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Weakened cyclones, intensified anticyclones and recent extreme cold winter weather events in Eurasia

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Abstract

Extreme cold winter weather events over Eurasia have occurred more frequently in recent years in spite of a warming global climate. To gain further insight into this regional mismatch with the global mean warming trend, we analyzed winter cyclone and anticyclone activities, and their interplay with the regional atmospheric circulation pattern characterized by the semi-permanent Siberian high. We found a persistent weakening of both cyclones and anticyclones between the 1990s and early 2000s, and a pronounced intensification of anticyclone activity afterwards. It is suggested that this intensified anticyclone activity drives the substantially strengthening and northwestward shifting/expanding Siberian high, and explains the decreased midlatitude Eurasian surface air temperature and the increased frequency of cold weather events. The weakened tropospheric midlatitude westerlies in the context of the intensified anticyclones would reduce the eastward propagation speed of Rossby waves, favoring persistence and further intensification of surface anticyclone systems.

Keywords: cyclones, anticyclones, extreme cold events

1. Introduction

Along with the generally increased global mean surface air temperature, extreme cold winter weather events have more frequently occurred in recent years over Eurasia (e.g., Zhang et al. 2008, Overland et al. 2011, Cohen et al. 2010). The occurrence and persistence of the extreme cold weather events have been attributed to various contributing factors, including a temporally polarized negative Arctic/North Atlantic Oscillation (AO/NAO; e.g., Thompson and Wallace 1998, Deser and Teng 2008), a spatially shifted Northern Hemisphere atmospheric circulation leading pattern (e.g., Zhang et al. 2008 and their figures 1 and 2, Overland et al. 2011), and increased snow cover (e.g., Cohen et al. 2010). Temporal and spatial changes in atmospheric circulation pattern are significant drivers of reduced Arctic sea ice and Arctic and Eurasian surface warming (e.g., Rigor et al. 2002, Zhang et al. 2003, Zhang et al. 2008, Overland and Wang 2010); the circulation changes may also have been amplified through feedback processes from the underlying reduced sea ice and warmed surface (e.g., Honda et al. 2009, Petoukhov and Semenov 2010, Wu and Zhang 2010, Blüthgen et al. 2012, Francis and Vavrus 2012).

Although the hemispheric-scale atmospheric circulation pattern plays an important steering role, extreme cold events have prominent regional features associated with dramatically intensified or unusually persistent weather systems, such as...
those recently observed in Europe and China (e.g., Pinto et al. 2007, Wen et al. 2009, Zhou et al. 2009). Zhang et al. (2008) indicate that, when the transformed dipolar Arctic Rapid change Pattern (ARP) goes to a negative phase, the monthly mean Siberian high (SH) intensifies tremendously and expands northward and the Icelandic low weakens and contracts southward, leading to enhanced lower latitude warmer air transport into the Arctic Ocean and colder polar air transport to Eurasia. This meridional flow within the Arctic Ocean also has strong projection on the Arctic Dipole defined north of 70°N (e.g., Overland and Wang 2010). However, the association of synoptic activities, which cause daily weather events, with regional or large-scale circulation changes and extreme cold events in Eurasia is not well understood, though a weakened Eurasian cyclone activity was detected (Zhang et al. 2004). This weakening change would be the downward phase of an oscillation related to decadal-scale natural variability.

Here we hypothesize that daily-based, synoptic-scale cyclone and anticyclone activities have also changed in conjunction with the monthly based, large-scale atmospheric circulation spatial pattern shift, and have played a direct driving role in daily-based extreme cold events in Eurasian winters. Considering interactions between synoptic-scale cyclones/anticyclones and large-scale atmospheric circulation, we therefore test this hypothesis through examining changes in cyclone and anticyclone activities, their relationship with the SH, and their impacts on extreme cold weather.

