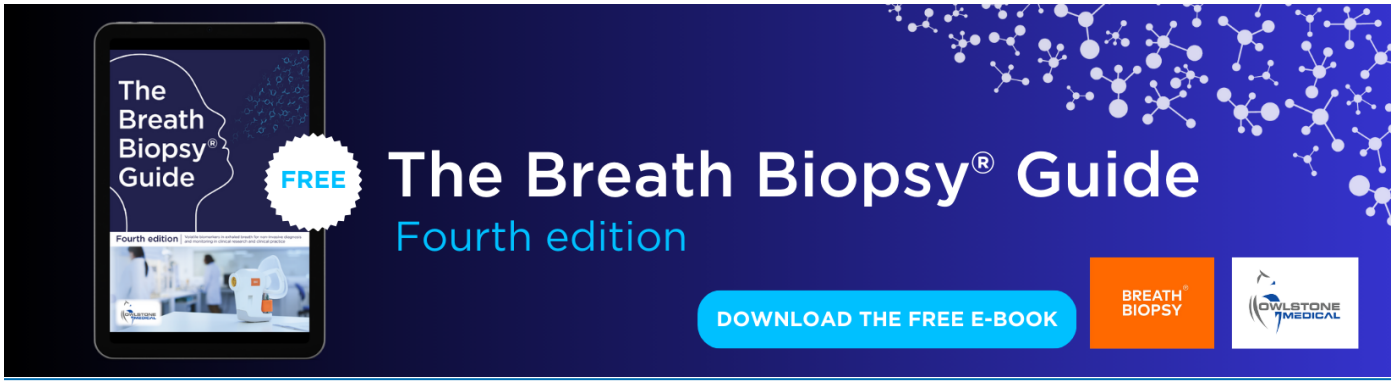
ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Coincidence of increasingly volatile winters in China with Arctic sea-ice loss during 1980–2018

To cite this article: Yang Chen *et al* 2019 *Environ. Res. Lett.* **14** 124076



Environmental Research Letters

LETTER

Coincidence of increasingly volatile winters in China with Arctic sea-ice loss during 1980–2018

Yang Chen, Zhen Liao and Panmao Zhai

State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, No. 46, South Ave., Zhong-Guan-Cun, Haidian, Beijing, People's Republic of China

E-mail: ychen@cma.gov.cn

Keywords: volatility in winter weathers, temperature whiplash events, forcings from Arctic sea-ice melt, observation-based detection

Supplementary material for this article is available online

OPEN ACCESS

RECEIVED
24 August 2019

REVISED
26 November 2019

ACCEPTED FOR PUBLICATION
28 November 2019

PUBLISHED
18 December 2019

Abstract

Despite intense discussions on the recent boom of mid-latitude wintertime cold extremes, co-variations of warm and cold extremes, i.e. winter temperature volatility, has garnered substantially less attention. Apart from using temperature extremes' frequency and intensity, we also define 'temperature whiplash', which depicts rapid switches between warm and cold extremes, to measure winter temperature volatility in China. Results show that Northeast-, Northwest-, Southwest-, Southeast-China and the Yangtze River Valley have experienced increasingly volatile winters after 1980, co-occurring with precipitous decline in Arctic sea-ice. This enhanced volatility has a strong expression in significant increases in temperature whiplash events, with some hotspots also seeing both warm and cold extremes become more frequent and/or intense. An observation-based detection analysis highlights the dominance of intrinsic atmospheric variability over both anthropogenic warming and sea-ice decline during 1980–2018 in driving winters in China to be more volatile over this period.

1. Introduction

It is reported that human activities have caused approximately 1.0 °C of global warming above the pre-industrial level (Masson-Delmotte *et al* 2018) and 2015–2018 are the warmest four years on record (World Meteorological Organization 2019). This establishes a built-in notion that climate change relates more to warming and warm-related extremes. By contrast, the Northern mid-latitude continents experienced recurrent severe or even recording-smashing wintertime cold extremes in the past warmest decade. For instance, in late January 2016, a strong cold surge swept across China, with new cold records set in extensive regions (Qian *et al* 2018, Ma and Zhu 2019, figure S1(b) is available online at stacks.iop.org/ERL/14/124076/mmedia). The unexpected resurgence of cold extremes since 2010 sparks an interesting yet open question, namely 'are recent extratropical winters becoming more volatile?'

There are multifaceted interpretations for winter temperature volatility. A straightforward way is to expect increasing occurrences of both warm and cold extremes during winter. Central Eurasia, East Asia and North America appear to be experiencing this kind of winter weather volatility (Cohen *et al* 2014, Tang *et al* 2013, Mori *et al* 2014, Johnson *et al* 2018, Kretschmer *et al* 2018). In this regard, the increase in cold extremes takes center stage in most literatures, but co-variability of warm extremes remains largely under-examined (Sung *et al* 2019). Some studies attributed cold extremes' increases to forced dynamic responses to rapid loss of Arctic sea-ice (Petoukhov and Semenov 2010, Tang *et al* 2013, Kug *et al* 2015, Ma *et al* 2018, Mori *et al* 2019, Ma and Zhu 2019, Luo *et al* 2019). While others argued the opposite that atmospheric internal variabilities dictated the recent boom of mid-latitude cold events (Screen *et al* 2014, Mccusker *et al* 2016, Sun *et al* 2016, Sorokina *et al* 2016, Blackport and Kushner 2017, Blackport *et al* 2019). Although this casual linkage remains inconclusive (Screen *et al* 2018), the era of precipitous decline in Arctic sea-ice since 1979/1980 has been brought into prominence. Mechanistic explanations, detection and attribution of unexpected changes in extremes during this unique period have become cutting-edge issues

(Mccusker *et al* 2016, Sorokina *et al* 2016, Johnson *et al* 2018, Mori *et al* 2019).

Winter temperature volatility was also measured by temperature variance, e.g. standard deviation or width of probability density function (PDF) of daily temperatures (Screen *et al* 2014, Kunkel *et al* 2015, Cohen 2016). An increase in standard deviation or the widening of PDF is deemed indicative of amplified fluctuations between cold and warm conditions, implying simultaneous strengthening of warm and cold extremes (Francis and Vavrus 2012, Kunkel *et al* 2015). However, signs and magnitudes of changes in winter temperature variance at the Northern mid-latitudes remain highly uncertain, due to great sensitivity of quantifications to temporal-spatial scales, analysis periods, seasonality and datasets (Fischer and Knutti 2014, Screen *et al* 2014, Bathiany *et al* 2018, Ma *et al* 2018).

