent need for a more intensive analysis of the recent Arctic warming trend and its consequences for the broader Earth system.

INTRODUCTION

The global mean surface temperature has risen by about 1.1°C above preindustrial temperature,¹ making it the warmest period in the history of modern civilization, especially in the Arctic.² The Arctic has warmed 2 to 4 times faster than the globe as a whole, often called as Arctic amplification.^{3,4} This has been the most prominent and robust feature of the climate system in the past two decades,⁵ clearly indicating the Arctic's high vulnerability to climate change. The phenomenon of Arctic amplification is evident in observations⁶ and climate models⁷ as well as proxy paleoclimate records.⁸

The amplified Arctic warming has triggered a range of impacts on the Arctic climate system, including reduction of sea ice extent and thickness,⁹ melting of the Greenland ice sheet,¹⁰ carbon release from thawing permafrost,¹¹ and the weakening of the Atlantic Meridional Overturning Circulation (AMOC).¹² Arctic amplification also affects changes in weather patterns and extreme weather events in the midlatitudes, such as extreme cold events,¹³ heat waves,¹⁴ variations in the westerly jets,¹⁵ extreme precipitation events,¹⁶ and forest fires.¹⁷ In addition, Arctic amplification can also exert significant impacts on tropical climate systems, including El Niño–Southern Oscillation (ENSO), monsoon circulation, and tropical cyclone.^{18–20}

Given the far-reaching impacts of Arctic amplification on human and natural systems, it's crucial to understand whether Arctic amplification will continue with ongoing greenhouse warming. It is generally agreed that the majority of Arctic amplification is closely associated with Arctic sea ice loss.^{9,21,22} However, recent studies have revealed the weakened impact of sea ice on Arctic amplification during the twenty-first century.^{23,24} This raises the possibility that the rate of Arctic amplification might become slowdown in recent decades. In this paper, we provide observational evidence of the recently apparent slowdown of Arctic amplification during the winter season (from December to February) when Arctic amplification is strong (Figure S1).⁶ We show that the slowed sea ice loss in the Arctic might contribute to the slowdown of winter Arctic amplification. Our results offer a new insight that the wide impacts of winter Arctic amplification on natural ecosystems and life-supporting environments have changed in recent years.

MATERIALS and METHODS

Datasets

Five monthly surface temperature datasets were used in this study: (1) the

European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis fifth generation (ERA5; 1940–2024),²⁵ (2) the National Centers for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) Reanalysis 1 (NCEP1; 1948–2024),²⁶ (3) the National Centers for Environmental Prediction Reanalysis 2 (NCEP2; 1979–2024),²⁷ (4) the Japanese 55-year Reanalysis (JRA55; 1958–2024),²⁸ (5) the Berkeley Earth observations (BEST; 1950–2024).²⁹ Two monthly sea ice concentration datasets were used: (1) the Met Office Hadley Centre Sea Ice and SST dataset version 1 (HadISST; 1871–2024),³⁰ (2) the National Snow and Ice Data Center (NSIDC; 1978–2023).³¹ The monthly salinity field was derived from the Hadley Centre EN4 dataset (EN4; 1990–2024).³² Three monthly SST datasets were used: (1) the NOAA Extended Reconstructed SST V5 (ERSST; 1854–2024),³³ (2) the Centennial in situ Observation-Based Estimates SST version 2 (COBESST; 1850–2024),³⁴ (3) the Hadley Center Sea Ice and SST dataset version 1 (HadISST; 1871–2024).³⁰ The observed surface wind speed dataset was taken from the Global Surface Summary of the Day (GSOD; 1929–2024) dataset.³⁵

The definition of Arctic amplification index

We followed the definition³⁶ of Arctic amplification index as the difference in surface temperature between the Arctic (65°N–90°N) and Northern Hemisphere (0°–90°N). We also defined Arctic amplification index as the difference in surface temperature between 65°N–90°N (60°N–90°N) and 30°N–50°N (0°–60°N) used in previous studies^{37,38} and the ratio of the Arctic to the global mean surface temperature using a 19-year window.³⁹

The definition of slowdown

The slowdown in Arctic amplification primarily refers to the definition of global warming hiatus used in previous literature⁴⁰ but has slight modifications: if the estimated short-term trend of Arctic amplification is lower than the preceding short-term trend and generally shows a continuous decrease, this characterizes a slowdown.

The definition of AMOC intensity

To estimate the observed AMOC intensity, two indirect AMOC indicators were employed due to the inadequacy of direct observation data. The first indicator was used from the salinity, following the criteria below. Given that the AMOC carries salty water from the subtropical to the subpolar region, it was characterized by the integrated salinity in 0–1500 m and 45°N–65°N in the Atlantic.⁴¹ The second indicator was defined as the difference between subpolar North Atlantic (65°W–0°; 45°N–63°N) sea surface temperature (SST) and global mean SST during winter.⁴²

Selection of observed wind speed stations

We applied strict criteria to selecting stations of GSOD. First, stations covering the entire 46 years from 1978 to 2023, with each year having continuous records in winter, were selected; second, an effective month was calculated when the month has at least 15 days records. The approach has been widely used in previous studies.^{43,44} We also relaxed our selection criteria to obtain more stations, for instance by allowing one month in one year with missing data.

