Frequency of winter temperature extremes over northern Eurasia dominated by AMOC

Huan Wang

Fudan University

Zhiyan Zuo (✉ zuozhy@fudan.edu.cn)

Fudan University

Liang Qiao

Fudan University

Kaiwen Zhang

Fudan University

Cheng Sun

Beijing Normal University <https://orcid.org/0000-0003-0474-7593>

Dong Xiao

Chinese Academy of Meteorological Sciences, China Meteorological Administration

Zouxing Lin

Fudan University

Lulei Bu

Fudan University

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Abstract

Widespread observed and projected increases in warm extremes, along with decreases in cold extremes, have been confirmed to be consistent with global and regional warming. However, in our study, decadal variations in surface air temperature (SAT) extremes over northern Eurasia in winter are primarily dominated by the Atlantic Meridional Overturning Circulation (AMOC), rather than an anthropogenically forcing. Based on reanalysis and state-of-the-art model simulations, we highlight that the decadal weakening of AMOC narrowed the generalized extreme value (GEV) distribution of winter SAT via diminishing its variance, and thus inducing fewer SAT extremes. On the contrary, the decadal enhancing of AMOC corresponded to the increase in the SAT variance over northern Eurasia, making a milder GEV distribution and generating more warm and cold extremes. These AMOC induced variations in SAT extremes may depend on the ocean heat transported into the atmosphere for air motion over northern Eurasia and the Arctic amplification caused by the heat advection from the northward-flowing Atlantic water.

Introduction

The surface air temperature (SAT) in northern Eurasia increased with the fastest warming rate in the last 50 years¹⁻². As a result, a strong increase in extreme winter warming events via an increase in the magnitude and frequency of high maximum temperatures has been observed³⁻⁴. Even during the leveling of global mean temperatures after the late 1990s, the so-called global warming hiatus, an increase in warm extremes has been detected⁵⁻⁶. On the contrary, some suggested that observational winter cold spells showed a long-term decreasing frequency in Eurasia along with global warming⁷. However, frequent occurrences of severe winter cold⁸, including 2005/2006⁹, 2009/10¹⁰⁻¹¹, and 2010/11¹² over portions of Eurasia, have generated a contradictory perception of increasing winter cold extremes.

IPCC AR5 Ch10¹³ has concluded that greenhouse gas forcing is the dominant factor for the increases in intensity, frequency, and duration of warm extremes and the decrease in those of cold extremes. However, the apparent contrast in variations between global SAT and regional warm and cold extremes implies a distinct mechanism responsible for these variations. The ephemeral lived extremes are also affected by decadal and multidecadal natural variabilities, such as the Pacific-North American (PNA)¹⁴, and atmosphere-ocean coupled modes such as the Atlantic Multidecadal Oscillation (AMO)¹⁵. Nevertheless, most of these studies focused on the causes of a specific extreme event or short-term behaviors of SAT extremes. The effect of natural variability on the decadal-scale changes of their frequencies has not been paid much attention.

The Atlantic Meridional Overturning Circulation (AMOC), including the northward flow of warm salty water in the upper Atlantic and the southward flow of the transformed cold fresh water in the deep Atlantic, is a major source for the substantial northward Atlantic heat transport¹⁶⁻¹⁷. The AMOC-induced anomalous Atlantic meridional heat transport and surface heat fluxes released into the atmosphere is critical for the

climate over mid- to high latitude in the northern hemisphere^{18–20}. For example, the positive shift in AMOC is associated with European climate shifts in the 1990s^{21–22} and the early 20th century²³. Previous studies aiming at the AMOC effect on regional SATs make us wonder if it likewise impacts winter temperature extremes over northern Eurasia.

Winter extremes have received major public attention due to their serious impacts on living creatures and ecosystems, as well as human society. Nevertheless, the dominant factor regulating their decadal variations has not been clearly established^{24–25}. In this study, we examine the frequencies of winter SAT extremes over northern Eurasia based on reanalysis data and climate model simulations and explore the dominated effect of AMOC on the decadal variations in SAT extremes.