Volatile winter weathers also take the form of 'winter temperature whiplash (whiplash event hereinafter)' (Bates 2018, Casson *et al* 2018, Cohen *et al* 2019), a term already popularly used in mainstream media to describe drastic and rapid swings between extreme warm and cold. A potent case is a wild swing from bone-chilling cold to unseasonably warm within five days in the Midwest and Northeast US during late January 2019. Such out-of-alignment of temperature extremes is more impactful than their occurrence in isolation. Rapid shifts from freezing to thawing can cause severe damages to infrastructure (Laucelli *et al* 2013), falling of icicles, unsafe ice for outdoor activities, flash floods, and air pollution (Zou *et al* 2017); while an antecedent unseasonal warmth easily leaves people and the energy sector ill-prepared against closely-ensuing cold extremes, thereby substantially aggravating cold-related consequences. In particular, whiplash events from warm to cold at the end of winter may produce a 'false spring', which disrupts plant phenology and therefore threatens agricultural yields (Marino *et al* 2011, Chamberlain *et al* 2019). Although these impacts made headlines frequently, a formal scientific definition for winter temperature whiplash is still lacking. Resultant knowledge gap about changes in this type of volatile weather constrains the community from developing tailored adaptation and mitigation strategies.

Severer consequences of volatile weathers occur in populous regions like China, due to higher exposure of population and infrastructure there. In the past few years, parts of China did suffer from volatile winters. For instance, both record-warm and record-cold were observed in the same place in the same winter (figure S1). The nature of recent volatile wintertime weathers in China, i.e. individual winter phenomenon or part of a regime shift/long-term tendency, remains to be illuminated. Moreover, there is growing clues linking Arctic sea-ice loss to wintertime weather extremes in China (Wu *et al* 2015, Zou *et al* 2017, Sun *et al* 2019, Zhou *et al* 2018, Blackport *et al* 2019, Ma and Zhu 2019). These impacts, knowledge gaps and emerging evidences provide an impetus to quantify past changes in winter temperature volatility in China and further address the role of external forcings (e.g. anthropogenic warming and Arctic sea-ice melt) on those unexpected changes.

To this end, we examine co-variations of frequency/intensity of wintertime cold and warm extremes in China, with particular attention paid to changes in whiplash events. The period over 1980–2018 is used to cover the epoch of Arctic sea-ice melt, with sub- and longer-periods also scanned. Section 2 will introduce data and methods. Main results will be presented in section 3, followed by discussions, outlooks and a brief summary.

2. Data and methods

2.1. Data

Observations of wintertime daily maximum and minimum temperatures over 1961–2018 from 2474 meteorological stations in China are used. A winter persists from previous year's December to this year's February. This dataset is provided and preliminarily quality-controlled by the National Meteorological Information Center (NMIC), China Meteorological Administration (http://nmic.cn/site/index.html). To minimize influences of missing values and inhomogeneities due to site relocation, additional data preprocessings are conducted as follows:

(1) Missing observations of both Tmax and Tmin account for no more than 5% of wintertime records each year;

(2) Through 1961–2018, site relocations are restricted within 20 km horizontally and 50 m vertically.

These left us 1226 stations for further analysis. We also used the homogenized gridded Berkeley Earth surface temperature dataset (Rohde *et al* 2013, https://climatedataguide.ucar.edu/climate-data/global-surface-temperatures-best-berkeley-earth-surface-temperatures), and station-based Global Summary of the Day (GSOD) dataset (https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00516) to assess the contingence of detectability of external forcings on spatial scales (section 2.2.2). With the GSOD data over 1979–2018 also subject to constraint (1), 2144 stations in this dataset across the Northern Hemisphere are qualified for the following analysis.

2.2. Methods

2.2.1. Definitions

Our measure of winter temperature volatility includes (i) co-variation of warm and cold extremes' frequency, i.e. whether both warm and cold extremes occur more/less frequently; (ii) co-variation of warm and cold extremes' intensity, i.e. whether the warm gets

warmer and the cold gets colder; (iii) changes in frequency of whiplash events, i.e. whether rapid swings between cold and warm extremes become increasingly common.

A warm (cold) extreme occurs when either of Tmax or Tmin is higher (lower) than the 90th (10th) percentile. For each calendar day, its 90th (10th) percentile of Tmax/Tmin is derived by ranking multi-year 15 d samples (seven days on either side of this specific day) over 1961–1990 (i.e. total samples $15 \times 30 = 450$ d, Della-Marta *et al* 2007), a period less influenced by anthropogenic warming and sea-ice loss than later counterparts.

The frequency counts the number of extremes. The intensity is calculated as the departure of daily Tmax/Tmin from their thresholds (observation minus threshold). If a warm (cold) extreme event involves both extreme warm (cold) Tmax and Tmin, the stronger departure is adopted.

We define temperature whiplash as a 'sudden' swing from one state of extreme to the opposite. Here, 'sudden' refers to a span no longer than a week. Whiplash events are classified into two categories, i.e. warm to cold (W2C) and cold to warm (C2W) events. Whiplash events of different transition spans are non-overlapping. A one-day W2C, for instance, consists of a warm day and a subsequent cold night (within 24 h). Those W2C events spanning from 2 to 7 d start with a warm extreme belonging to either of 'warm day-normal night, normal day-warm night or warm day-warm night' and end up with a cold extreme typical of 'cold day-normal night, normal day-cold night or cold day-cold night', without any form of warm/cold extremes sandwiched in-between. This differs from 'cold wave' in that the latter one places more emphasis on the magnitude of temperature drops but cares little about the nature and extremity of temperature states before and after the drop. Similar identification scheme but with reversed sign constraints on warm/cold extremes is applied to identify C2W whiplash events.

2.2.2. Statistical methods

Linear trends and significance (at the 0.1 level at least) are evaluated via Kendall's tau slope estimator, which is sufficiently insensitive to outliers and free from assuming distributional forms (Sen 1968). Apart from estimating linear trends, we also utilize a time slice method, which calculates the difference between two period-average matrix values. Presented are pairwise differences between two 15-year periods, i.e. 2004–2018 versus 1980–1994. Using pairs of different lengths, e.g. 2009–2018 versus 1980–1989, did not alter the pattern and magnitude of changes in any significant manner (figure omitted).

To isolate the impact of changing temperature variability on whiplash event changes, we remove linear trends for seasonal-mean Tmax and Tmin from daily observations in each station/grid and then re-calculate trends for whiplash events identified based on detrended temperature residuals. Apparently, the variability here involves a wide spectrum of signals spanning from sub-daily (diurnal cycle), sub-seasonal, seasonal, interannual to interdecadal time scales (Collow *et al* 2019). As a cross validation, we also separate the influence of mean warming on whiplash event changes. We do this in each station/grid by positively shifting daily Tmax/Tmin in the former period (1980–1994) by the warming magnitude of seasonal-mean Tmax/Tmin between the latter (2004–2018) and the former, and then re-calculate changes via the time slice method. This is equivalent to rigidly shifting the daily temperature PDF, with its shape fixed (details see Guirguis *et al* 2018).