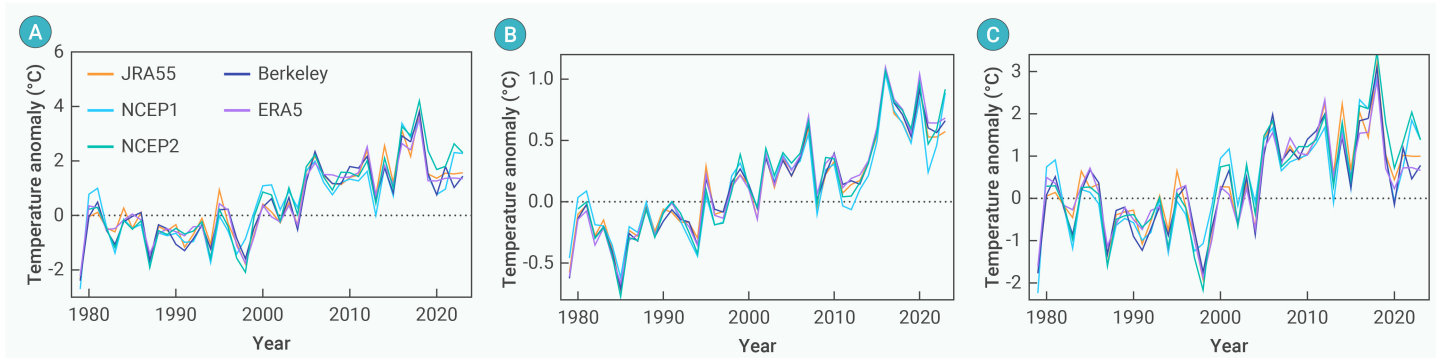


Figure 1. Temporal evolution of winter surface temperature anomalies (A) Temporal evolution of winter surface temperature anomalies in the Arctic (65°N–90°N). (B), (C) Same as (A), but for the Northern Hemisphere (0°–90°N), differences between the Arctic and Northern Hemisphere from 1978 to 2023, respectively. Colored lines represent different datasets.