Results

The temporal variations and spatial patterns of SAT extremes over northern Eurasia in winter are shown in Fig. 1. Distinct from the symmetrical number of warm and cold extremes defined in the procedure described by the Expert Team on Climate Change Detection and Indices (ETCCDI), the frequency of cold extremes is more (512 times) than warm extremes (399 times) over northern Eurasia in winter (from November in the current year to February in the next year, February 29 was excluded) during 1960–2017 based on our definition using the reanalysis dataset (see Methods). And the decadal variation in the sum of warm and cold extremes is likely to be dominated by AMOC (Fig. 1a) with their correlation coefficient of 0.63 (significant at the 99% confidence level). Along with the AMOC variation, the changes in the sum of warm and cold extremes manifested an overall decreasing trend of about 6 times per decade from the mid-1960s to the early 1990s, followed by a rapid increase tendency of more than 10 times per decade from the early 1990s to the early 2000s, and an abrupt decrease to approximately 7 times per decade after then. Neither the dataset used to identify SAT extremes nor the selection of the AMOC index will affect the result (see Supplementary Fig. S3, S4), suggesting the robust relationship between SAT extremes and AMOC. For the decadal change in the frequency of warm extremes, there is an overall augment with a relatively conspicuous increase before the end of the 1970s and a slow growth after then. And the decadal variation in the frequency of cold extremes performs a similar tendency to the sum of warm and cold extremes, albeit not comparable in terms of the amplitude, especially after the 21st century (Fig. 1a).

Composite distributions of SAT anomalies in winter exhibit regional consistency over northern Eurasia for the occurrences of extremes (Fig. 1b, c). When warm extremes happen (Fig. 1b), distinct from the negative SAT distribution in the lower latitudes, significant positive SAT anomalies are demonstrated over mid- to high latitudes with a maximum temperature range of more than 7 °C over the whole northern Eurasia. An opposite spatial characteristic in Fig. 1c is shown with a maximum temperature range of less than – 7 °C occupying northern Eurasia for cold extremes. Similar patterns can also be seen in the distributions of SAT anomalies for each winter month (see Supplementary Fig. S5). These spatial consistencies guarantee the feasibility of our definition.

Previous studies have attributed the Atlantic multidecadal oscillation (AMO) primarily to internal variability associated with AMOC in reanalysis and model simulations^{26–27}, supporting us in using the hist-resAMO runs in the Coupled Model Intercomparison Project, Phase 6 (CMIP6) of the World Climate Research Program (WCRP) to represent the AMOC impact. And we compared the multi-model means of the hist-resAMO runs and the historical runs in 1960–2014 to examine the AMOC role in the decadal variations of SAT extremes over northern Eurasia in winter (details see Methods). The results are shown in Fig. 2. The sum of the frequencies for warm and cold extremes (Fig. 2a) in the hist-resAMO runs shows a quite close decadal variation to the reanalysis, demonstrating an overall decreasing trend before the early 1990s, an increasing trend from the 1990s to the early 2000s, and a roughly decreasing trend after then. The correlation coefficient between this variation and the decadal change in AMOC is 0.55 (significant at 99% confidence level). However, the sums of warm and cold extremes in the multi-model means of the historical runs and hist-GHG runs present much feeble amplitudes. There is a small leap during the mid-1960s to mid-1970s and a continuous decline after then in the hist-GHG runs. The overall changing amplitude is about 2 times in the 55 years of 1960–2014. The constant decreasing trend is reasonably faint in the historical runs with the range of one time in the 55 years. These suggest the relatively inconsequential effect of global warming on winter SAT extremes over northern Eurasia.

The changing amplitude of warm extremes and cold extremes in the multi-model mean of the hist-resAMO runs (Supplementary Fig. S6) are comparable to the reanalysis (Fig. 1a) with overall increasing and decreasing trends during 1960–2014. By contrast, the decadal changes in SAT extremes of the hist-GHG runs (Supplementary Fig. S7) and historical runs (Supplementary Fig. S8) manifest inconspicuous (less than one time per decade) increasing and decreasing trends for warm and cold extremes, respectively. For the spatial SAT distribution when extremes happen in the hist-resAMO runs (Supplementary Fig. S9), similar patterns with the reanalysis can be obtained, showing the maximum SAT anomalies over northern Eurasia, despite of the weak positive SAT anomalies in lower latitude when warm extremes occur.