We adopt the 'spatially-aggregated PDF method' developed by Fischer and Knutti (2013) to address the detectability issue, answering whether forcings from external drivers, here including decline in Arctic sea-ice and anthropogenic warming, have already been distinguishable from influences of internal variability statistically. For each index, observed station/grid-level differences between two 15 year periods (2004–2018 versus 1980–1994) are pooled as samples for the PDF fitting via a kernel density estimate. Similar PDF fitting is implemented with respect to pairwise differences between randomly sampled 15-year sets ($N = 1000$) within 1980–2018, with derived 5%–95% interval modeling the range of changes expected from internal variability. If the PDF for observed differences lies outside that range, the role of external forcings is deemed detectable in the fraction of stations/areas where observational changes exceed the 95th percentile amongst those bootstrapped differences in magnitude (schematic see figure 5(a)).

This observation-based method circumvents the uncertainty of model-based detection sourced from models' misrepresentation in key physical processes (Jang *et al* 2019). Also, it is superior to the fingerprint detection method (Tett *et al* 1999) in avoiding erroneous averaging-out between opposing signals within the region of interest.

3. Results

Overall, the frequency of wintertime warm extremes showed significantly increasing trends across China over 1980–2018, with larger increases over 4 events decade^{-1} observed in North China, Central-Eastern China, Northwest China and Southwest China (figure S2(a)). For occurrences of cold extremes, decreasing trends are prevalent in regions south of 40 °N (figure S2(b)). By contrast, Northeast China and Northwest China observed slight increases in cold extremes during 1980–2018, with some of them being significant. Accordingly, much of China has been experiencing milder winters characteristic of more warm extremes and less cold extremes (figure 1(a)), even in the era of unprecedented decline in Arctic sea-ice.

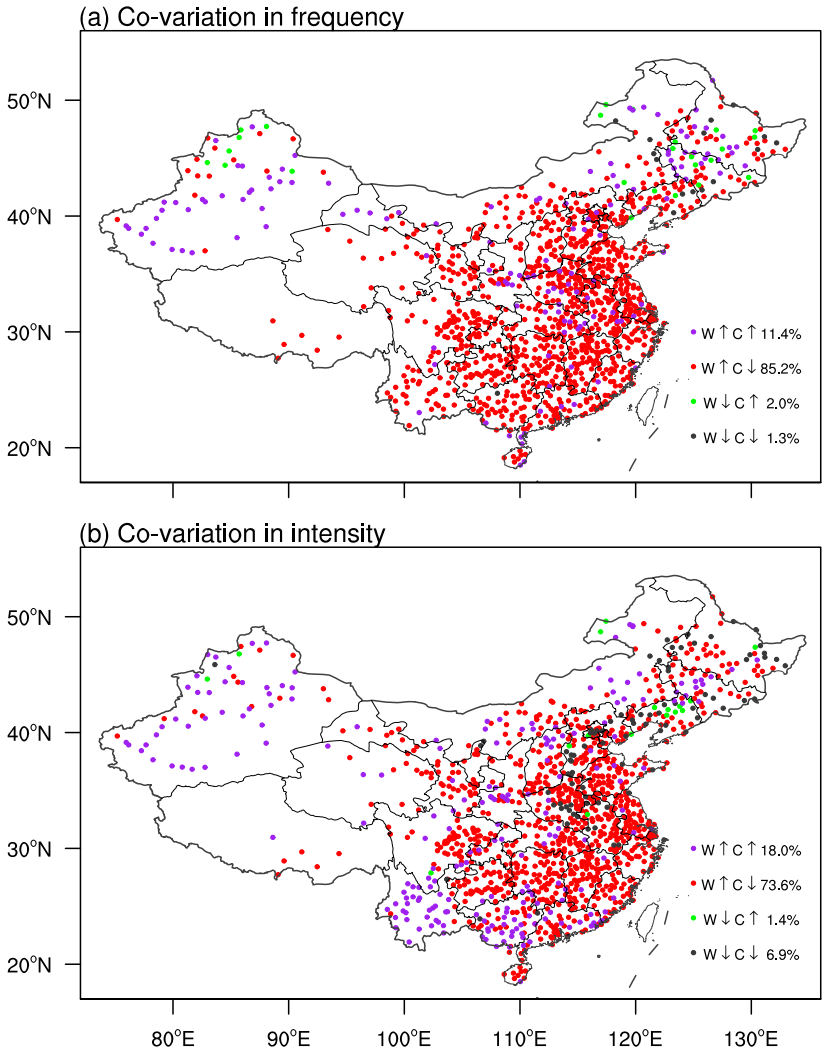


Figure 1. Co-variations in frequency (a) and intensity (b) of wintertime warm and cold extremes during 1980–2018. Symbol '↑' indicates increasing frequency and intensity, and '↓' indicates declining frequency and intensity. 'W' and 'C' refer to warm and cold extremes, respectively. Different configurations of co-variability are distinguished by colors, with their fractional proportions in total stations indicated. See figure S2 for the magnitude and significance of these trends.

Roughly 11% stations, mostly located in Northeast and Northwest China, observed a tendency toward more volatile winters with concurrent increases in warm and cold extremes, but this strengthening of volatility is not significant.

In terms of intensity, significant warming is the dominant mode for both warm and cold extremes over 1980–2018 (figures S2(c), (d)), with magnitude and significance of trends for warm extremes markedly greater. Trends for cold extremes' intensity exhibit a more spatially-heterogeneous pattern constituted by warming ones (decreased intensity) clustered in eastern part and cooling ones (intensification) distributed in Northwest, Southwest, and South China. In this context, the pattern of 'warm getting warmer and cold getting colder' occurred in about 18% of stations mostly in Northeast, Northwest, South and Southwest China (figure 1(b)), with those particularly significant in Southwest China (figures S2(c), (d)). Northeast China and Northwest China are therefore hotspots for more volatile winters seeing simultaneous growth in the occurrence and severity of both warm and cold extremes.

Compared to insignificant co-variability in frequency/intensity of warm and cold extremes, enhanced winter temperature volatility has a much stronger expression in significant increases in whiplash events across broad swaths of China (figure 2). During 1980–2018, around one fifth of stations experienced significant increases in either type of whiplash events (W2C-figure 2(a), C2W-figure 2(b) or W2C&C2W-figure 2(c)). For W2C events, strong and significant increases occurred preferentially in the Yangtze River Valley, southeast coastal areas and eastern part of Southwest China (figure 2(a)). These regions also observed stronger and more significant increases in C2W events during the period (figure 2(b)). Apart from these spatial overlaps, the frequency of C2W events also increased significantly in Northwest China, Northeast China, and some inland areas in Southeast China. As a consequence, the total frequency (W2C&C2W) of whiplash events showed