2. Data and methodology

The data sets used are 6-hourly sea level pressure (SLP), monthly SLP, surface air temperature (SAT), geopotential height and wind from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) from 1978–2012. The daily minimum SAT ($T_{\text{min}}$) data at 1337 Eurasian met stations were obtained from the National Climate Data Center (NCDC) of the National Ocean and Atmospheric Administration (NOAA, ftp://ftp.ncdc.noaa.gov/pub/data/gsod/). The data at these stations were continuously available at least for 31 years during 1978–2012.

A cyclone storm identification and tracking algorithm was employed. Details of this modified algorithm, following Serreze (1995) and Serreze et al. (1997), and its application to detecting variability of and changes in Northern Hemisphere storm activities can be found in Zhang et al. (2004). Here we extend this algorithm to identify and track anticyclones by modifying parameters related to the different characteristics of cyclones and anticyclones (see supplementary material available at stacks.iop.org/ERL/7/044044/mmedia). The cyclone and anticyclone identification and tracking area covers all of Eurasia, from 0 to 110°E and 40 to 75°N.

We then introduced indices of cyclone intensity (CI) and anticyclone intensity (ACI) to measure CI and ACI fluctuations and changes in the study area. The CI and ACI were produced via the following two steps: (1) we calculated mean differences between cyclone or anticyclone central SLP and climatological monthly mean SLP at corresponding grid points for each individual cyclone or anticyclone throughout its duration, and (2) we averaged SLP differences over all cyclones or anticyclones in the study area per season. Winter is defined as December, January and February (DJF).

3. Results

3.1. Variability and changes of cyclones, anticyclones and the Siberian high

A weakening of surface-based synoptic-scale cyclone activity over Eurasia was reported in conjunction with a global mean poleward shift of storm tracks and intensified Arctic storm activity in the second half of the 20th century (e.g., Zhang et al. 2004). This shift would be a part of long-term nature variability (e.g., Ulbrich et al. 2009). The analysis presented here covers a time period from the winter of 1978/79 to the winter of 2011/12 and continually supports the previous finding, although a large positive anomaly of winter CI occurred around the mid 2000s superimposed on a long-term CI weakening trend (figure 1). The weakened Eurasian cyclone changes found here are also consistent with a recent multi-method comparison study, which indicates a significant, relatively large ensemble negative trend of cyclone track density over center Eurasia in past 20 years (figure 8(b) in Neu et al. 2012).

As discussed by Zhang et al. (2004), the positive CI polarity around 1990 is consistent with the positively amplified AO/NAO. A deepening Icelandic low and strengthening jet stream in the AO/NAO positive phase favor cyclone development over Eurasia, and steer cyclone propagation towards Eurasia. The anomalous large CI in the mid 2000s, however, demonstrates good correspondence with the swift phase transition of ARP from negative to positive, which
was characterized by anomalous cyclonic SLP circulation that developed over Eurasia (Zhang et al. 2008).

The regionally integrated intensity of winter anticyclones has also exhibited large fluctuations and changes from interannual to decadal scales (figure 1). A prominent feature is the pronounced weakening before the mid 2000s. ACI anomaly values remained persistently negative from the late 1980s to the early 2000s. After the mid 2000s, ACI increased notably. Comparing CI and ACI time evolution reveals a general negative correlation of $-0.7$ between them at a significance level of 99.99% by using Student’s $T$-test. The negative correlation is especially prominent before the mid 1990s.

To identify the influence of synoptic-scale cyclone and anticyclone activities on shaping the seasonal Eurasian atmospheric circulation pattern represented by SH, we computed SH intensity (SHI) defined as the standardized regional mean of anomalous winter SLP in the main body area of SH, $70^\circ$E–$120^\circ$E, $40^\circ$N–$60^\circ$N. SH is not stationary on a daily basis; its semi-permanent features are generally revealed in monthly or seasonal mean. Variability of and changes in SH result from the regionally, monthly or seasonally integrated activities of traveling anticyclones, although the large-scale circulation can steer anticyclone movement and development. Due to the general negative correlation between CI and ACI, we focus on anticyclones and their relationship with SH.

