

# No detectable trend in mid-latitude cold extremes during the recent period of Arctic amplification

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It is widely accepted that Arctic amplification—accelerated Arctic warming—will increasingly moderate cold air outbreaks to the mid-latitudes. Yet, an increasing number of recent studies also argue that Arctic amplification can contribute to more severe winter weather. Here we show that the temperature of cold extremes across the United States east of the Rockies, Northeast Asia and Europe have remained nearly constant over recent decades, in clear contrast to a robust Arctic warming trend. Analysis of trends in the frequency and magnitude of cold extremes is mixed across the US and Asia but with a clearer decreasing trend in occurrence across Europe, especially Southern Europe. This divergence between robust Arctic warming and no detectable trends in mid-latitude cold extremes highlights the need for a better understanding of the physical links between Arctic amplification and mid-latitude cold extremes.

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The Arctic has experienced accelerated warming, observed to be between two to four times greater in the Arctic relative to the rest of the globe<sup>1</sup>, which is known as Arctic amplification (AA). Coincident with part or all of the period of AA, regions of the mid-latitude continents have experienced a cooling trend, with the most pronounced and consistent winter cooling trends in the interior of both Eurasia and North America<sup>2–4</sup>. The simultaneous occurrence of a relatively warm Arctic and cold continents is referred to as the warm Arctic/cold continents pattern<sup>5</sup>. Whether the juxtaposition of the two opposite anomalies, a north-south dipole, are coincidental and physically unrelated or whether the two are dynamically linked whereby the rapidly warming Arctic is contributing, at least in part, to more severe winter weather in parts of Eurasia and/or North America, has been debated for at least a decade and remains unresolved<sup>3</sup>. However, in recent years, targeted community-wide efforts have been developed to work toward a consensus view<sup>6</sup>.

Despite the accelerated Arctic warming, there have been a surprising number of historic cold air outbreaks in the United States (US) and Asia in recent years, which may even be increasing<sup>4, 7–10</sup> in frequency. In both 2021 and 2022, two of the deadliest and costliest US natural disasters have been related to extreme cold and/or heavy snowfall<sup>11</sup>. These societally impactful extreme weather events have garnered much media attention<sup>12–15</sup>.

Overall, however, global warming is clearly reducing the number of cold extremes<sup>16</sup>. A common argument applied to mid-latitude cold events is that, given that the Arctic is the source region for cold extremes across the mid-latitudes, as the Arctic warms more rapidly than other regions of the globe, cold extremes will moderate or warm and occur less often<sup>17–19</sup>. A recent report from the National Academies of Science when assessing the change in frequency of all weather extremes, was most confident in the decrease of cold extremes<sup>20</sup>.

The recent events in the US and Asia suggest that there may be exceptions to the overall decreasing trend in cold extremes, and that the link between AA and cold extremes may not be straightforward and linear but rather more complex. In particular, the potential for AA to contribute to a dynamical cooling across the mid-latitudes that at least partially offsets radiational and thermodynamic warming of the Arctic needs to be considered. It has been shown that a local anomalous meridional circulation, especially blocking, plays an important role in bridging AA and mid-latitude extreme cold events<sup>21</sup>. It has been a recent topic of interest if AA can increase or amplify meridional circulations, especially blocking events.

There are two generalized theories as to how AA can contribute to an increased meridional circulation that delivers severe winter weather across the mid-latitudes. The first theory is that a weakening of the equator-to-North Pole temperature gradient results in a slackening of the westerly jet stream, which then favors more amplified and more slowly eastward propagating large scale- or Rossby-waves across the mid-latitudes. The more amplified and persistent flow contributes to more extreme weather in general, including more severe winter weather<sup>22</sup>. The second theory is that heterogenous heating across the Arctic forced by uneven melting sea ice and/or greater snowfall across the continental regions of the Arctic acts to amplify or persist high latitude blocking that forces a weaker stratospheric polar vortex<sup>23,24</sup>. In apparent support of this theory, the frequency of severe winter weather across the mid-latitudes increases following a relative weak and distorted stratospheric polar vortex<sup>2,4</sup>.

In an effort to better contextualize the relationship between AA and mid-latitude cold extremes, we conduct a comprehensive trend analysis starting before and during the period of AA. For our

analysis we have computed trends spanning the winter season of both Arctic temperatures and extreme cold in the major population centers of the Northern Hemisphere mid-latitudes: the Eastern US, Northeast Asia, Northern Europe, and Southern Europe.

## Results

To test whether observational analysis shows that AA is contributing to a moderation or warming of cold extremes in the mid-latitudes, we computed temperature trends in both the daily cold extremes for the midlatitude regions and for the Arctic just prior to observed mid-latitude cold extremes. For each region, trends in both the number of events and the temperature of events are compared to the corresponding Arctic values for the period extending through the present and starting from three different starting points: 1960, 1990, and 2000. This allows a comparison of trend behavior over the longer period with the more recent period of AA. Since there is some disagreement about the start date of AA, with some studies arguing an earlier start date circa 1990<sup>2,25</sup> and some a later start date circa 2000<sup>26,27</sup>, we computed trends for both AA periods. Assuming that it takes a few days for the cold air to travel from the Arctic to the mid-latitudes and following the results of Li et al.<sup>28</sup> who found that the strongest high latitude circulation anomalies and associated cold air advection are observed three days prior to the greatest Eurasian cooling related to Arctic warming, we used a three-day lead time to compute Arctic temperatures; however, our results are not sensitive to choice of lead time. All cold extreme events are plotted as a series in sequential order. We then compute the winter trends starting in 1960 (decades earlier than the observed start of AA), and then we recompute the trends limited to the more recent period of AA, for both the longer and shorter definitions.