We eliminated the global warming signal (details in Method) by taking outputs of the hist-resAMO runs subtracting those of the historical runs (hereafter A-H runs). The variation in the sum of warm and cold extremes is almost identical to the hist-resAMO runs and significantly associated with AMOC (Fig. 2b), further corroborating the dominate effect of AMOC on the decadal change in winter extremes over northern Eurasia. During the AMOC decreasing period from the mid-1960s to the end of 1980s, both the frequencies of warm and cold extremes reduced, especially since the early 1980s. On the contrary, when AMOC was increasing since the 1990s to the early 2000s, warm and cold extremes showed overall increasing trends throughout this period.

It is noteworthy that there is decrease in cold extremes in the late 1990s in the A-H runs (Fig. 2b), and the hist-resAMO simulations (Supplementary Fig. S6) cannot capture the increasing frequency of cold extremes since the end of the 1990s recognized in the reanalysis (Fig. 1b). In the meantime, the reduced occurrences of warm extremes in the early 2000s seems inconceivable when the AMOC was still powerful. These will be explained in the following sections.

The probability density function (PDF) of SAT anomalies over northern Eurasia in winter is approximate Gaussian distribution, both in the reanalysis data and model simulations (Supplementary Fig. S1), indicating that the mean and variance of SAT suffice to account for its extremes. The SAT PDFs were regional averaged over northern Eurasia and divided into periods of 1964–1977 and 1978–1990 during the AMOC decreasing phase, and 1990–1998 and 1999–2008 during the AMOC increasing phase. A generalized extreme value (GEV) distribution was used to better characterize the frequencies of extremes as the upper or lower PDF tails. The GEV distribution is motivated by the Fischer-Tippett Theorem²⁸, and used to describe the distribution of extreme events^{29–30}. The SAT PDFs of the reanalysis in two periods are like Gaussian distribution (Fig. 3a, b). The decadal decrease in AMOC (Fig. 3a) produced a steeper GEV and made it shifting towards a warmer state, and the GEV right (left) tail of the latter period is above (below) the line in the former period, favoring an increase in the frequency of warm extremes and a decrease in cold extremes. While during the AMOC increasing period (Fig. 3b), the GEV line of the latter period became milder, implying augments of both warm and cold extremes. These results are consistent with the decadal variations in warm and cold extremes in Fig. 1b. Besides, the SAT PDFs over northern Eurasia in winter were reproduced based on the multi-model means of the historical runs and hist-resAMO runs in Fig. 3c, d and Fig. 3e, f. In the historical runs (Fig. 3c, d), the PDFs are like right-skewed distributions, and the GEV lines generally shifted toward higher temperatures, as one expects for global warming. The GEV right tails in the latter period almost overlay the former ones, implying that winter extremes over northern Eurasia can hardly be determined by external forcings, especially, global warming. The PDFs of the hist-resAMO runs are also like Gaussian distributions (Fig. 3e, f). Similar to the reanalysis, when AMOC was decreasing, the GEV line turned into a steeper shape and the left (right) tail in the latter episode is below (above) the former one, accounting for more warm extremes and less cold extremes. And during the AMOC increasing stage, the GEV line became milder and moved to a higher temperature, inducing more warm extremes and less cold extremes. However, there is a bias between the reanalysis and the hist-resAMO simulations that more cold extremes occurred in the reanalysis (Fig. 1b and Fig. 3b), while less occurred in the hist-resAMO runs (Fig. 3f and Supplementary Fig. S6) since the late 1990s during the enhancing AMOC. We will analyze the possible mechanism of how the AMOC change affects SAT extremes and explain this bias.