Both ACI and SHI have exhibited consistent interannual variability with a positive correlation coefficient of 0.81 at a significance level of 99.99%, suggesting interplay between the 6-hourly-based synoptic weather and the seasonally based semi-permanent regional circulation pattern. Similar to the anticyclones, prolonged SH weakening occurred in the 1980s and 1990s. The large warming trend over the Eurasian continent during the same time period would be a thermodynamic contributor to the weakening SH (Panagiotopoulos et al. 2005). By contrast, the SHI has increased considerably since the mid 2000s, following the same trajectory as the ACI; maximum values occurred in the winters of 2005/06, 2007/08, and 2011/12.

3.2. Changed surface climate in the context of anticyclones

Due to the tremendous changes in the tight relationships between CI, ACI and SHI, we investigated the changes in the broader scale SLP spatial structure and temporal evolution, and to seek plausible causes of the recently observed extreme cold winter weather. Zhang et al. (2008) and Overland and Wang (2010) have identified a pattern shift of the atmospheric circulation, which would be a particular phase of decadal-scale natural variability and began around the mid 1990s with the meridionally oriented ARP taking over from the zonally oriented AO/NAO. Therefore we elected to analyze surface climate changes after the mid 1990s.

Climatologically, the entire Eurasian continent is dominated by high pressure; the major SH body is centered southwest of Lake Baikal (figure 2(a)). Low pressures reside over the Barents Sea, its adjacent coastal area, and the northwestern North Pacific. Cold SAT, below $-5^\circ$C, spreads from the Arctic Ocean and East Siberia southward and southwestward into Eurasia (figure 2(b)). The high cyclone center density occurs over the Norwegian Sea, Barents Sea and along the Eurasian coast (figure 2(c)). This climatological distribution is consistent with other analysis results (e.g., Neu et al. 2012). The high anticyclone center density exists in the areas southwest of Lake Baikal and the East Siberia (figure 2(d)).

After the mid 1990s an obvious upward SLP trend is seen over almost all of Eurasia except the Mediterranean area, and a striking cooling trend appeared from western Europe to midlatitude Eurasia and further south to southeastern China (figures 2(c) and (d)). The maximum SLP increase of 7 hPa per decade occurred northwest of the climatological SH and over the Barents Sea coast, suggesting intensification and a northwestward shift or expansion of SH. The intensified, northwestward-shifted SH enhanced cold air invasion into midlatitude Eurasia and east China from the climatologically coldest Arctic area (figure 2(b); e.g., Pinto et al. 2007, Wen et al. 2009, Zhou et al. 2009). Simultaneously, the strengthened SH also favors clear skies and increased outgoing longwave radiation, furthering cold weather development. The cold SAT changes shown in figure 2(d), a maximum decrease of $-4^\circ$C per decade, would be a consequence of these combined effects.

As discussed above, integrated synoptic anticyclone activities based on 6-hourly data are highly correlated with the intensity of the major body of the seasonally based large-scale SH. To untangle causal processes underlying the pronounced changes in surface climate properties, we regressed monthly SLP and SAT anomalies on to the winter ACI index (figures 2(e) and (f)). Regressed SLP anomalies show positive values over most of Eurasia with a spatial structure and maximum value location almost identical to those seen in the SLP linear trend from winter 1997/98 to winter 2011/12. The regressed SAT anomalies also capture the changed SAT in Eurasian midlatitudes and east China. Considering its independence from the trend analysis above, the regression analysis and increased anticyclone count suggest that 6-hourly-based synoptic anticyclone activities play an important role in forming the changed seasonal mean surface circulation pattern over all of Eurasia. Intensified anticyclone activities contributed integratively to a strengthened, northwestward-shifted SH and decreased SAT. Meanwhile, we found that both anticyclone count and negative relative vorticity also increased in the area of the large SLP increase associated with ACI fluctuations, reinforcing our finding here (not shown).