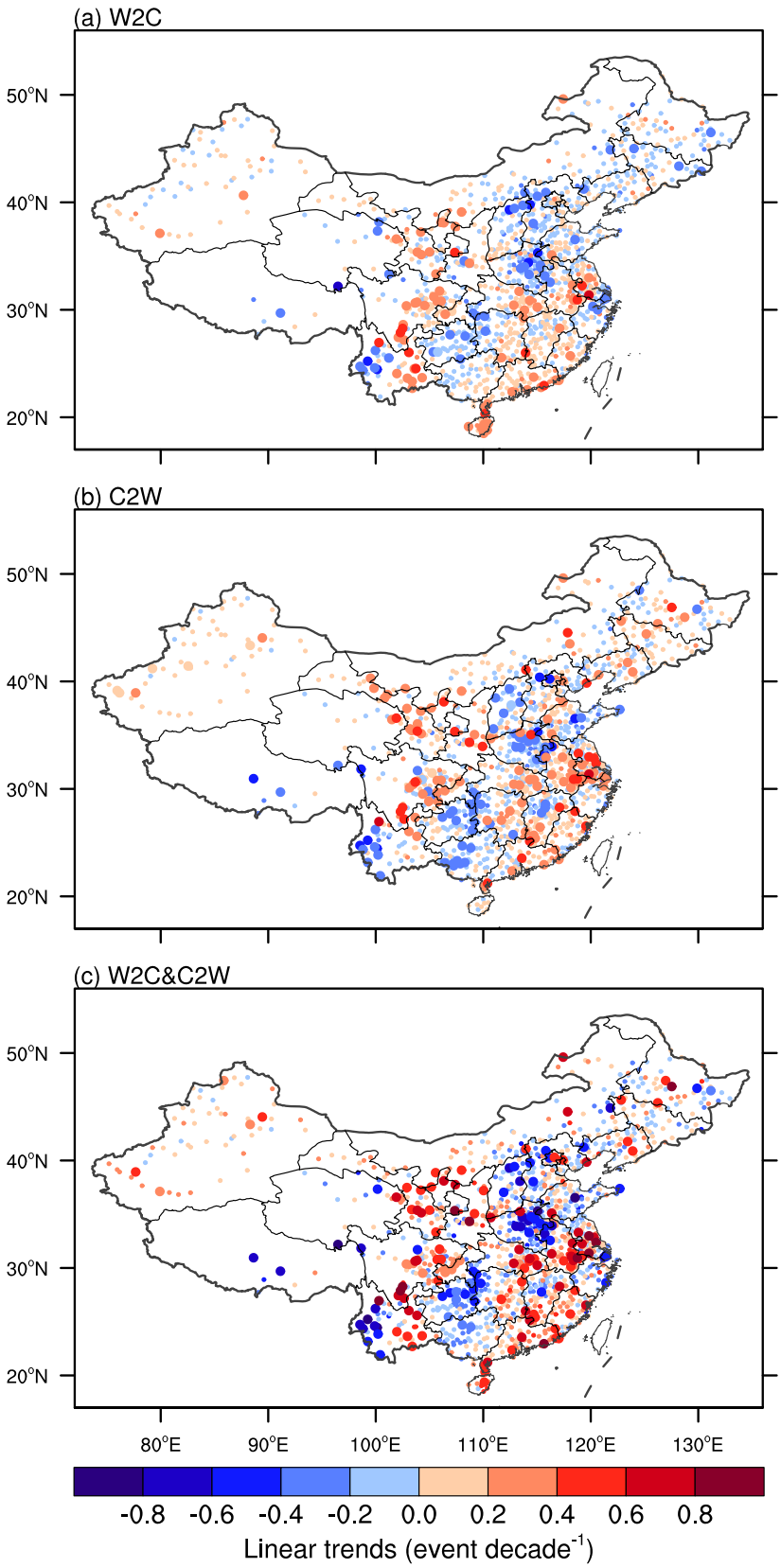


Figure 2. Linear trends for frequency (events decade^{-1}) of winter temperature whiplash events during 1980–2018. (a) for W2C events, i.e. a transition from warm to cold extremes; (b) for C2W events, i.e. a transition from cold to warm extremes; (c) for W2C&C2W, total events of W2C and C2W type. Significant trends at the 0.1 level at least are highlighted by larger size. The significance is attached only to those stations in which whiplash events occurred in different 15 years at least.

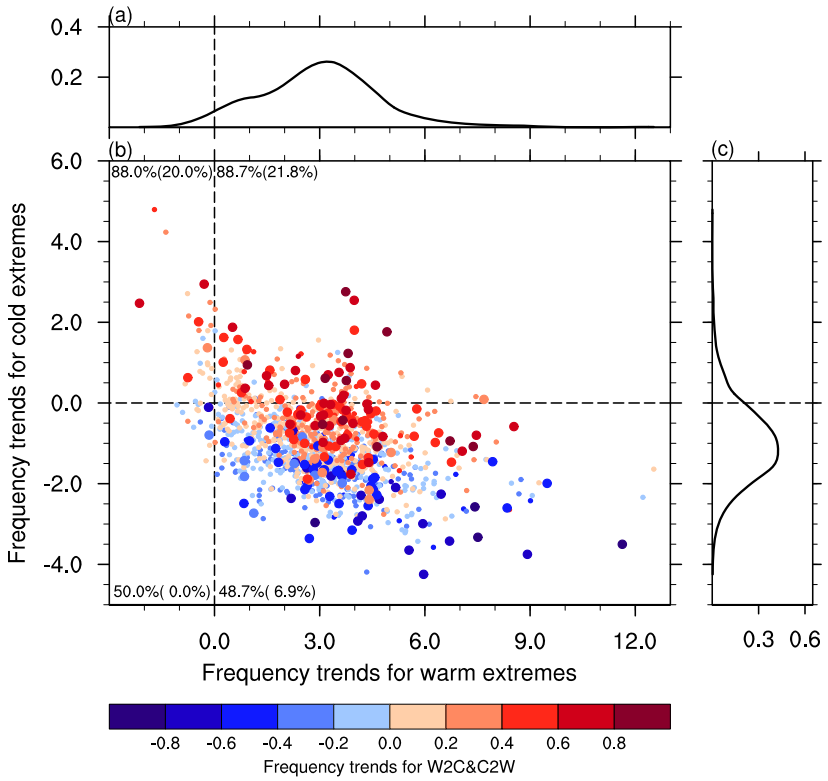


Figure 3. Scatter-plot of trends for frequency (dots, event decade^{-1}) of whiplash events (W2C&C2W) during 1980–2018 against trends for frequency of warm extremes (*x*-axis in (b)) and cold extremes (*y*-axis in (b)). Significant trends are highlighted by larger dots. The numbers in each quadrant denote the percentage of dots with increasing trends (outside the bracket) and significant increasing trends (within the bracket) in total dots falling into that quadrant. (a) and (c) show the probability density function (PDF) of trends for warm and cold extremes respectively, with dashed lines labeling their zero-trends and used for quadrant division.

significant increases in above hotspots, with magnitudes ranging from 0.4 to 1.3 events decade^{-1} during 1980–2018. Actually, these significant increases are mainly due to sharp growths in the number of faster-switching (1–3 d) whiplash events (figure omitted), which pose greater adaptation burden on human and natural system. Similar hotspots for whiplash event increases could also be mapped out by using the time slice method (figure S3) and different observational datasets (figure S4). Apparently, trends for frequency and intensity underestimate the spatial extent, magnitude and significance of enhanced winter volatility in China. Moreover, rapid and drastic swings between opposite extreme thermal conditions make the temperature whiplash more 'perceivably volatile' than individual cold and warm extremes (Bates 2018). Namely, the newly-developed temperature whiplash index better characterizes winter temperature volatility.