We define a cold extreme when the December, January and February (DJF) daily average temperature falls below the 5th percentile of the daily average temperature distribution for DJF (see Methods). As for many extreme weather events there is no single standard definition of cold extremes. Thompson and Wallace<sup>29</sup> and Tang et al.<sup>30</sup> define cold extremes as when the daily minimum temperature drops below the threshold of 1.5 standard deviations of the seasonal mean. Johnson et al.<sup>31</sup> define a cold extreme when the maximum temperature anomaly based on the seasonal mean for a given day falls below the 10th percentile of the maximum temperature anomaly distribution of 5-day rolling means. van Oldenborgh<sup>32</sup> defined a cold extreme as the lowest minimum temperature at any given location. At the end of our study, we repeated the analysis with other previously used definitions of cold extremes and did not find that our conclusions are sensitive to a specific definition.

For this analysis, we define four mid-latitude regions and an Arctic region. The Arctic region is defined as the area poleward of 70°N, to closely match the region of accelerated warming in Fig. 1 of the analysis of Rantanen et al.<sup>1</sup>. We also analyze four mid-latitude regions to compute regional average temperatures and cold extremes, with the regions chosen based on societally impactful cold events and their relationship to high-latitude variability. The regions are the Central-Eastern US region (labeled CEUS), the Northeast Asia region (labeled SSNC for Southern Siberia/Northern China), Northern Europe (NEUR) and Southern Europe (SEUR), outlined with boxes in Fig. 1. The teleconnection index that is most closely related with extreme winter weather in the mid-latitudes is the Arctic Oscillation (AO)<sup>29</sup> where the negative polarity is associated with an increase in severe winter weather including below- to well below-normal temperatures widespread across the mid-latitudes. This index is also the teleconnection pattern most closely associated with stratospheric polar vortex variability<sup>33</sup>, where a weak

stratospheric polar vortex favors the negative polarity of the AO and widespread below-normal temperatures across the mid-latitudes<sup>34</sup>. In Fig. 1 we show the regression of the negative polarity of the North Atlantic Oscillation (NAO), which we treat as equivalent to the AO, and Northern Hemisphere surface temperatures. The three mid-latitude regions where cold air outbreaks are most strongly related to a negative NAO or AO are the US east of the Rockies, East Asia and Northern Europe (CEUS, SSNC, and NEUR, respectively). Siberian surface temperature is also highly sensitive to NAO or AO variability but is of less interest because of its northern latitude and sparse population.

We also analyze a fourth region where cold air outbreaks are less common, Southern Europe (SEUR), for comparison. This is one region in the mid-latitudes where below-normal temperatures are not associated with a negative AO or NAO and a weak stratospheric polar vortex. Additionally, as will be shown, it is in clear contrast from the other three analyzed regions in that it has a consistent trend for all three periods analyzed in this study and in previous studies when mid-latitude cooling trends were more widespread and of greater magnitude (see Fig. 2 of Cohen et al.<sup>2</sup>).

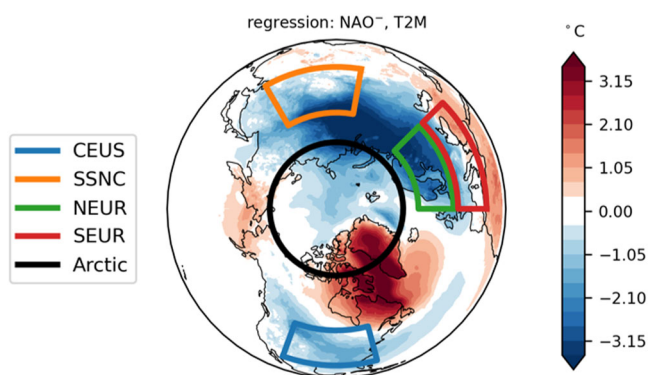
To provide seasonal context, the DJF seasonal mean surface temperature trends and the time series of winter surface temperature trends for each of the five regions analyzed in this study

(CEUS, SSNC, NEUR, SEUR and Arctic) are shown in Fig. 2. All trends are shown for all three periods: since 1960, 1990 and 2000. For the DJF seasonal mean, all four mid-latitude regions are warming but the Arctic is warming at least twice as fast as the mid-latitude regions since 1960 and 1990 consistent with the results of Cohen et al.<sup>2</sup>. However, since 2000, the warming trend in the Arctic has slowed while the warming in the mid-latitudes has accelerated and consequently, Arctic warming is comparable to the warming trend in the mid-latitudes since the beginning of the twenty-first century.

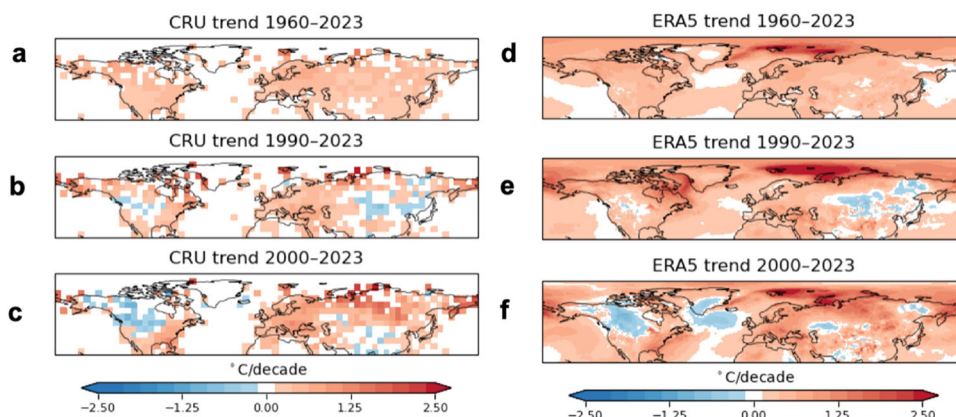
We then establish consistency with previous work by repeating the analysis of Cohen et al.<sup>2</sup> that showed since 1960 the entire Arctic and Northern Hemisphere (NH) extratropical land regions were warming using the Climate Research Unit (CRU) land station temperature version five (CRUTEM5) dataset derived from station data only to exclude any bias introduced by reanalysis. Here too, all land regions of the Northern Hemisphere are warming since 1960 (shown in Fig. 3). The NH trend analysis is consistent with the idea that global warming contributes universally to warming winter surface temperatures. Next, we repeat the trend analysis for both periods of AA since 1990 and 2000. Similar to the analysis in Cohen et al.<sup>2</sup>, over the period of AA cooling trends appear in the continental region of the mid-latitudes but are of smaller extent and magnitude than shown in Cohen et al.<sup>2</sup>. Interestingly, the cooling trend in North America has strengthened in the most recent period while it has weakened in Eurasia. It could be argued that the North American cooling since 2000 is more impressive than previous similar winter trend analysis during AA shown in Fig. 1 of Cohen et al.<sup>35</sup> and Fig. 2 of Cohen et al.<sup>2</sup>. In contrast, Eurasian cooling is weaker and contracted compared to earlier winter trend analysis.