3.3. Corresponding changes in vertical atmospheric circulation

To examine vertical atmospheric circulation corresponding to the changed surface ACI, we analyzed the circulation along the vertical section across the large SLP anomalies associated with the ACI variability from 30 to 90$^\circ$N, as depicted in figure 2(e) (figure 3). All circulation features are zonally averaged between 30–90$^\circ$E.
A dipolar structure of the winter geopotential height anomalies occurred along the vertical section when anticyclone intensified (figure 3(a)). Both positive and negative geopotential anomalies are found to be equivalent barotropic; their magnitudes increase with height. The anomalous meridional geopotential height gradient reaches its maximum around 300 hPa. This anomalous meridional gradient is opposite to the climatological mean, leading to anomalous easterlies and suppressing climatological westerlies in the Eurasian midlatitudes (figure 3(b)). Thus, eastward transport of moist, warm North Atlantic Ocean air is reduced, contributing to the cold Eurasian SAT. Also, weakened tropospheric westerlies may also influence Doppler effects on Rossby wave frequency according to $c = \bar{U} - \frac{\beta k^2}{2}$; $c$ is the Rossby phase speed, $\bar{U}$ the mean westerly wind speed, $\beta$ the Rossby parameter, and $k$ the zonal wavenumber. Slowed Rossby wave propagation by the decreased westerlies favors amplification, increasing surface high pressure system persistence and intensity over the Eurasian continent (e.g., Francis and Vavrus 2012), and giving rise to extended cold weather events.
Figure 3. Differences of the composite (a) geopotential height (unit: gpm) and (b) zonal wind (unit: m s\(^{-1}\)) along the vertical section across 30–90\(^\circ\)E between standardized positive and negative winter anticyclone intensities (ACIs) from 1997/1998 to 2011/12. The contours in (b) denote the climatological zonal winds with 2.0 m s\(^{-1}\) interval. The dotted areas denote significant differences at the 95% confidence level.

3.4. Recently observed extreme cold weather events

Cold air and an anticyclone may interact to reinforce each other. Close examination of figure 2 indicates that no cold SAT occurs in the area with the large increased SLP and anticyclone count/intensity, northwest of the climatological SH. Cold SAT is apparently not a trigger for changed anticyclones though cold air accumulation can feedback to further intensify anticyclones. Analysis above suggested that intensified overall anticyclone activity and a consequently strengthened, northwestward-expanded/shifted SH contributed to forming cold winters (figure 2). Superimposed upon these cooling changes, what drives the recently observed daily extreme cold weather events? To answer this question, we conducted a composite analysis of wintertime daily \(T_{\text{min}}\) during occurrences of negative or positive ACI from 1997/98 to 2011/12. The differences of the composite analysis results between negative and positive ACI indicate tremendous decreases in \(T_{\text{min}}\) in the Eurasian midlatitudes, from western Europe to east Asia, when ACI increases (figure 4(a)). The decreased \(T_{\text{min}}\) even extended to southeastern China, Korea, and Japan, suggesting that intensified Eurasian anticyclones in recent years have played a driving role in the increased frequency of extreme cold weather events.

In contrast, intensified anticyclones caused a slight warming in northern Eurasia, indicated by a slight \(T_{\text{min}}\) increase (figure 4(a)). These anticyclone-driven changes are consistent with a large-scale atmospheric circulation spatial shift, as mentioned in the previous section. The shifted pattern or negative ARP enhances lateral atmospheric and oceanic heat transport from the North Atlantic to the Arctic Ocean, leading to a warm Arctic Ocean and Eurasian coastal areas. Surplus Arctic heat then circulates to inland Eurasia (figures 2 and S1 in Zhang et al (2008)).
To further improve understanding of wintertime daily $T_{\text{min}}$ changes, we conducted frequency analysis by using the probability density function (PDF) when ACI went to positive or negative. Due to large differences between the climatological SAT across the entire Eurasian continent and adjacent areas, we divided the analysis area into three domains: western Eurasia (WE; 0–25°E, 40–60°N), middle and eastern Eurasia (MEE; 25–145°E, 40–60°N), and eastern Asia (EA; 105–140°E, 20–40°N).