It is reasonable to expect that simultaneous growth in the number of cold extremes and warm extremes is the most conducive to significant increases in whiplash events (figure 3(b)), as manifested in Northwest and Northeast China (figure 1(a)). To the contrary, the concurrent reduction in warm and cold extremes is the least conducive configuration. However, there remains a large portion of significant increases in whiplash events falling into the quadrant configuring decreasing cold extremes and increasing warm extremes (figure 3). This may elicit a seemingly-plausible speculation that the past winter-mean warming contributed to significant increases in whiplash events through elevating the probability of warm extremes and further narrowing the temporal gap between warm and cold extremes.

If this hypothesis makes sense, the removal of winter-mean warming should substantially weaken the magnitude and significance of increases in whiplash events. However, trends for re-identified whiplash events via linearly-detrended Tmax and Tmin (see Methods) are highly consistent with raw estimates in sign, magnitude and significance as well as the location of hotspots (compare figures 4(a) and 2(c)). The spatial correlation between trends for whiplash events' frequency in presence and absence of mean warming reaches 0.71, significant at the 0.01 level. This suggests the dominance of changing temperature variability over anthropogenically-caused mean warming in determining significant increases in whiplash events. Alternatively, using a PDF-shifting method (see Methods) produces either opposite signs or substantially weaker magnitudes of trends (compare figures 4(b) and S3(c)). The spatial correlation between trend patterns for raw observations (figure S3(c)) and the PDF-shifting reconstructions (figure 4(b)) is smaller than

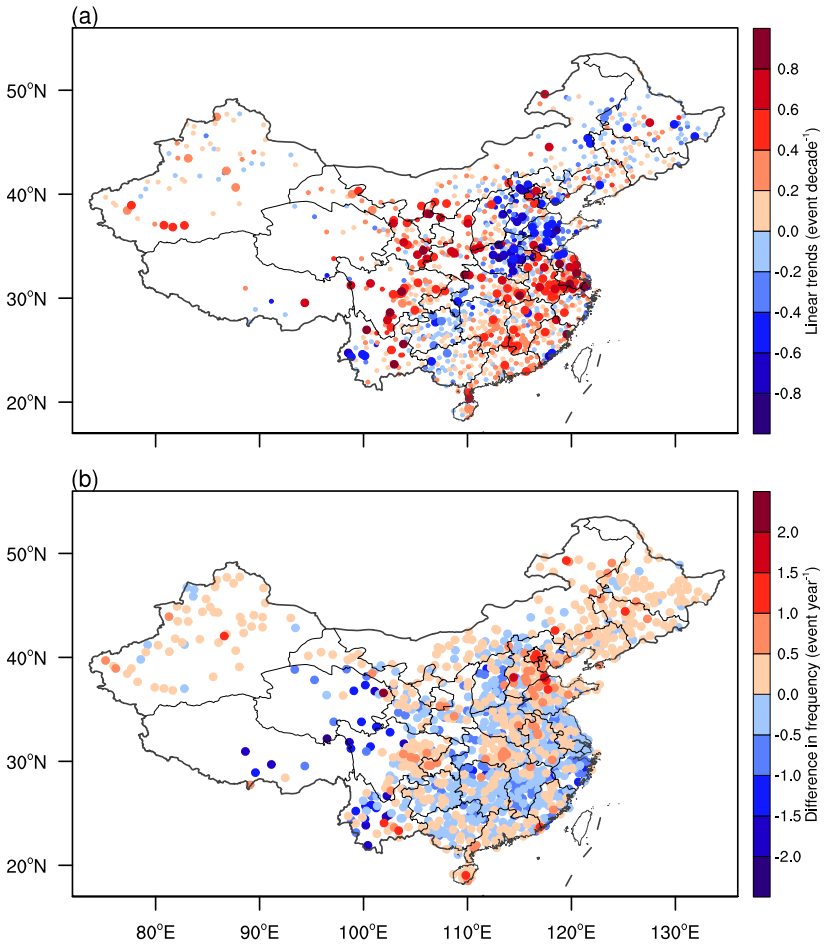


Figure 4. Changes in frequency of whiplash events (W2C&C2W) due merely to changing temperature variability (a) and winter-mean warming (b) during 1980–2018. (a) Similar to figure 2(c), but for whiplash events identified based on linearly-detrended Tmax and Tmin. (b) Differences between pairwise (2004–2018 versus 1980–1994) 15 year average frequency of whiplash events (W2C&C2W), derived via the PDF-shifting method (details see Methods).

0.3 and insignificant. Hence, these two methods consistently highlight the dominant role of changing temperature variability in driving significant increases in wintertime whiplash events in China, in the era of sea-ice melt.

The Arctic amplification of global warming due to diminishing sea-ice is believed to be capable of inducing changes in winter temperature variability at mid-high latitudes (Barnes and Screen 2015). Physically, the greater warming of the Arctic could weaken the polar jet stream and shift it more equatorward, facilitating increases in temperature variability (Overland *et al* 2011, Francis and Vavrus 2012). It is also reported that the Arctic sea-ice melt could augment temperature variability through amplifying mid-latitude ridges and troughs via stratospheric pathways (Zhang *et al* 2016, Kretschmer *et al* 2018, Zhang *et al* 2018). These reported connections may raise a follow-up question that could the fingerprint of the declining sea-ice, as a steady external forcing, be robustly detected in observed increases in whiplash events? The spatially-aggregated difference between whiplash events' frequency in the latter (2004–2008) and the former period (1980–1994) are well enclosed within the range of internal variability (figure 5(b)). Given both strong anthropogenic warming and precipitous decline in sea-ice in the latter period, this preliminary detection outcome should be interpreted as that forced responses of whiplash events' frequency to these two external forcings combined have not yet emerged from influences of internal variability till 2018. Note that circulations and surface air temperatures may show opposite responses to anthropogenic radiative forcing and Arctic sea-ice loss (McCusker *et al* 2017, Oudar *et al* 2017). To overcome this potential cancellation, detection analysis is repeated with respect to re-identified whiplash events using linearly-detrended Tmax and Tmin. Still, no forcings of sea-ice loss can be robustly detected against internal variability (figure 5(c)). In brief, significant increases in wintertime whiplash events over 1980–2018 and resultant enhanced winter temperature volatility in China represent a clear articulation of atmospheric internal variability during the period, co-occurring with rapid Arctic sea-ice melt by coincidence.