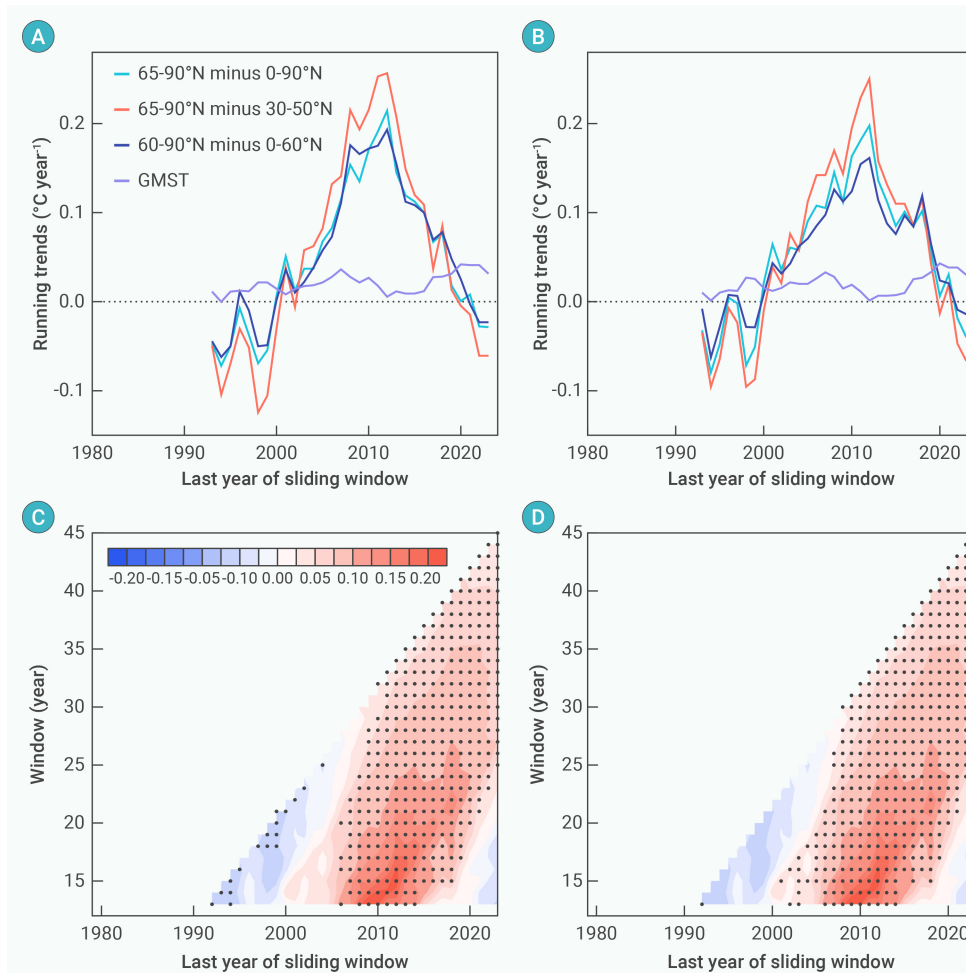


Figure 2. The trends of Arctic amplification and global mean surface temperature during winter (A) Winter Arctic amplification trend (the cyan, red and blue lines represent different Arctic amplification indices defined using different regions, respectively) and global mean surface temperature (GMST) trend (purple lines) from the ERA5 dataset. (B) Same as (A), but for the Berkeley dataset. The trend is calculated using a 15-year running window during 1978–2023. (C) The trends of winter Arctic amplification as a function of different windows from the ERA5 dataset. (D) Same as (C), but for the Berkeley dataset. The dotted areas denote significant values at the 90% confidence level.

subsequent analyses primarily utilize only two datasets, the ERA5 and Berkeley.

We note that the Arctic winters have continued to warm since the 1990s (Figure 1A). However, the rate of winter Arctic amplification index (estimated as the difference of winter surface temperature between the Arctic and Northern Hemisphere³⁶ (see Methods) is relatively small before the late 1990s, increases steadily to a peak around 2012, and then decreases rapidly (Figure 2). However, the rate of winter global warming generally shows a continuous increase since 2012. This indicates that the rate of winter Arctic amplification becomes slowdown post-2012. This phenomenon is robust, regardless of the running window (Figures 2C–D) and definition of the Arctic amplification index (see Methods; Figure S2).

Spatial analysis further confirms the recent slowdown of winter Arctic amplification. Most Arctic regions (north of 65°N) exhibit significant winter warming trends during 1978–2012 (Figures 3A–B), with the Barents Sea and Kara Sea (BKS) experiencing a maximum warming rate of around 0.4 °C year^{−1}. Regional winter cooling trends occur over midlatitude Eurasia. This meridional dipole pattern, known as the warm Arctic–cold Eurasian pattern, has been documented in previous studies.^{50,51}

Conversely, most Arctic regions display a negative trend in winter surface temperature from 2012 to 2023, with an obvious cooling rate of around −0.6 °C year^{−1} in the BKS (Figures 3C–D), while midlatitude regions exhibit a warming trend. This dipole pattern seems to experience a reversal after 2012. Furthermore, in conjunction with the slowdown of winter Arctic amplification, the zonally-averaged winter surface temperature trend also reveals a reversal between the two periods (Figures 3E–F).

The reversal of trends in winter surface temperature between the Arctic and midlatitudes may lead to an increase in meridional surface temperature gradients (Figure S3) and thus an increase in winter surface wind

Significance tests

The Mann–Kendall (M-K) nonparametric test was used together with the Sen's slope estimation for qualifying the trends of surface temperature, surface wind speed and sea ice concentration.^{45–47} The M-K test is a nonparametric statistical test and there is no requirement for the data to meet the assumption of normal distribution. Moreover, the M-K test has also ability to estimate the trend in nonlinear time series.^{48,49}

RESULTS

The observed slowdown in Arctic amplification

We investigate the evolution of winter surface temperature in the Arctic and Northern Hemisphere during 1978–2023 using five datasets (Figure 1). The changes of winter surface temperature in two regions are generally consistent across different datasets (Figures 1A–B) and their differences in anomalies remain minor (Figure 1C). Owing to the high agreement across datasets, our