For the remainder of the trend analysis, we use the fifth-generation ECMWF atmospheric (ERA5) reanalysis. The advantage of ERA5 is that coverage of the Arctic Ocean is complete in contrast to CRUTEM5 which is limited to land points only and the main focus of our analysis is to relate AA to mid-latitude cold extremes. For the period since 1960, ERA5 also exhibits universal warming across the Northern Hemisphere (Fig. 3). For the two AA periods, a general pattern of amplified Arctic warming with some cooling in the mid-latitudes is evident but the cooling is less in ERA5 when compared to CRU. It is beyond the scope of this study, but it is possible that ERA5 introduces a warm bias in the latter years of the record in the mid-latitudes that weakens the observed cooling trends.

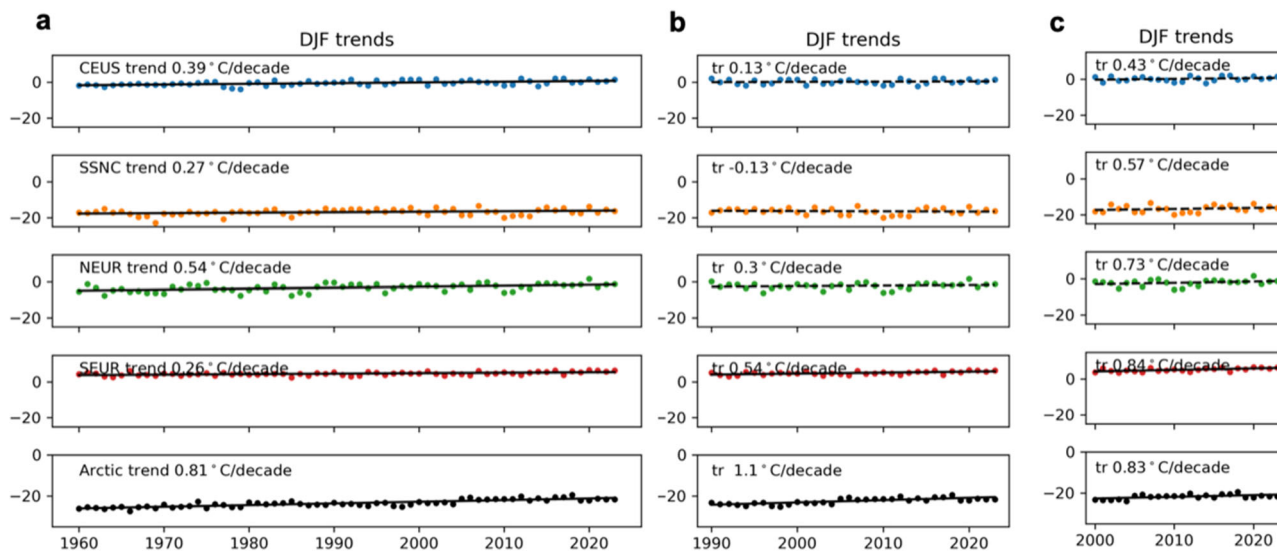
Next, in Figs. 4–7, we present the trends in cold extreme events for each of the midlatitude regions analyzed in comparison to the Arctic, in terms of both event number and temperature, for all three



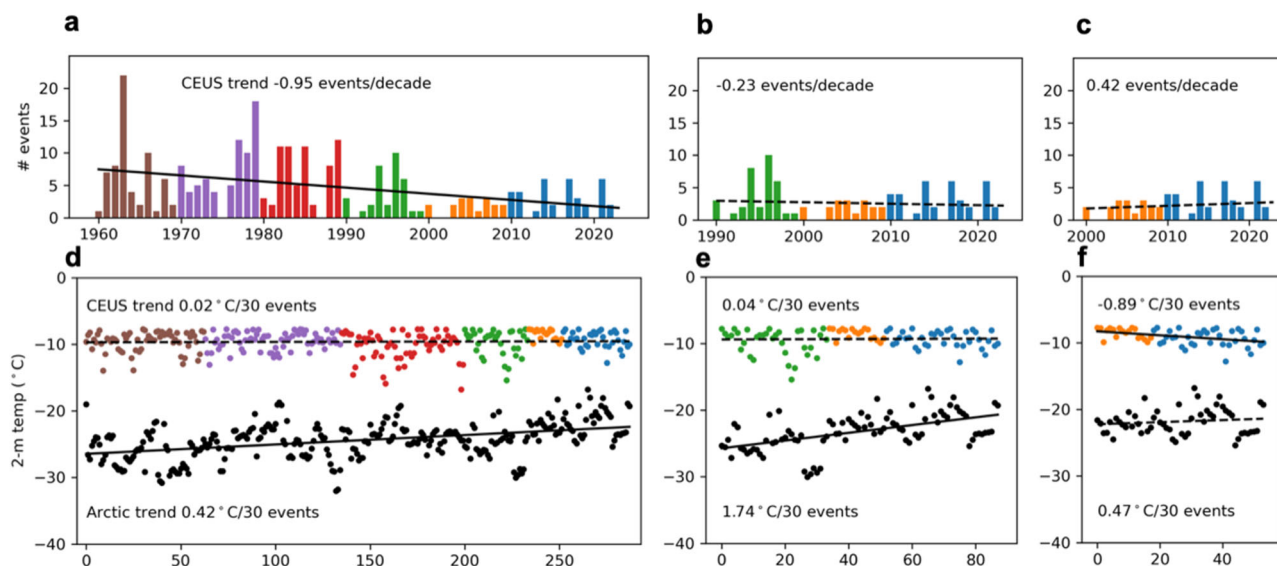
**Fig. 1 Eastern US, Northern Europe, and East Asia all share cold temperatures during the negative polarity of the NAO.** Northern Hemisphere December–February (DJF) surface temperatures are regressed onto the NAO index shown for the negative polarity. Also shown are the five regions of analysis: the Arctic and four mid-latitude regions, Central and Eastern US (CEUS), Southern Siberia and Northern China (SSNC), Northern Europe (NEUR), and Southern Europe (SEUR).