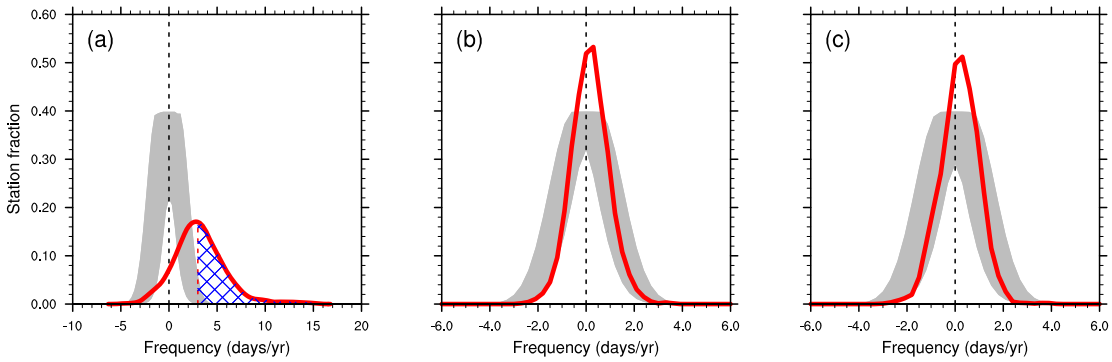


Figure 5. Probability density function of the station fraction experiencing a certain magnitude of changes between pairwise 15 year (2004–2018 versus 1980–1994) average frequency of whiplash events (W2C&C2W). Red curves show observed differences and light-gray shadings frame the 5%–95% range expected due to internal variability alone estimated from the bootstrap procedure ($N = 1000$, see methods). (a) A schematic diagram for detection adapted from Chen *et al* (2018). The dashed red line locates the 95th percentile amongst those bootstrapped samples of changes. The role of external forcings is deemed detectable in the fraction of stations hatched by blue. (b) Changes in whiplash events based on raw Tmax and Tmin. (c) Changes in whiplash events based on linearly-detrended Tmax and Tmin.

4. Discussion

Parts of North America (Kug *et al* 2015), UK (Hanna *et al* 2017), and mid-latitude Eurasia (Mccusker *et al* 2016) are also hotspots for cooling in the era of Arctic sea-ice decline. As a matter of fact, the cooling only represents one side of the coin. These hotspots also experienced increasingly volatile winters punctuated by strong increases in temperature whiplash events like in China (figures S4(a), (c)). Similarly, till 2018, external forcings have not yet emerged from influences of internal variability at a hotspot-scale (figure omitted), within 30° latitudinal bands (0–30 °N, 30–60 °N, 60–90 °N, figure omitted), or across the entire Northern Hemisphere continents (figures S4(b), (d)), although a wider spatial-pooling should have yielded a greater signal-to-noise ratio and therefore higher detectability (Fischer and Knutti 2013).

Of particular note, the failure to detect external forcings does not necessarily mean zero contribution from them. Instead, there is possibility that considered 39 years of observations represent an insufficient sample size or insufficient amount of sea-ice loss to robustly distinguish forced responses from internally-generated low-frequency varability (Mori *et al* 2014, Chen *et al* 2016, Sun *et al* 2016, Overland *et al* 2016, Screen *et al* 2014, 2018). Contrary to this hypothesis, most of modeling studies support the view that even with larger magnitude of sea-ice melt, forced responses in mid-latitude circulations and extreme weathers are still far weak compared to internal variability-driven changes (Suo *et al* 2016, Blackport and Kushner 2017, Oudar *et al* 2017). Apparently, the detection of Arctic sea-ice melt's role in unexpected increases in mid-latitude cold extremes and more volatile winters needs to be further reconciled (Blackport *et al* 2019). Model-based detection and attribution efforts are worth further exerting, in order to cross-validate the observation-based conclusion and formally quantify contributions from various external forcings to the changing winter volatility. Relevant outcomes hold great promise to constrain projections of winter whiplash events to inform preparations for this overlooked type of winter hazard in the future.

Although this work mainly addressed the detectability of external forcings, understandings about thermodynamic-dynamic drivers and processes (e.g. large-scale atmospheric and oceanic modes) should not be downplayed. These information are fundamental to evaluate models' performance in simulating changes in winter temperature whiplash for the right reason, in turn better informing attribution and projection. Diagnosis of physical mechanisms for winter temperature whiplash, therefore, may be a future avenue for follow-up works.

Linear trend estimates may be fairly sensitive to the length of analysis periods, as well as to the choice of starting/ending year. Actually, any longer period starting in the 1960s and ending at 2018 commonly observed increasingly mild winters in China featuring the prevalence of significant decreases in whiplash events spatially (figure S5(a)). So the reported enhanced winter volatility over 1980–2018 should be viewed as a temporary excursion from this long-term tendency toward milder winters. Fixing the ending year at 2018 (figure S5(a)), widespread (gray shaded) strengthening of temperature volatility co-occurred with the rapid sea-ice melt commencing since 1980–1991. Given varying starting years and period lengths, all periods during which over one-quarter stations recorded significant increases in whiplash events similarly start after 1980 (figure S5(b)). Interestingly, regardless of starting years, the period recording the most widespread (i.e. largest station number) significant increases in whiplash events coincidentally ends at 2011 (inserted figure in figure S5(b)), even though Arctic sea-ice melt continues or even accelerates thereafter. This peak-structure for the number

of significant stations (figures S5(a), (b)) alludes to the transient and intermittent nature of recent enhanced winter volatility. This intermittency is essentially dictated by chaotic internal variability (figure S5(c)), which may have an origin from atmosphere intrinsically or from decadal to inter-decadal modes of sea surface temperatures remotely (Sun *et al* 2016, Overland *et al* 2016, Osborne *et al* 2017, Screen and Francis 2016, Sung *et al* 2019). In view of this, the reported observational fact of increasingly volatile winters during 1980–2018 can not be used to predict any directional and persisting tendency of winter volatility in the future. Despite the non-detectability and intermittency, the coincidence of widespread enhanced volatility with the rapid sea-ice loss after 1980 implies the possibility that the sea-ice melt may contribute to recent increases in whiplash events through amplifying internal variability (Overland *et al* 2015, Wilhite *et al* 2017).

The proposed definition of temperature whiplash expands the current matrix for temperature extremes (Zhang *et al* 2011) not only in the number of indices but also in the complex nature of them. Essentially, whiplash events belong to the category of 'sequential extremes', which overlay and further amplify risks from temporally-aligned extremes (Bates 2018, Zscheischler *et al* 2018, Matthews *et al* 2019).

5. Conclusions

In summary, in the era of rapid Arctic sea-ice loss during 1980–2018, changes in winter temperature extremes across China have deviated from the generalized expectation of 'increases in warm extremes and decreases in cold extremes' in a warming climate. Instead, much of China, including Northeast, Northwest, Southeast, Southwest, and the Yangtze River Valley, observed a tendency toward more volatile winters as accentuated by significant increases in temperature whiplash events. It is the changing temperature variability rather than the human-caused winter-mean warming that enhances the volatility in wintertime temperatures. Although co-occurring with precipitous decline in Arctic sea-ice melt in timing, the strengthening of winter temperature volatility still lies within the range expected due to atmospheric internal variability, leaving the forcing from sea-ice loss still non-detectable.