The frequency of extreme events can not only be modulated via shifting in mean climate but also by changing variability^{31–32}. AMOC transports warm saline surface water from the subtropical Atlantic to the subpolar Atlantic, where heat loss to the cold atmosphere and increases water density. In accordance with its high salinity, it sinks and returns southward at depth³³. This means that, when AMOC was decreasing, less surface heat of the Atlantic Ocean was released into the atmosphere and transported northwards into northern Eurasia, thus reduced the SAT variance (Fig. 4e) because of the low atmospheric energy for air movement, while no significant change happened in the mean SAT (Fig. 4a). The approximate Gaussian distribution of SAT PDFs in the hist-resAMO runs in Fig. 3e entails the frequencies of extremes determined by the mean (GEV shifting) and variance (GEV shape) of SAT. The decreased SAT variance (Fig. 4e) and the slightly reduced SAT mean (Fig. 4a) indicate a steeper GEV accompanied by moving towards colder temperature, which is in accordance with Fig. 3e. On the contrary,

when AMOC was increasing, both the SAT mean and variance over northern Eurasia increased (Fig. 4b, f) due to the more extra heat transmitted into the atmosphere from the Atlantic Ocean, generating the GEV line to become milder and shift towards warmer temperature in SAT PDFs (Fig. 3f). There are significant increases in the SAT means (Fig. 4c, d) and almost no change in the SAT variances (Fig. 4g, h) over the whole region during both time periods in the historical runs, so that the GEV lines shifted towards warmer temperature without changing much in the GEV shape (shown in Fig. 3c, d). These substantiate how AMOC performs in dominating winter temperature PDFs of northern Eurasia, which are critical to SAT extremes over there.

Northward flowing Atlantic Water, the major means of heat advection toward the Arctic, strongly affects the sea ice distribution^{20, 33–34}, and is presumably linked to the Arctic amplification (AA) in the late 1990s and early 2000s^{33, 35}. AA reduces the temperature gradient from the equator to pole in the Northern Hemisphere, and weakens upper-level jet stream by the thermal wind balance. The weakening of the zonal jet stream increases meridionality in Rossby Wave circulations and prolongs periods of extreme blockings. Thus, more cold air from the Arctic is transported into the relative lower latitudes and entails an increasing probability of extreme weather, for example, cold outbreaks—although the globe overall is warming^{36–38}. Moreover, AA feedback further makes autumn–winter Arctic sea ice reduce, especially in the Barents and Kara seas^{39–41}, and favors cold winter extremes over northern continents^{10, 42}. In addition, the reduced Arctic sea ice causes a weakened stratospheric polar vortex^{43–44}, making the Arctic circumpolar vortex more unpredictable. For example, it has been revealed that the Arctic polar vortex shifted persistently towards the Eurasian continent in the 2000s, and induced cooling over some parts of the Eurasian continent, which partly offsets the tropospheric climate warming there⁴⁵. However, the model simulations in our study cannot precisely capture the AA effect caused by the enhancing AMOC in the 2000s found in the reanalysis (Fig. 5). In other words, there is no conspicuous SAT gradient between the Arctic and northern Eurasia (Fig. 5b), thus fewer cold outbreaks supporting cold extremes happened over this region. This explains the discrepancy that the frequency of cold extremes is less in the hist-resAMO runs than that in the reanalysis since the late 1990s. We speculate the reason for this model bias is that the extra ocean heat transferred from the Atlantic to the Arctic, as a result of the increasing AMOC, may not be sufficient for strengthening AA. In the same way, the ocean heat transferred into the atmosphere to warm SAT over northern Eurasia may not be enough to increase the frequency of warm extremes, supporting the variation in the A-H runs in Fig. 2b.