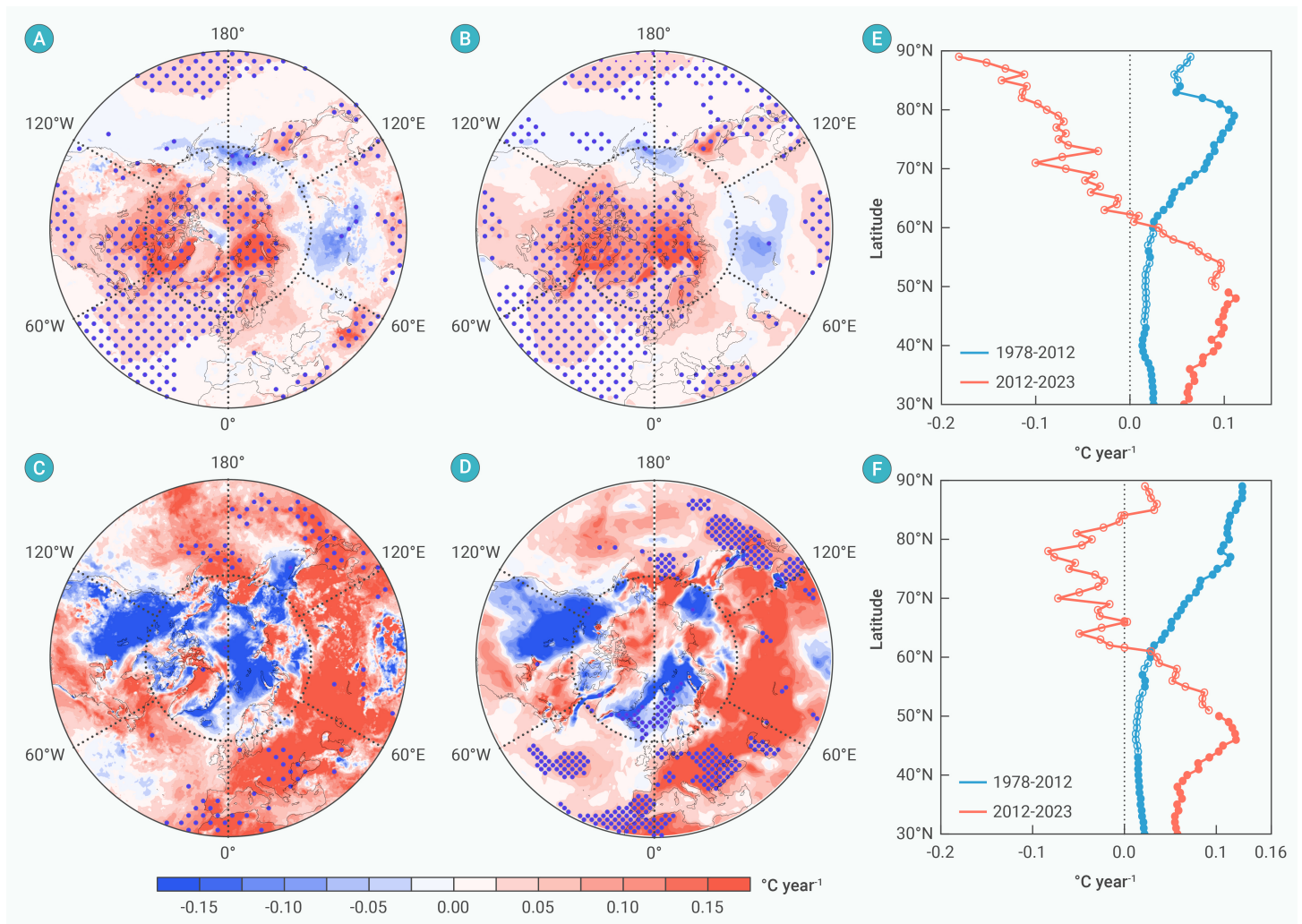


Figure 3. Surface temperature trend pattern and zonally averaged surface temperature trend during winter Spatial patterns of winter surface temperature trend for the periods 1978–2012 from the ERA5 dataset (A) and Berkeley dataset (B), respectively. (C), (D) Same as (A), (B), but for the periods 2012–2023. The dotted areas denote significant values at the 90% confidence level. (E) The zonally averaged winter surface temperature trends for the periods 1978–2012 (blue lines) and 2012–2023 (red lines) from the ERA5 dataset. Solid dots represent significant trends at the 90% confidence level, while hollow dots indicate no significant trends. (F) Same as (E), but from the Berkeley dataset.

speed in the midlatitudes (35°N–50°N). Spatially, a majority (61.13%) of the stations in the midlatitudes, where winter surface wind speed has decreased significantly for the period of 1978–2012, exhibit positive trends since 2012. Specifically, in North America (170°W–40°W; 35°N–50°N), Europe (20°W–10°E; 35°N–50°N) and Asia (85°E–130°E; 35°N–50°N), the stations show upward trends post-2012 at a ratio of 72.30%, 57.63% and 57.14%, respectively (Figures 4A–B). The reversal is also detected in the zonal average of winter surface wind speed trend in the midlatitudes. Before 2012, the surface wind speed in the midlatitudes shows a significant decreasing trend of $-0.1 \text{ m s}^{-1} \text{ decade}^{-1}$ ($p < 0.01$). Since 2012, however, a rapid increasing trend of $0.05 \text{ m s}^{-1} \text{ decade}^{-1}$ ($p < 0.1$) occurs over the same region (Figure 4C), which corresponds well with the strengthened meridional temperature gradient bands (Figure S4). The results remain unchanged after excluding the inhomogeneous stations or increasing the number of stations (Figure S5). Previous research has attributed the surface wind speed reversal around 2010 at global scales to decadal shifts in the global ocean-atmosphere oscillations.⁴³ This finding suggests that the reversal in winter surface wind speed in the midlatitudes may be linked to the slowdown of winter Arctic amplification in recent decades.

Potential causes of the slowdown in winter Arctic amplification

Considering the definition of the winter Arctic amplification index (see Methods), we first investigate how changes in winter surface temperature in the Arctic and the Northern Hemisphere individually contribute to the slowdown of winter Arctic amplification. The rate of Arctic winter warming has

slowed since 2012, while the rate of warming in Northern Hemisphere shows a continuous increase (Figure 5A). This result suggests that the slowdown of winter Arctic amplification may be primarily attributed to the decreased winter warming rate in the Arctic.