**Fig. 2 Arctic and mid-latitude temperature trends have been consistent since 1960 but in parts, diverge during AA.** Northern Hemisphere DJF temperature anomaly trends since **a** 1960, **b** 1990 and **c** 2000 using CRU data. **d–f** same as (**a–c**) but using ERA5.



**Fig. 3** Mid-latitude winter temperatures have been warming since 1960 but are mixed since 1990. **a** DJF temperature trend 1960–2023 from ERA-5 for the CEUS, SSNC, NEUR, SEUR, and Arctic regions, **b** same as (a) but for 1990–2023 and **c** same as (a) but for 2000–2023.

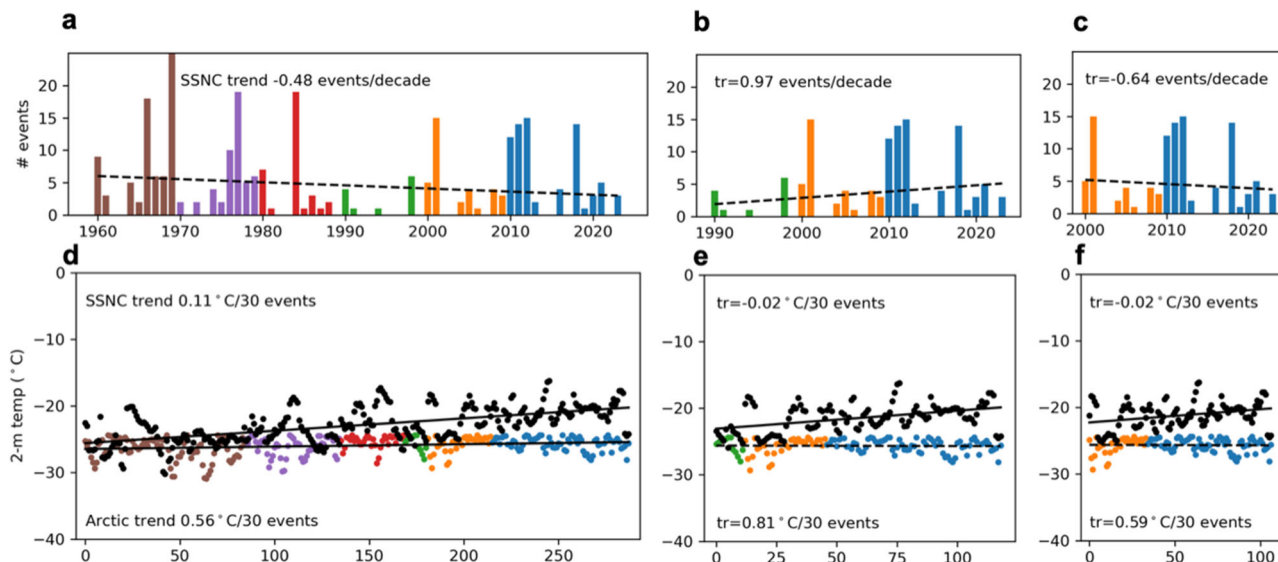


**Fig. 4** A robust warming trend is observed in the Arctic but no consistent trend is found for Eastern US cold extremes. Frequency of Central-Eastern US (CEUS; shown in Fig. 1) DJF 5% coldest events for (a) 1960–2023, (b) 1990–2023, and (c) 2000–2023, demarked with colored bars to represent each decade, and showing the linear trend line. The slope of the trend line is indicated in each panel (events/decade). The temperature for each cold CEUS event (colored dots) is shown in (d, e, and f) for the same time periods as in (a, b, and c). Corresponding Arctic temperatures are shown with black dots. The trend lines indicate tendency in temperature over the ordered events, and the slope of the trend is indicated in each panel ( $^{\circ}\text{C}$  per 30 events). Trend lines are shown solid if trend is significant at the 0.05 level, dashed otherwise.

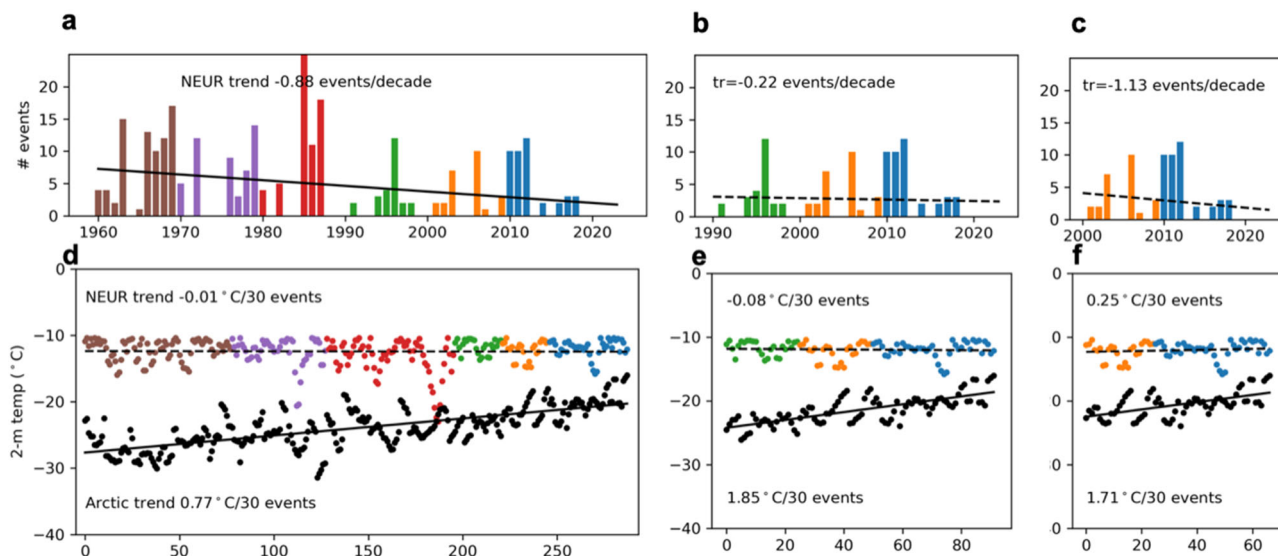
periods. In Fig. 4, we plot the annual frequency and area average surface temperature for the US east of the Rockies (CEUS; Fig. 1 blue box) for the 5% coldest DJF days of the entire period (color-coded by decade) and the Arctic (Fig. 1 bold black circle) surface temperature from three days earlier than the date of the observed cold extreme. Consistent with the universal warming of the NH there is a statistically significant decreasing number of extreme cold days in the US since 1960. Though there is a warming trend in the coldest days of the year, the trend is not statistically significant in contrast to the warming trend in Arctic temperatures, which is statistically significant. We then repeat the analysis limited to the two AA periods. The Arctic is warming for both AA periods but is only statistically significant for the longer period. In contrast, the