Discussions

In this study, we have used a new definition of temperature extremes focusing on consistent SAT anomalies over northern Eurasia. This provides us more realistic behaviors of regional warm and cold extremes, thereby yielding robust statistics. A limitation of this approach, however, is that we do not address changes in the extent of SAT extremes. It has been found that most ‘extreme’ hot extremes have risen more dramatically than less extreme warm events⁶. Is there any correlation between the extent of SAT extremes and AMOC, or other factors, such as land-atmosphere feedbacks^{46–47}, land use, and land

cover changes⁴⁸? Here we do not deny the anthropogenic impact on the temperature extremes, but it should affect little on the sum of warm and cold extremes since its effect on the increase of warm extremes is approximately offset by the decrease of cold extremes. Besides, we did not rule out the possibility that the AMOC changes were caused by human-induced global warming. More analyses will be carried out to understand how large-scale climate variability interacts with local-scale feedbacks and their mutual effect on regional SAT extremes. On the other hand, the physical mechanism of the AMOC effect on SAT extremes was preliminarily discussed in this study. Further studies concerning their relationship with ocean-air energy budget, large-scale air circulation, and local thermodynamical anomalies are needed in the future.

Methods

Warm and cold extremes. We used daily SAT datasets in boreal winter (from November in the current year to February in the next year, February 29 was excluded) during 1960-2017 from the Berkeley Earth Land + Ocean dataset (<http://berkeleyearth.org/data/>) to identify SAT extreme events. The horizontal resolution is $1.875^\circ \times 1.875^\circ$. The PDFs of winter SAT anomalies over northern Eurasia (50° - 70° N, 70° - 130° E) in the reanalysis and model simulations are essentially Gaussian distribution (Supplementary Fig. S1), making the following definition of SAT extremes feasible.

For a certain day in winter months of the 57 years (winter from 1960 to 2016), if there are more than 50% grids in northern Eurasia with the SAT anomalies lying above (falling below) one (one negative) standard deviation, and among these grids, there are more than 70% of them with the SAT anomalies above 1.28 (below -1.28) standard deviation, then an extreme warm (cold) day is identified. Then we count the frequencies of warm (cold) extremes in the four months of each year, and isolate decadal time series by doing 9 years' moving average.

This new definition is distinct from the procedure described by the Expert Team on Climate Change Detection and Indices (ETCCDI), where a cold (warm) extreme is identified if the SAT anomaly falls below the 10th percentile (lies above the 90th percentile) of its distribution. There should be equivalent extreme warm and cold events at each grid point in a fixed time period according to ETCCDI. However, this is not necessarily corresponding to the real world, where warm and cold days may not be equal and the frequencies vary with grids. As our new definition shows, cold extremes are more than warm extremes over northern Eurasia (Supplementary Fig. S2). Even so, the two definitions demonstrate fairly close decadal variations (correlation coefficients are all above 0.9), confirming the fidelity of our definition in representing SAT extremes, although the frequencies of warm and cold extremes in each year using ETCCDI (hereafter D2) are both higher than the values of our definition (hereafter D1).

AMOC index. The subpolar upper ocean salinity index of AMOC is defined as the average over 45° - 65° N in the Atlantic basin and integrated over 0-1,500 m. They are derived from ref. ⁴⁹, including ISHII dataset of 1960-2012, Scripps dataset of 2004-2016, and EN4 dataset of 1960-2016. The AMOC fingerprint index is derived from (http://www.pik-potsdam.de/~caesar/AMOC_slowdown/).

CMIP6 simulations. The daily mean of near-surface air temperature outputs from 1960-2014 were obtained from CMIP6 (<https://esgf-node.llnl.gov/projects/cmip6/>) historical simulations, hist-GHG simulations and hist-resAMO simulations. Here we consider historical simulations⁵⁰ for a total of 341 members from 44 models (see Supplementary Table. 2 for details) corresponding to daily SAT outputs based on realizations (r), initialization (i) schemes, different physics (p), and forcing (f) indexes. The relatively large ensemble size can avoid model dependence and allows us to believe the ensemble mean (multi-institution mean after doing multi-model mean of the same institution) as the externally-forced signal⁵¹, and the decadal scale SAT variation after the 1970s can be mainly regarded as the human-induced increase in green-house gases, in other words, the global warming signal⁵²⁻⁵⁵. This statement was also verified in our study by the relatively consistent decreasing trend since the mid-1970s in the historical runs and hist-GHG runs in Fig. 2a.