The winter surface warming in the Arctic is a result of local and remote forcings and feedbacks.⁵² Under the influence of greenhouse warming, winter Arctic sea ice loss is expected to increase. This change can lead to more heat release from the ocean into the atmosphere, thereby modulating Arctic winter surface warming.^{9,21,22} We speculate that changes in the rate of winter Arctic sea ice loss may lead to the slowdown of winter Arctic amplification. To test such speculation, we analyze the change in Arctic winter sea ice. The rate of Arctic winter sea ice loss is relatively small before the late 1990s, peaks around 2012, and becomes slowdown thereafter (Figure 5B). This shift in Arctic winter sea ice loss coincides well with the rate of winter Arctic amplification (Figure 2).

Previous studies have shown that winter sea ice loss in the BKS accounts for a large portion of the overall Arctic sea ice loss during winter.⁵³ We find that during the period of slowdown of winter Arctic amplification, the change of Arctic winter sea ice primarily occurs in the BKS (Figure S6). At the same time, the obvious cooling trends in the BKS also contribute to a large part of the observed Arctic winter cooling trends (Figure S7). These findings suggest that the slowed decline of sea ice in the BKS (Figure S8) seems to have made a major contribution to the recent slowdown of winter Arctic amplification. Some studies have also emphasized the BKS's importance in modulating Arctic amplification through influencing Arctic sea ice loss, as it serves as the

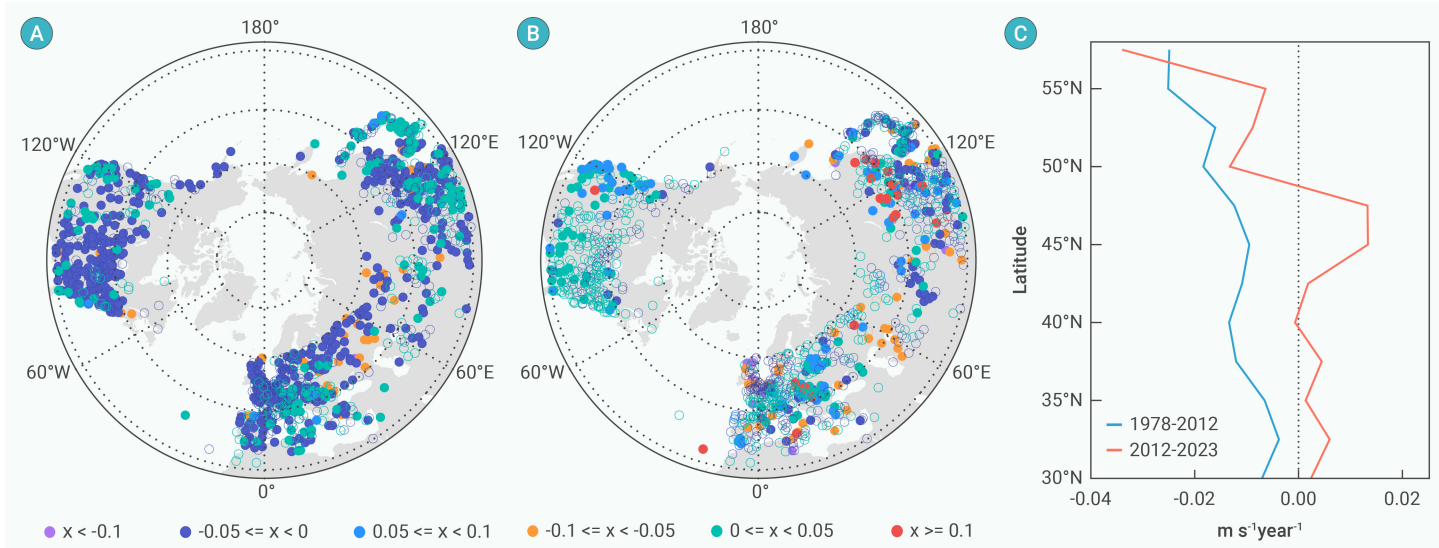


Figure 4. Observed surface wind speed trend pattern and zonally averaged surface wind speed trends during winter (A) Spatial patterns of observed winter surface wind speed trend in the midlatitudes during 1978–2012. (B) Same as (A), but during 2012–2023. Solid colored dots are stations that pass the 90% confidence level, while hollow colored dots are stations without a significant trend. (C) The zonally averaged winter surface wind speed trend during 1978–2012 (blue line) and 2012–2023 (red line).