trend in CEUS cold extremes frequency is decreasing for the longer period but increasing for the shorter period, although neither trend is statistically significant. Similarly, the temperature trend of CEUS cold extremes is mixed for both AA periods. The only statistically significant trend in cold extremes for CEUS, is a statistically significant cooling trend for the shortest period since 2000. There is a clear divergence in the trends of Arctic temperatures, which are robustly warming, and cold extremes in the US, which exhibit no statistically significant trends during the period of AA and even for the longer period since 1960.

In Fig. 5, we repeat the analysis of Fig. 4 but for Northeast Asia (SSNC; Fig. 1 orange box) and the Arctic. Though there has been a decreasing number of extreme cold days in the SSNC region



**Fig. 5 A robust warming trend is observed in the Arctic but no consistent trend for Northeast Asia cold extremes.** Frequency of Northeast Asia (SSNC; see Fig. 1) DJF 5% coldest events for (a) 1960–2023, (b) 1990–2023, and (c) 2000–2023, demarked with colored bars to represent each decade, and showing the linear trend line. The slope of the trend line is indicated in each panel (events/decade). The temperature for each cold SSNC event (colored dots) is shown in (d, e and f) for the same time periods as in (a, b and c). Corresponding Arctic temperatures are shown with black dots. The trend lines indicate tendency in temperature over the ordered events, and the slope of the trend is indicated in each panel (°C per 30 events). Trend lines are shown solid if trend is significant at the 0.05 level, dashed otherwise.

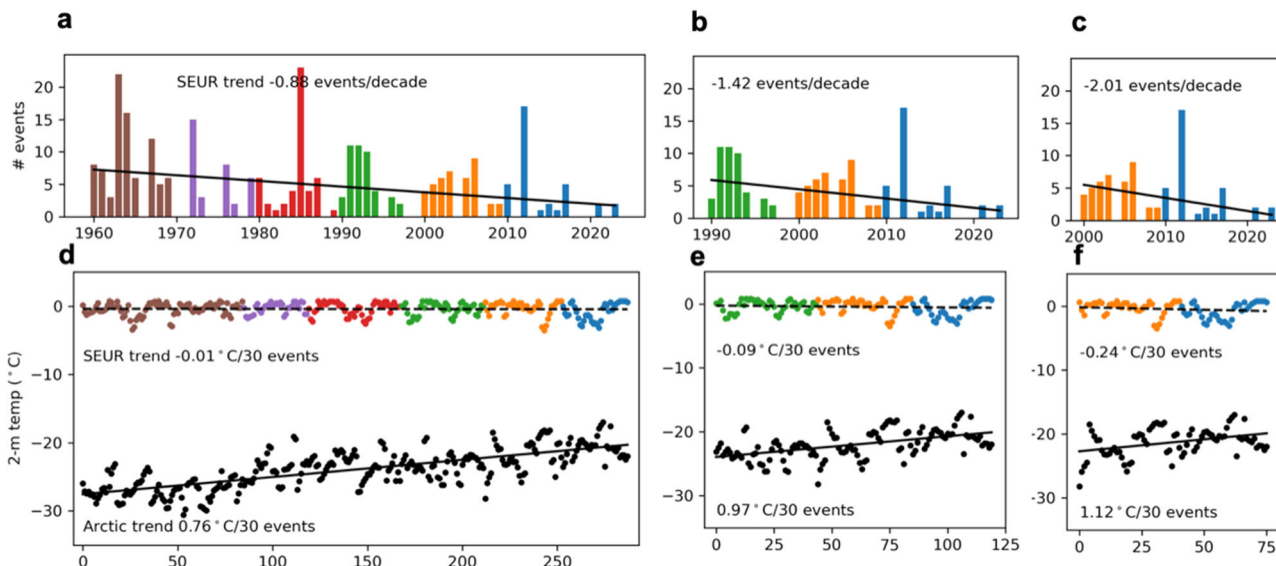


**Fig. 6 A robust warming trend is observed in the Arctic but no consistent trend is found in the magnitude of Northern Europe cold extremes.** Frequency of Northern Europe (NEUR; see Fig. 1) DJF 5% coldest events for (a) 1960–2023, (b) 1990–2023, and (c) 2000–2023, demarked with colored bars to represent each decade, and showing the linear trend line. The slope of the trend line is indicated in each panel (events/decade). The temperature for each cold NEUR event (colored dots) is shown in (d, e, and f) for the same time periods as in (a, b, and c). Corresponding Arctic temperatures are shown with black dots. The trend lines indicate tendency in temperature over the ordered events, and the slope of the trend is indicated in each panel (°C per 30 events). Trend lines are shown solid if the trend is significant at the 0.05 level, dashed otherwise.

since 1960, it is not statistically significant. Over the period of AA, the frequency of extreme cold days is mixed for Northeastern Asia with the frequency of extreme cold days increasing for the longer period of AA but decreasing for the shorter AA period, reversed of what is found the Eastern US. However, similar to the CEUS, the trend is not statistically significant. For both AA periods, there is a very slight negative trend in the temperature of coldest days of the year but again neither trend is statistically significant. Consistent with what was shown for North America, there is a clear divergence between the trends in Arctic

temperatures, which are robustly warming, and cold extremes in Northeast Asia, which exhibit no statistically significant trends over the period of AA.