The hist-GHG experiments resemble the historical simulations but instead are forced by well-mixed greenhouse gas changes only. Time varying global annual mean concentrations for CO₂ and other long-lived greenhouse-gases, including CH₄, N₂O, HFCs, PFCs, SF₆, several ODS, and NF₃ are served as inputs⁵⁶. Multi-model average of the 8 models including 34 members (details in Supplementary Table. 2) which provide daily SAT outputs was done as historical runs.

The hist-resAMO experiments were used to examine the AMOC effect, and the global warming signal was eliminated by taking outputs of the hist-resAMO runs subtracting those of the historical runs. Limited by the number of ensemble members in the hist-GHG runs, we chose the multi-model mean of historical runs as global warming signal. The hist-resAMO runs are initialized from the historical run year 1870 and integrated up to the year 2014 with historical forcings, and are pacemaker-coupled historical climate simulation that includes all forcings but with SST restored to the model climatology plus observational historical anomaly in the AMO domain (0-70°N, 70°W-0°) using the same model resolutions as the CMIP6 historical simulation⁵⁷. Multi-model average of the four members, which provide daily SAT outputs (details in Supplementary Table. 2), was done as historical runs. All the model results were interpolated into the resolution of 2.5°×2.5°.

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Declarations

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Author contributions

H.W. and Z.Z. contributed to designing the study, conducting analyses and writing the paper. L.Q. and K.Z. contributed to analyzing the CMIP6 model data. C.S. and D.X. contributed to conceiving the experiments and interpretation of the results. Z.L. and L.B. contributed to writing the paper. All authors reviewed the manuscript.

Competing financial interests

The authors declare no competing financial interests.

Figures

Figure 1

Temporal variations and spatial patterns of SAT extremes over northern Eurasia in winter. a Decadal change (9 years' moving average) in the frequencies (day season-1) of warm, cold extremes and their summation over northern Eurasia in winter and the AMOC index during 1960-2016 (the year 1964 representing 9 years' moving average from 1960 to 1968). b, c Composite distribution of SAT anomalies (units: °C) in winter when warm (b) and cold (c) extremes happen. Black box in b and c is the northern Eurasia region we choose, and stippling indicates areas of statistical significance at the 95% confidence level using a Student's t-test.

Figure 2

Decadal variations in the frequencies of SAT extremes over northern Eurasia in winter for model simulations during 1964-2010. a Decadal variations in the frequencies for sum of warm and cold extremes in the multi-model means of the historical runs (pink line), hist-GHG runs (orange line), and hist-resAMO runs (green line), and the decadal change in AMOC (black line). b Decadal variations in the frequencies for warm extremes (red dashed line), cold extremes (blue dashed line), and sum of warm and cold extremes (purple line) in the A-H runs, and the decadal change in AMOC (black line). Year 1964 representing the 9 years' moving average of 1960-1968.

Figure 3

SAT PDFs over northern Eurasia in winter. SAT PDFs over northern Eurasia in winter during the decadal decreasing period of AMOC in 1964-1990 (upper panel) and decadal increasing period of AMOC in 1990-2008 (lower panel) in the reanalysis (a, b), historical runs (c, d), and hist-resAMO runs (e, f). The x axes are the SAT anomalies, and y axes are the PDF distributions.

Figure 4

Differences in the means and variances of winter SATs over northern Eurasia for model simulations. Differences in the multi-model means of winter SAT anomalies (units: K) over northern Eurasia in the A-H runs (a, b), and historical runs (c, d), and differences in the multi-model means of winter SAT variances (units: K²) over northern Eurasia in the A-H runs (e, f), and the historical runs (g, h) between 1978-1990 and 1964-1977 when AMOC was decreasing (left panel), and between 1999-2008 and 1990-1998 when AMOC was increasing (right panel). Stippling in a, b, c, d indicates areas of statistical significance at the 95% confidence level using a Student's t-test.

Figure 5

SAT differences in winter. SAT differences in winter between 1998-2008 and 1990-1998 based on the reanalysis data (a) and the multi-model mean of the A-H runs (b). Stippling indicates areas of statistical significance at the 95% confidence level using a Student's t-test.

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