The casual linkage between Arctic sea-ice loss and elevated odds of cold extremes in mid-latitude continents is overwhelmingly underpinned by observational studies but not by modeling studies (Cohen *et al* 2019). Our detection result, however, suggests that even in observational records, those proposed casual linkages may be not as clear and robust as previously assumed.

Observed significant increases in whiplash events remind people to take precautions not only against warm and cold extremes separately but also against elevated risks from wild swings between them.

Acknowledgments

We acknowledge funding support from the National Key Research and Development Program of China (Grant No. 2018YFC1507700) and from Regional Program of Natural Science Foundation of China (Grant No. 41565005). We also thank the Editor and reviewers for their thorough review and constructive suggestions.

Data availability statement

Any data that support the findings of this study are included within the article.

ORCID iDs

Yang Chen https://orcid.org/0000-0002-1765-3783
Panmao Zhai https://orcid.org/0000-0002-1813-0159

References

Barnes E A and Screen J A 2015 The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it? *Wiley Interdiscip. Rev. Clim. Change* **6** 277–86
Bathiany S, Dakos V, Scheffer M and Lenton T M 2018 Climate models predict increasing temperature variability in poor countries *Sci. Adv.* **4** eaar5809
Bates S 2018 Drastic shifts in weather give people winter weather whiplash *EOS* **99**
Blackport R and Kushner P J 2017 Isolating the atmospheric circulation response to Arctic sea ice loss in the coupled climate system *J. Clim.* **30** 2163–84
Blackport R, Screen J A, van der Wiel K and Bintanja R 2019 Minimal influence of reduced Arctic sea ice on coincident cold winters in mid-latitudes *Nat. Clim. Change* **9** 697–704
Casson *et al* 2018 Winter weather whiplash: impacts of extreme meteorological events misaligned with natural and human systems in seasonally snow-covered regions *AGU Fall Meeting* **GC31G**1337
Chamberlain C J, Cook B I, Atauri I G and Wolkovich E M 2019 Rethinking false spring risk *Glob. Change Biol.* **25** 2209–20
Chen H W, Zhang F and Alley R B 2016 The robustness of midlatitude weather pattern changes due to Arctic sea ice loss *J. Clim.* **29** 7831–49
Chen Y, Zhai P and Zhou B 2018 Detectable impacts of the past half-degree global warming on summertime hot extremes in China *Geophys. Res. Lett.* **45** 7130–9
Cohen J 2016 An observational analysis: tropical relative to Arctic influence on mid-latitude weather in the era of Arctic amplification: Arctic vs. tropical forced trends *Geophys. Res. Lett.* **43** 5287–94
Cohen J, Screen J A, Furtado J C, Barlow M, Whittleston D, Coumou D, Francis J, Dethloff K, Entekhabi D and Overland J 2014 Recent Arctic amplification and extreme mid-latitude weather *Nat. Geosci.* **7** 627–37
Cohen J *et al* 2019 Divergent consensuses on Arctic amplification influence on mid-latitude severe winter weather *Nat. Clim. Change* accepted
Collow T W, Wang W Q and Kumar A 2019 Reduction in northern midlatitude 2-m temperature variability due to Arctic sea ice loss *J. Clim.* **32** 5021–35
Della-Marta P M, Haylock M R, Luterbacher J and Wanner H 2007 Doubled length of western European summer heat waves since 1880 *J. Geophys. Res.-Atmos.* **112** D15103