To complete the analysis of those regions that experience frequent cold air outbreaks across the Northern Hemisphere during the negative polarity of the NAO or AO and/or a weak stratospheric polar vortex, we show the same analysis for Northern Europe (NEUR; Fig. 1 green box) in Fig. 6, despite that previous cooling trends in Europe (e.g., Cohen et al.<sup>2</sup>) have all but disappeared with the inclusion of the most recent winters, in



**Fig. 7 Southern Europe is experiencing a notable decrease in the frequency of cold extremes.** Frequency of Southern Europe (NEUR; see Fig. 1) DJF 5% coldest events for (a) 1960–2023, (b) 1990–2023, and (c) 2000–2023, demarked with colored bars to represent each decade, and showing the linear trend line. The slope of the trend line is indicated in each panel (events/decade). The temperature for each cold SEUR event (colored dots) is shown in (d, e, and f) for the same time periods as in (a, b, and c). Corresponding Arctic temperatures are shown with black dots. The trend lines indicate tendency in temperature over the ordered events, and the slope of the trend is indicated in each panel (°C per 30 events). Trend lines are shown solid if trend is significant at the 0.05 level, dashed otherwise.

**Table 1 Temperature trends show divergence between Arctic warming and mid-latitude cold extremes.**

	CEUS	Arctic	SSNC	Arctic	NEUR	Arctic	SEUR	Arctic
1960–2023	0.02	<b>0.42</b>	<b>0.11</b>	<b>0.56</b>	−0.01	<b>0.77</b>	−0.01	<b>0.76</b>
1990–2023	0.04	<b>1.74</b>	−0.02	<b>0.81</b>	−0.08	<b>1.85</b>	−0.09	<b>0.97</b>
2000–2023	−0.89	0.47	−0.02	<b>0.59</b>	0.25	<b>1.71</b>	−0.24	<b>1.12</b>

Temporal trend in CEUS, SSNC, NEUR, and SEUR DJF 5% coldest days and corresponding (3 days previous) Arctic temperatures (°C/30 events) from ERA-5. Bolded values are statistically significant at 0.05 confidence level.

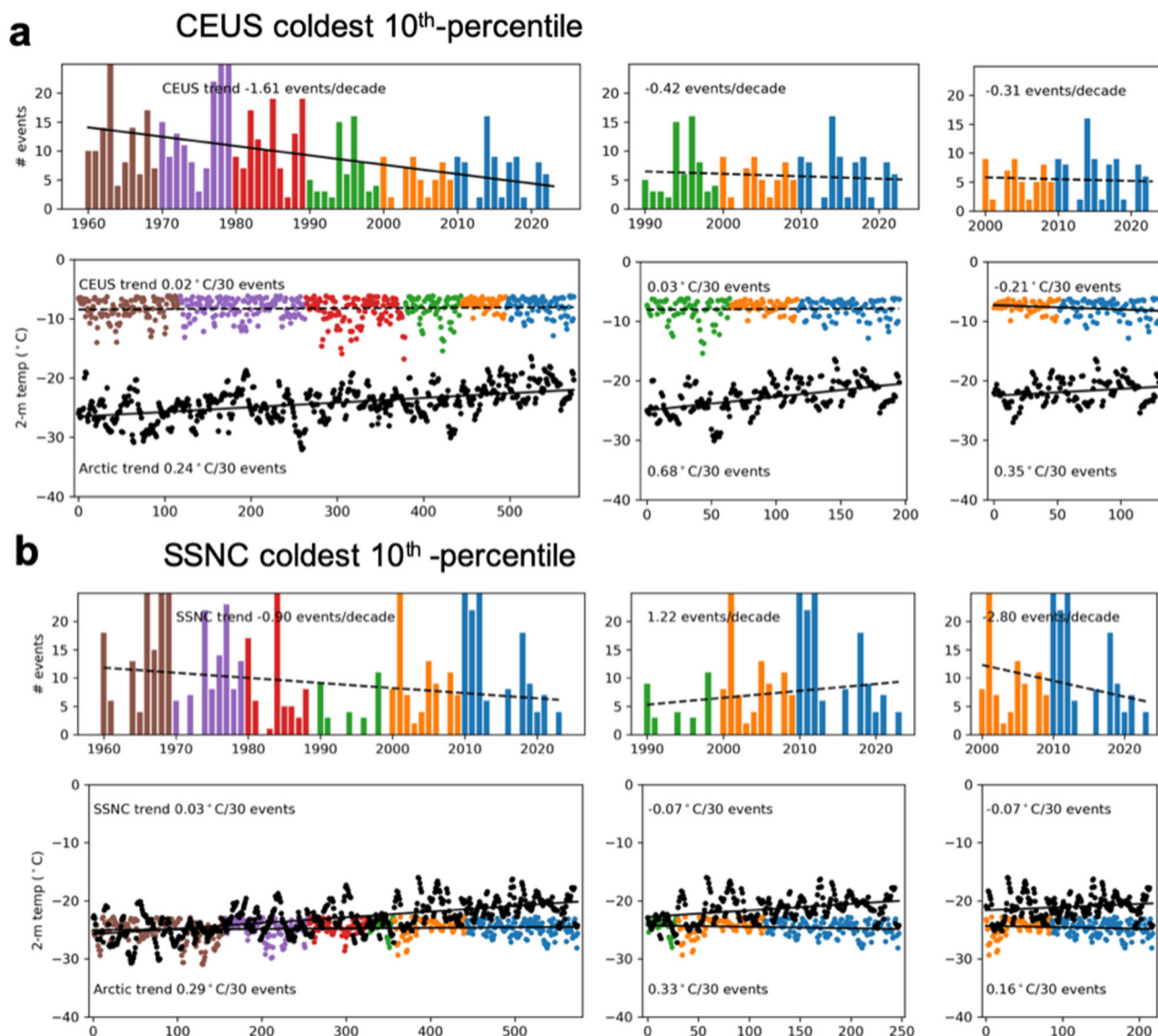
contrast to North America and Asia, as shown in Fig. 3. Cold extremes in Europe also lack a warming trend not only during both AA periods, but even starting in 1960, though the frequency is decreasing at a rate similar to the US. Also like the US for the two periods of AA, the temperature trend of cold extremes is mixed between the two AA periods. However, in contrast to the US and Asia, the frequency of cold extremes is decreasing for all periods, especially since 2000, though it is only statistically significant for the longer period since 1960.