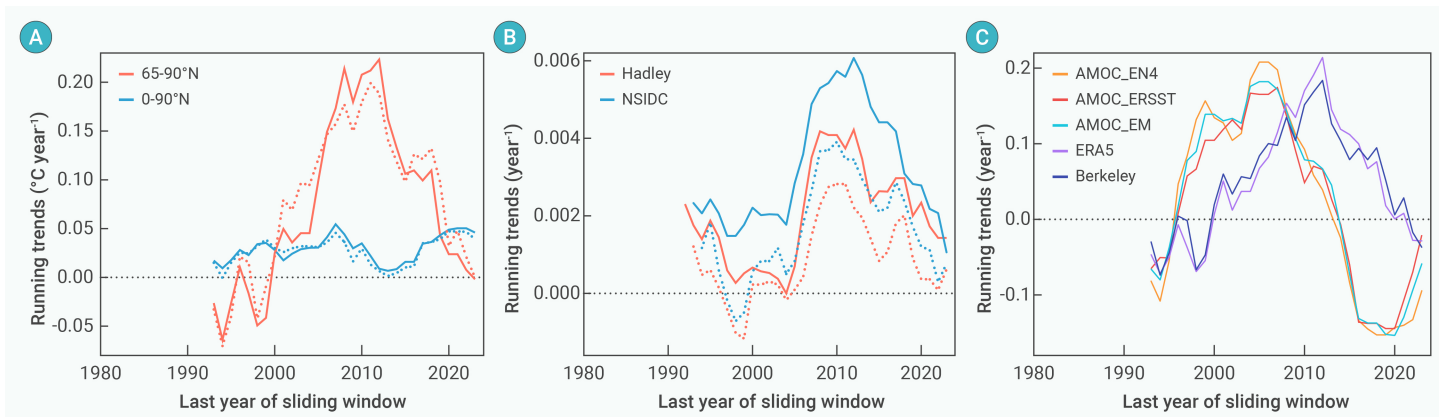


Figure 5. The trends of surface temperature, Arctic sea ice loss, AMOC strength and Arctic amplification during winter (A) Winter surface temperature trend in the Arctic (red lines) and in the Northern Hemisphere (blue lines). The solid and dashed lines are derived from the ERA5 and Berkeley datasets, respectively. (B) Winter (dashed lines) and annual-mean (solid lines) Arctic sea-ice loss rates multiplied by -1, derived from the Hadley (red lines) and NSIDC (blue lines) datasets. (C) The trend of standardized winter AMOC strength (the orange and red line represent the trends of different AMOC indicators; the cyan represents the ensemble mean of AMOC indicators), winter Arctic amplification trend from the ERA5 (purple line) and Berkeley (blue line) datasets. The trend is calculated using a 15-year moving window.

only warm Atlantic currents' gateway to the Arctic Ocean.^{53,54}

What drives the winter sea ice loss in the BKS? Earlier studies have suggested that the change in AMOC-driven heat transport can modulate the rate of winter sea ice loss in the BKS¹² through affecting the sea surface temperature (SST) warming in the BKS. It has been reported that the AMOC strength shows an upward trend since the mid-1990s, reaches a peak around the mid-2000s, and subsequently declines.^{41,42} We also find that the AMOC weakens approximately in 2004 (Figure 5C), which leads the slowdown of winter Arctic amplification by around 8 years (a significant correlation ($r = 0.79$, $p < 0.01$) is found when the trend of winter AMOC leads winter Arctic amplification by 8 years for the periods of 1978–2023). We then examine the rate of winter SST warming in the BKS and find that the warming rate has rapidly decreased since 2012 (Figure 6). The ocean-induced variability of SST in the BKS lags behind the AMOC, possibly because the Atlantic Ocean heat transport associated with the AMOC takes several years to reach the BKS.^{55,56} The composite differences in SST regressed with the AMOC between pre-2012 and post-2012 show a cooling in the BKS (Figure S9). The BKS SST cooling would subsequently lead to decreased sea ice loss, which in turn results in reduced upward sensible and latent heat flux (Figure S10B), as well as decreased upward longwave radiation (Figure S11B), thereby facilitating a reduction in surface temperature. These results imply that the weakening of AMOC during winter could lead to a decreased rate of sea ice loss in the BKS by affecting SST there, which subsequently contributes to the slowdown of

winter Arctic amplification.

DISCUSSIONS and CONCLUSIONS

In summary, we find that the rate of winter Arctic amplification has lessened since 2012, which is associated with the recent reversal in winter surface wind speed in the midlatitudes (35°N–50°N). The slowdown is primarily attributed to the decreased rate of Arctic sea ice loss. In particular, the change in winter sea ice in the BKS plays an important role in the slowdown of winter Arctic amplification. The weakened AMOC can mitigate sea ice loss in the BKS by decreasing the warming rate in SST there. These findings indicate a fundamental shift in uneven warming patterns in the Northern Hemisphere mid-to-high-latitude regions. This change may influence regional fire weather¹⁷ and the carbon balance of Arctic ecosystems.⁵⁷ However, given that the atmosphere continues to warm, Arctic sea ice may hit a tipping point in which rapid sea ice loss will begin again,⁵⁸ eventually influencing the rate of Arctic warming. Therefore, more attention should be paid to change of the rate of Arctic amplification.