Fischer E M and Knutti R 2013 Robust spatially aggregated projections of climate extremes *Nat. Clim. Change* **3** 1033–8
Fischer E M and Knutti R 2014 Heated debate on cold weather *Nat. Clim. Change* **4** 537–8
Francis J A and Vavrus S J 2012 Evidence linking Arctic amplification to extreme weather in mid-latitudes *Geophys. Res. Lett.* **39** L06801
Guirguis K, Gershunov A, Cayan D R and Pierce D W 2018 Heat wave probability in the changing climate of the Southwest US *Clim. Dyn.* **50** 3853–64
Hanna E, Hall R J and Overland J E 2017 Can Arctic warming influence UK extreme weather *Weather* **72** 346–52
Jang Y-S, Kug J-S and Kim B-M 2019 How well do current climate models simulate the linkage between Arctic warming and extratropical cold winters *Clim. Dyn.* **53** 4005–18
Johnson N C, Xie S P, Yu K and Li X 2018 Increasing occurrence of cold and warm extremes during the recent global warming slowdown *Nat. Commun.* **9** 1724
Kretschmer M, Coumou D, Agel L, Barlow M, Tziperman E and Cohen J 2018 More-persistent weak stratospheric polar vortex states linked to cold extremes *Bull. Am. Meteorol. Soc.* **99** 49–60
Kretschmer M, Cohen J, Matthias V, Runge J and Coumou D 2018 The different stratospheric influence on cold-extremes in Eurasia and North America *NPJ Clim. Atmos. Sci.* **1** 44
Kug J S, Jeong J H, Jang Y S, Kim B M, Folland C K, Min S K and Son S W 2015 Two distinct influences of Arctic warming on cold winters over North America and East Asia *Nat. Geosci.* **8** 759–62
Kunkel K E, Vose R S, Stevens L E and Knight R W 2015 Is the monthly temperature climate of the united states becoming more extreme *Geophys. Res. Lett.* **42** 629–36
Laucelli D, Rajani B, Kleiner Y and Giustolisi O 2013 Study on relationships between climate-related covariates and pipe bursts using evolutionary-based modelling *J. Hydroinfom.* **16** 743–57
Luo D, Chen X, Overland J, Simmonds I, Wu Y and Zhang P 2019 Weakened potential vorticity barrier linked to recent winter Arctic sea-ice loss and mid-latitude cold extremes *J. Clim.* **32** 4235–62
Ma S and Zhu C 2019 Extreme cold wave over east asia in january 2016: a possible response to the larger internal atmospheric variability induced by Arctic warming *J. Clim.* **32** 1203–16
Ma S, Zhu C, Liu B, Zhou T, Ding Y and Orsolini Y J 2018 Polarized response of East Asian winter temperature extremes in the era of Arctic warming *J. Clim.* **31** 5543–57
Marino G P, Kaiser D P, Gu L and Ricciuto D M 2011 Reconstruction of false spring occurrences over the southeastern United States, 1901–2007: an increasing risk of spring freeze damage *Environ. Res. Lett.* **6** 024015
Masson-Delmotte V *et al* (ed) 2018 *An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (Geneva: World Meteorological Organization)
Matthews T, Wilby R L and Murphy C 2019 An emerging tropical cyclone-deadly heat compound hazard *Nat. Clim. Change* **9** 602–9
Mccusker K E, Fyfe J C and Sigmond M 2016 Twenty-five winters of unexpected Eurasian cooling unlikely due to Arctic sea-ice loss *Nat. Geosci.* **9** 838–42
McCusker K E, Kushner P J, Fyfe J C, Sigmond M, Kharin V V and Bitz C M 2017 Remarkable separability of circulation response to Arctic sea ice loss and greenhouse gas forcing *Geophys. Res. Lett.* **44** 7955–64
Mori M, Kosaka Y, Watanabe M, Nakamura H and Kimoto M 2019 A reconciled estimate of the influence of Arctic sea-ice loss on recent Eurasian cooling *Nat. Clim. Change* **9** 123–9
Mori M, Watanabe M, Shiogama H, Inoue J and Kimoto M 2014 Robust Arctic sea-ice influence on the frequent Eurasian cold winters in past decades *Nat. Geosci.* **7** 869–73
Osborne J M, Screen J A and Collins M 2017 Ocean-atmosphere state dependence of the atmospheric response to Arctic sea ice loss *J. Clim.* **30** 1537–52
Oudar T, Sanchez-Gomez E, Chauvin F, Cattiaux J, Terray L and Cassou C 2017 Respective roles of direct GHG radiative forcing and induced Arctic sea ice loss on the Northern Hemisphere atmospheric circulation *Clim. Dyn.* **49** 3693–713
Overland J, Francis J A, Hall R, Hanna E, Kim S-J and Vihma T 2015 The melting Arctic and midlatitude weather patterns: are they connected *J. Clim.* **28** 7917–32
Overland J E, Dethloff K, Francis J A, Hall R J, Hanna E, Kim S-J, Screen J A, Shepherd T G and Vihma T 2016 Nonlinear response of mid-latitude weather to the changing Arctic *Nat. Clim. Change* **6** 992–9
Overland J E, Wood K R and Wang M 2011 Warm Arctic—cold continents: climate impacts of the newly open Arctic Sea *Polar Res.* **30** 15787
Petoukhov V and Semenov V A 2010 A link between reduced Barents-Kara sea ice and cold winter extremes over northern continents *J. Geophys. Res.-Atmos.* **115** D21111
Qian C, Wang J, Dong S, Yin H, Burke C, Ciavarella A, Dong B, Freychet N, Lott F C and Tett S F 2018 Human influence on the record-breaking cold event in January of 2016 in Eastern China *Bull. Am\r. Meteorol. Soc.* **99** S118–22
Rohde R, Muller R, Jacobsen R, Perlmutter S, Rosenfeld A, Wurtele J, Curry J, Wickham C and Mosher S 2013 Berkeley earth temperature averaging process *Geoinform. Geostat: Overview* **1** 1–13
Screen J A, Deser C, Simmonds I and Tomas R 2014 Atmospheric impacts of Arctic sea-ice loss, 1979–2009: separating forced change from atmospheric internal variability *Clim. Dyn.* **43** 333–44
Screen J A and Francis J A 2016 Contribution of sea-ice loss to Arctic amplification is regulated by Pacific Ocean decadal variability *Nat. Clim. Change* **6** 856–60
Screen J A, Deser C, Smith D M, Zhang X, Blackport R, Kushner P J, Oudar T, Mccusker K E and Sun L 2018 Consistency and discrepancy in the atmospheric response to Arctic sea-ice loss across climate models *Nat. Geosci.* **11** 155–63
Sen P K 1968 Estimates of the regression coefficient based on Kendall's Tau *Publ. Am. Stat. Assoc.* **63** 1379–89
Sorokina S A, Camille L I, Wettstein J J and Kvamstø N G 2016 Observed atmospheric coupling between barents sea ice and the warm-Arctic cold-Siberian anomaly pattern *J. Clim.* **29** 495–511
Sun B, Wang H and Zhou B 2019 Climatic condition and synoptic regimes of two intense snowfall events in eastern China and implications for climate variability *J. Geophys. Res.-Atmos.* **124** 926–41
Sun L, Perlwitz J and Hoerling M 2016 What caused the recent 'Warm Arctic, Cold Continents' trend pattern in winter temperatures *Geophys. Res. Lett.* **43** 5345–52
Sung M-K, Jang H-Y, Kim B-M, Yeh S-W, Choi Y-S and Yoo C 2019 Tropical influence on the North Pacific oscillation drives winter extremes in North America *Nat. Clim. Change* **9** 413–8
Suo L, Gao Y, Guo D, Liu J, Wang H and Johannessen O M 2016 Atmospheric response to the autumn sea-ice free Arctic and its detectability *Clim. Dyn.* **46** 2051–66
Tang Q, Zhang X, Yang X and Francis J A 2013 Cold winter extremes in northern continents linked to Arctic sea ice loss *Environ. Res. Lett.* **8** 014036
Tett S F B, Stott P A, Allen M R, Ingram W J and Mitchell J F B 1999 Causes of twentieth-century temperature change near the Earth's surface *Nature* **399** 569–72
Wilhite D A, Morrow K C and Shulski M 2017 Changes in Arctic climate and central US weather patterns: is there a link *Bull. Am. Meteorol. Soc.* **98** ES1–S2
2019 *WMO statement on the state of the global climate in 2018 WMO-No.1233* World Meteorological Organization pp 1–44 (https://library.wmo.int/doc_num.php?explnum_id=5789)
Wu B, Su J and D'Arrigo R 2015 Patterns of Asian winter climate variability and links to Arctic sea ice *J. Clim.* **28** 6841–58

Zhang J, Tian W, Chipperfield M P, Xie F and Huang J L 2016 Persistent shift of the Arctic polar vortex towards the Eurasian continent in recent decades *Nat. Clim. Change* **6** 1094–9

Zhang P, Wu Y, Simpson I R, Smith K L, Zhang X D, De B and Callaghan P 2018 A stratospheric pathway linking a colder Siberia to Barents-Kara sea sea ice loss *Sci. Adv.* **4** eaat6025

Zhang X, Alexander L, Hegerl G C, Jones P, Tank A K, Peterson T C, Trewin B and Zwiers F W 2011 Indices for monitoring changes in extremes based on daily temperature and precipitation data *Wiley Interdiscip. Rev. Clim. Change* **2** 851–70

Zhou B T, Wang Z Y, Shi Y, Xu Y and Han Z 2018 Historical and future changes of snowfall events in china under a warming background *J. Clim.* **31** 5873–89

Zou Y, Wang Y, Zhang Y and Koo J H 2017 Arctic sea ice, Eurasia snow, and extreme winter haze in China *Sci. Adv.* **3** e1602751

Zscheischler J, Westra S, Van Den Hurk B J, Seneviratne S I, Ward P J, Pitman A, AghaKouchak A, Bresch D N, Leonard M and Wahl T 2018 Future climate risk from compound events *Nat. Clim. Change* **8** 469–77