For comparison to the three mid-latitude regions where cold air outbreaks are more common, we analyze the temperature trends of cold extremes in Southern Europe (SEUR) in Fig. 7. In contrast to the other three regions analyzed, SEUR region experiences less frequent Arctic outbreaks and does not exhibit a strong relationship between cold extremes and either a weak stratospheric polar vortex or a negative AO or NAO. Unlike the US, Asia and even Northern Europe, Southern Europe is the only region experiencing a statistically significant decrease in the frequency of cold extremes during the two AA periods, which based on our analysis, is accelerating. Interestingly, though, it is also experiencing a negative trend in cold extremes for all three periods. This negative trend in cold extremes is largely due to the recent winters of 2012 and 2018. The severity of the cold in the 2000s was last matched in the 1960s for Southern Europe.

All trends shown in Figs. 4–7 are summarized in Table 1 for ease of comparison. In Supplementary Table 1 we compute an alternate temperature trend of extreme cold per decade, showing that our

analysis is not sensitive to whether we compute the trend by event or over time. What is immediately apparent from Table 1 (and Supplementary Table 1) is that the robust Arctic warming trend stands in contrast to all four mid-latitude regions where trends are mixed no detectable warming trends are found with the exception of Northeast Asia for the longest period since 1960.

Finally, we test whether our analysis and conclusions are sensitive to the definition of cold extremes by repeating key parts of the analysis with alternate definitions of a cold extreme. In Fig. 8 we repeat the trend analysis for the CEUS and SSNC regions where a cold extreme is defined as the 10% coldest DJF days of the entire period since 1960 and the two AA periods. For both regions the frequency of cold extremes is decreasing except for SSNC for the period since 1990 and the frequency is more volatile. However, the trend of the temperature of cold extremes for the US since 2000 and for SSNC since 1990 and 2000 are cooling and the cooling trend for all three trends is statistically significant. In Fig. 9, we use the definitions of Thompson and Wallace<sup>29</sup> and Johnson et al.<sup>31</sup> for cold extremes for the CEUS only. Different definitions do yield differences in the trends of cold extremes but none of the trends are statistically significant. In conclusion, our analysis most strongly supports that there are no statistically significant trends in cold extremes in the CEUS and SSNC regions in contrast to the Arctic which is warming and is statistically significant during the period of AA. Furthermore, this result does not appear to be sensitive to the definition of cold extreme or whether the trend is computed over event or time.



**Fig. 8** Alternate definition of cold extremes still shows a divergence between Arctic and cold extremes trends in the US and Asia. **a** Similar to Fig. 4 for the CEUS, except for the 10% DJF coldest events 1960–2023, **b** similar to Fig. 5 for the SSNC, except for the DJF 10% coldest events 1960–2023.

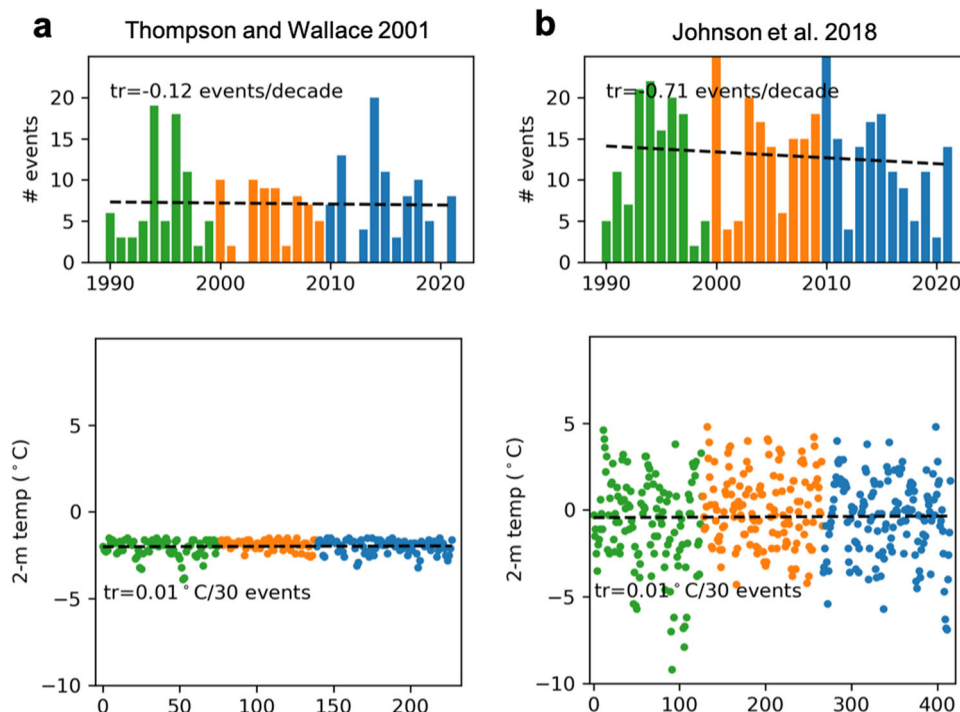
## Discussion

Due to increasing anthropogenic greenhouse gases, the Earth is warming, and this warming is amplified in the Arctic. The consensus has been, with strong support from global climate model future climate projections, that both global warming and accelerated Arctic warming will result in a moderation or warming of winter cold extremes in the mid-latitudes<sup>20</sup>. However, over the past decade a growing number of studies, mostly supported by observational analysis, suggest that AA may be contributing to more severe winter weather, at least episodically, which could project on to winter temperature means.