Previous literature has demonstrated that the weakening of AMOC under greenhouse warming is due to lighter surface waters⁵⁹ arising from both the reduced heat loss to the atmosphere and increased freshwater fluxes at high latitudes. Lighter surface waters may be linked to reductions or collapses in deep convection within sinking regions, thereby affecting AMOC strength.⁶⁰ In addition, Arctic sea ice loss can lead to the AMOC decline with a multi-

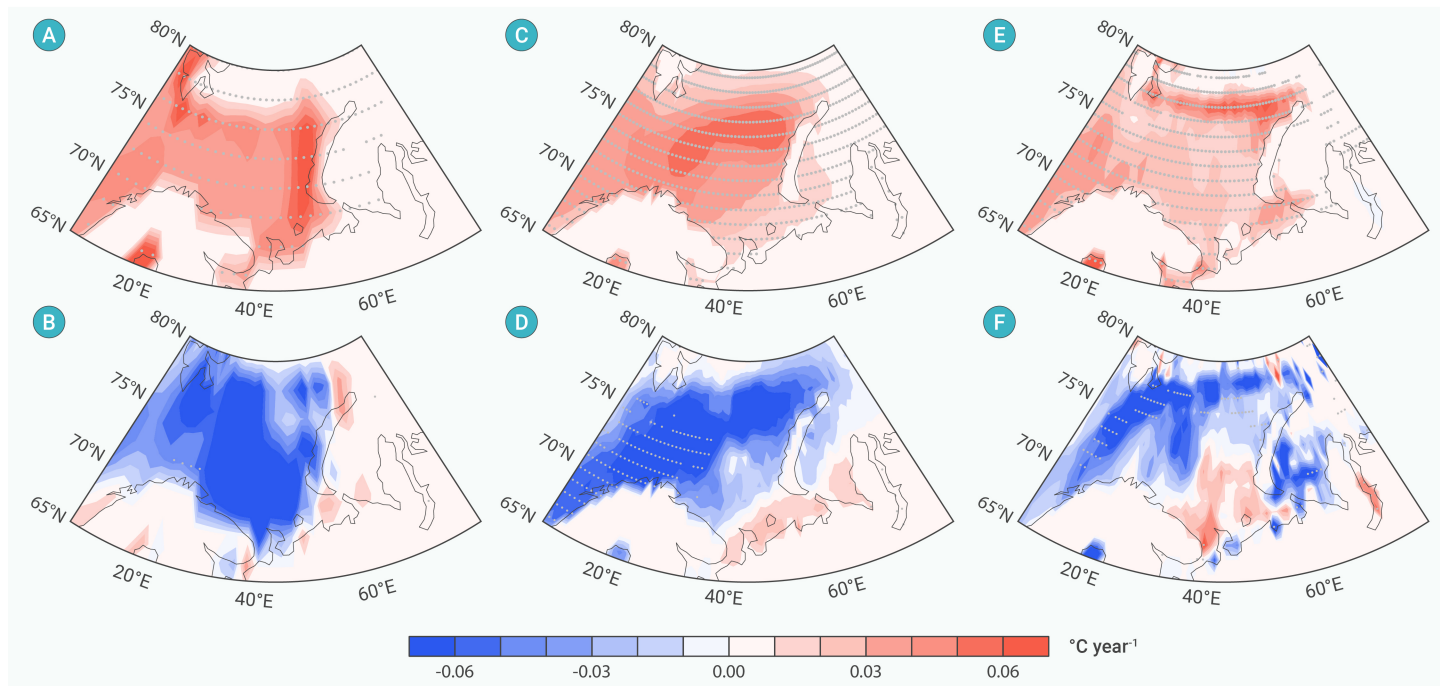


Figure 6. Spatial distributions of winter sea surface temperature trend Spatial distributions of winter sea surface temperature trend during 1978–2012 ((A), (C), (E)) and 2012–2023 ((B), (D), (F)), derived from the ERSST ((A), (B)), COBESST ((C), (D)) and HadISST ((E), (F)) datasets, respectively. The gray dots denote significant values at the 90% confidence level.