Changes in the PDFs have occurred across the entire analysis area; large differences between the negative and positive ACIs have appeared in MEE (figures 4(b)–(d)). When anticyclones are weaker, a broadly ranged high frequency occurs for the daily $T_{\text{min}}$ from $-24$ to $0^\circ\text{C}$ in MEE. However, the high frequency shifts towards a colder $T_{\text{min}}$ when anticyclones strengthen. The frequency of a $T_{\text{min}}$ binned from $-20$ to $-44^\circ\text{C}$ increases tremendously; a peak value occurs at $-24^\circ\text{C}$. At the same time the frequency of a $T_{\text{min}}$ between $-20$ and $10^\circ\text{C}$ decreases; the peak value occurs around $-4^\circ\text{C}$. These changes are consistent with those in the seasonal mean SAT (figure 2), indicating that intensified anticyclones are a significant contributing factor to an increase in extreme cold events, as has been observed in recent winters in 2004/05, 2007/08 and 2011/12 (e.g., Pinto et al. 2007, Scaife and Knight 2008, Wen et al. 2009, Zhou et al. 2009, Fereday et al. 2012).

Simultaneously, PDFs for WE and EA show an increased frequency of colder daily $T_{\text{min}}$ and a decreased warmer daily $T_{\text{min}}$ under conditions of stronger anticyclones, though the changes are not as large as those observed in MEE. Noticeable frequency increase mainly occurred for a daily $T_{\text{min}}$ ranging from 2 to $-8^\circ\text{C}$ in WE and from 2 to $-12^\circ\text{C}$ in EA, giving rise to an increased occurrence of local extreme cold weather events.

4. Concluding remarks

The mechanism underlying the recent occurrence of extreme, persistent cold Eurasian winter weather events under conditions of a generally warming climate, in particular with the amplified seasonal mean SAT increase in the northern high latitudes, has been a hotly debated topic, in both the scientific community. To understand why these events have occurred, we examined wintertime 6-hourly based synoptic cyclones and anticyclones over the Eurasian continent, and their integrative roles in shaping regional atmospheric circulation and causing SAT changes in the same season. The major findings are summarized below:

1. the Eurasian anticyclones have pronouncedly intensified since the mid 1990s after a substantial weakening of both cyclones and anticyclones;
2. the intensification of Eurasian anticyclones has caused the strengthened and northwestward-expanded/shifted SH and the cooled SAT; and
3. the intensified Eurasian anticyclones have also played a driving role in the frequency increase of extremely cold daily $T_{\text{min}}$ in Eurasian midlatitude.

Changes in the cyclones and anticyclones, and their resultant regional surface atmospheric circulation and SAT anomalies, are consistent with the recently identified spatial shift of the Northern Hemisphere atmospheric circulation leading pattern and associated surface climate consequences (e.g., Zhang et al. 2008, Overland and Wang 2010). The spatial shift of the hemispheric-scale atmospheric circulation pattern could be a particular phase of decadal-scale natural variability. Although underlying physical mechanisms for this shift have not been well understood, the triggering and driving role of the shifted circulation pattern in the rapid sea ice decline and extreme summer sea ice loss in 2007 has been clearly elucidated (e.g., Zhang et al. 2008, Graversen et al., 2010, Overland and Wang 2010). Decreased sea ice cover or enlarged open water in the Arctic would feed back to the overlying atmospheric circulation pattern by exciting stationary Rossby wave train propagation towards Eurasia and east Asia (e.g., Honda et al. 2009), influencing cyclone and anticyclone activities.

Extreme cold weather events in a warming climate have significant implications both for human society and infrastructure and for natural ecosystems. Accurate assessment and projection of future extreme cold weather events in conjunction with continually increasing global-warming forcing is important for decision-making processes. Such assessment and projection have been lacking, and the capability of state-of-the-art climate models to reproduce these extreme events has not been evaluated (e.g. Jeong et al. 2011). There exists an urgent need for more effort to be directed towards untangling the underlying physical mechanisms and providing credible prediction or projections through more data analysis and high-resolution model simulations and projections.

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