Our analysis shows that, despite the dramatic Arctic warming in the recent period, the temperature of cold extremes in three key midlatitude regions has stayed nearly constant; that is, there has not been a corresponding moderation of midlatitude cold extremes associated with AA. There is a clear divergence between Arctic temperatures, which are increasing rapidly, and the temperature of cold extremes in the central-eastern US, northeast Asia, and even Europe which have remained mostly stable. Over the full period, the frequency of cold extremes in those regions has decreased, although this trend is often neutral or increasing

during the more recent period of AA. That is, for the US east of the Rockies and Northeast Asia regions and to a lesser degree Northern Europe, the changes in frequency are consistent with an overall direct influence from global warming but not from AA, based on the trend behavior in the different periods.

Furthermore, the analysis does not present a clear relationship between global warming or AA and trends in the magnitude of cold extremes in the study regions of North America, Asia, and Northern Europe. The Arctic is experiencing a statistically significant warming trend whereas mid-latitude cold extremes exhibit no statistically significant trends with two notable exceptions—a statistically significant warming trend in Northeast Asia for the longer period since 1960 and a statistically significant cooling trend in the Central-Eastern US for the shorter AA period since 2000. However, in Europe, especially Southern Europe, where cold air outbreaks are not typically related to a disrupted stratospheric polar vortex or the negative polarity of the AO or NAO (although many of the more recent cold extremes, especially in 2018, followed a large disruption of the stratospheric polar vortex<sup>36</sup>), there is a statistically significant decreasing trend in the frequency of cold extremes. Although even in Southern Europe, despite the clear



**Fig. 9 Another alternate definition of cold extremes still shows a divergence between Arctic and cold extremes trends in the US. a** Similar to Fig. 4 (b, e) for the CEUS, except for DJF daily  $T_{\min}$  less than 1.5 standard deviations of climatological DJF  $T_{\min}$  for the region 1990–2023, **b** similar to Fig. 4 (b, e) for the CEUS, except using the DJF 10% coldest daily  $T_{\max}$  anomalies for the region (compared to the distribution of DJF 5-day rolling means of  $T_{\max}$  anomalies for each calendar day 1990–2023).

decreasing frequency of cold extremes, there is a lack of a warming trend in the temperatures of cold extremes.

While assessment of physical mechanisms is limited by the observational and statistical nature of this study, we note that the two regions where the frequency of cold extremes does not decrease during the period of AA, the Central-Eastern US and Northeast Asia, are the same two regions that experience statistically significant cold anomalies during stretched polar vortex events, that were shown to be increasing during the period of AA<sup>4</sup>. A stretched polar vortex is related to cold extremes in Asia and the US but not Europe<sup>4</sup> and could explain the discrepancy in frequency between Europe, Asia and the US in the period of AA. Additionally, the regions of North America and Central Asia, where cooling trends persist, are sensitive to tropical Pacific SSTs, which have experienced a cooling trend<sup>31,37</sup>. This study emphasizes the need for a better understanding of the direct dynamical influence of AA on cold extremes as well as more broadly in the context of natural variability and other boundary forcings.

## Methods

Daily temperature series are developed from the European Centre for Medium-Range Weather Forecasts (ECMWF) fifth-generation global analysis (ERA-5) 2-m temperature hourly dataset<sup>37</sup>. Here we use December through February hourly data from 1960–present (Feb 2023) to compute latitude-weighted daily areal means for the CEUS (30° to 50°N, –106° to –91°E), SSNC (40° to 60°N, 80° to 120°E), NEUR (50° to 65°N, 0° to 45°E), SEUR (40° to 50°N, 0° to 45°E), and Arctic (70° to 90°N, 0° to 360°E) regions. The 5% coldest values (288 events) for the CEUS, SSNC, NEUR, and SEUR region timeseries, respectively, are compared to the corresponding 3-day lead Arctic values. We also performed an identical analysis using the coldest 2% and coldest 10% days, respectively, and find similar results. We also compute

1960–present ERA-5 2-m temperature DJF seasonal mean time series for the CEUS, SSNC, NEUR, SEUR, and Arctic regions (time-averaged latitude-weighted areal-means) in order to compare background seasonal trends.

Global seasonal (1960–present DJF) time series of near-surface temperature anomalies are additionally developed using the fifth version of the daily 0.5° gridded Climatic Research Unit from the University of East Anglia, the Met Office Hadley Centre, and the National Centre for Atmospheric Science (CRUTEM5) daily anomaly dataset<sup>38</sup> as well as daily ERA-5. For ERA-5, daily anomalies are found by removing the long-term daily mean (01-Jan, 02-Jan, etc.) for each date.

The time series of monthly NAO index from the Climate Prediction Center is compared with the ERA-5 global DJF time series of 2-m temperature to establish the linear relationship (regression).

Trend lines for extreme cold frequency and trends for cold event temperatures are computed using the python scipy stats package, where statistical significance is evaluated at the 0.05 level. Regression data is from the python sklearn linear modeling package, using two standard deviations to model surface temperature response to the NAO.

## Data availability

The ERA5 reanalysis data<sup>37</sup> sets cover the period from 1950 to present with a resolution of ~30 km, which can be accessed at <https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5>. The CRUTEM5<sup>38</sup> observed gridded land surface temperature data at a resolution of 2.5°, covering from January 1850 to present day, can be found at <https://crudata.uea.ac.uk/cru/data/temperature/>. The NAO index can be found at <https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml>. Otherwise, no new datasets were created.

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## Author contributions

J.C., L.A., M.B., and D.E. all contributed to the writing of the text. JC and LA designed the figures.

## Competing interests

The authors declare no competing interests.

## Additional information

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