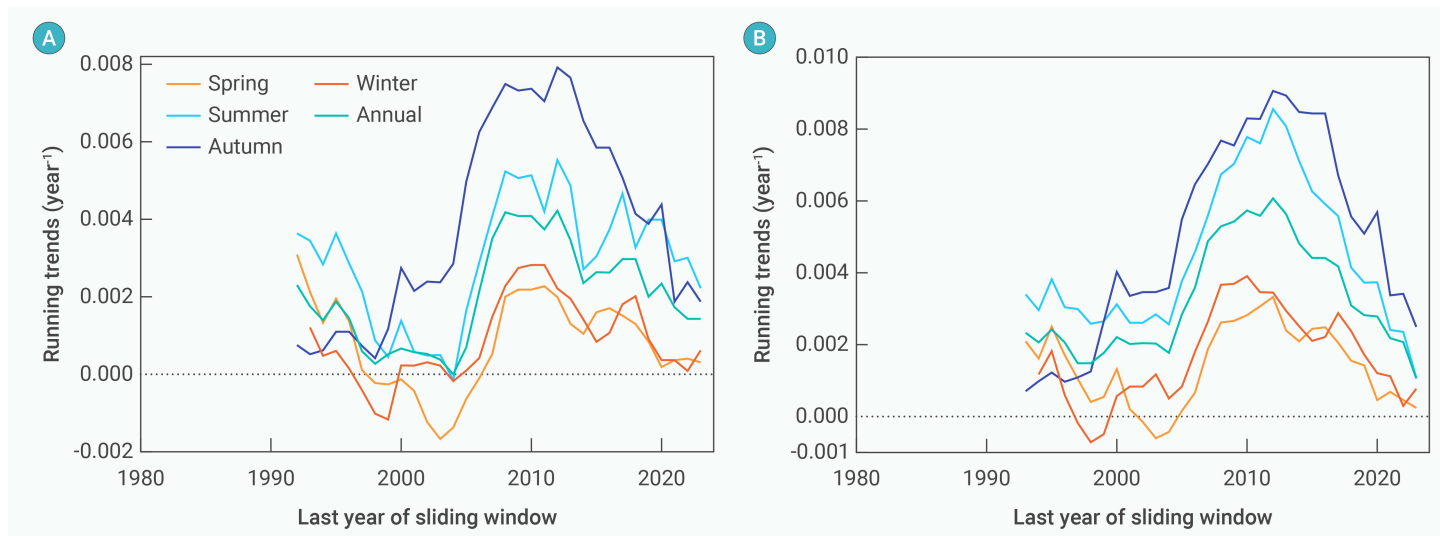


Figure 7. Seasonal and annual mean Arctic sea ice loss rates The rate of Arctic sea ice loss multiplied by -1 using a 15-year running window during 1978–2023, derived from the Hadley (A) and NSIDC (B) datasets. The orange, cyan, blue, red and green lines represent spring (from March to May), summer (from June to August), autumn (from September to November), winter (from December to February) and annual mean Arctic sea ice loss rates, respectively.

decadal delay through strengthening the upper ocean stratification.⁶¹ At the same time, the AMOC decline can also decelerate the decline rates of Arctic sea ice loss with several years lag.⁶² This implies that there may exist complex feedback between changes in Arctic sea ice and the AMOC, which remains to be explored in the future.

Previous studies have demonstrated that the decrease in Arctic sea ice loss due to the AMOC slowdown is a primary contributor to the diminished rate of Arctic amplification.⁶³ We find that the correlation between the rate of Arctic amplification and Arctic sea ice loss in winter is 0.87 ($p < 0.01$) from 1978 to 2023, indicating that variations in Arctic sea ice may account for roughly 75.69% of changes in Arctic amplification. However, changes in Arctic amplification can also influence changes in Arctic sea ice. Thus, quantitatively estimating the contribution of Arctic sea ice loss to the slowdown of Arctic amplification needs further investigation through numerical experiments. In addition, previous studies have reported that the Atlantic Multi-

decadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO) are important drivers of Arctic warming in the early 20th century,⁶⁴ and the combination of the different phases of the AMO and PDO modulates Arctic warming.^{65–67} The combined influences of the AMO, PDO, and AMOC on the slowdown of wintertime Arctic amplification need further study.

Our results have revealed that the slowdown of Arctic amplification is most pronounced in winter. Although not as pronounced as in winter, the rate of Arctic amplification is also found to decrease in spring (from March to May; Figures S12–13). In contrast, the slowdown is not obvious in autumn (from September to November) when Arctic amplification itself is also strong (Figure S1). This is probably because the rate of Arctic sea ice loss is relatively large and does not change much during autumn (Figure 7). Therefore, it is possible that the response of Arctic amplification in autumn to the weakened AMOC is weaker than that in winter. This point will be further explored in future research.

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FUNDING AND ACKNOWLEDGMENTS

This research was supported by the National Natural Science Foundation of China (42225501) and the Fundamental Research Funds for the Central Universities (2243300004). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

AUTHOR CONTRIBUTIONS

R.Q.D. and N.L. designed the study and wrote the paper. N.L. performed the analyses. J.P.L., C.D.X., Y.H.F., X.Y.L., C.S. and B.H. improved the manuscript. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

All datasets used in the paper are publicly available. The ERA5 is available at <https://cds.climate.copernicus.eu>. The NCEP1 is available at <https://psl.noaa.gov/data/ncep.reanalysis.html>. The NCEP2 is available at <https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html>. The JRA55 is available at https://jra.kishou.go.jp/JRA55/index_en.html. The Berkeley is available at <https://berkeleyearth.org/data/>. The Hadley Center Sea Ice and SST is available at <https://metoffice.gov.uk/hadobs/hadisst/data/download.html>. The NSIDC is available at <https://nsidc.org/data/g02202/versions/4>. The Hadley EN4 is available at <https://www.metoffice.gov.uk/hadobs/en4/download.html>. The ERSST is available at <https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html>. The COBESST is available at <https://psl.noaa.gov/data/gridded/data.cobe2.html>. The GSOD is available at <https://www.nci.noaa.gov/data/global-summary-of-the-day>. All relevant codes used in this study are available, upon request, from the corresponding author R.Q.D.

SUPPLEMENTAL INFORMATION

It can be found online at <https://doi.org/10.59717/j.xinn-geo.2024.100130>