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Changes in Winter Cold Surges over Southeast China: 1961 to 2012

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Abstract: The present study investigates the overall changes in occurrences of winter cold surges over Southeast China for the period 1961-2012, using instrumental observations, reanalysis and model simulation datasets. Based on objectively defined criteria, cold surges were classified into 3 types according to their dynamical origin as inferred from daily evolution patterns of surface pressure systems with a focus on the Siberian High (SH): type A with an amplification of a quasi-stationary SH associated with high-pressure anomalies over the Ural mountains, type B with a developing SH associated with fast traveling upper-level waves, and type C with a high-pressure originated in the Arctic. Examination of the long-term change in cold surge occurrences shows different interdecadal variations among the 3 types. During 1961-2012, type A events (37.8%) decreased, while type B events, accounting for the majority (52.5%) of total winter cold surges, increased slightly. The contribution by type C to the total occurrence of the cold surges was small (8.8%) compared to that of A and B, but it became more frequent in the latest decade, related to the tendency of the Arctic Oscillation (AO) being more in its negative phase. Overall, we found slightly increased occurrences of cold surges over Southeast China since the early 1980s, despite the weakened SH intensity and warmer mean temperature compared to previous decades. The climate model projections of the phase 5 of the Coupled Model Intercomparison Project (CMIP5) suggests similar trend in the late 21st century under warmer climate.

Key words: Cold surge, Siberian high, Arctic Oscillation, Southeast China, long-term climate change

1. Introduction

A cold surge, alternatively called a cold wave or northerly winter monsoon surge, is one of the primary subsystems of the East Asian winter monsoon (EAWM) (Wu and Chan, 1995, 1997; Jeong *et al*., 2005; Wang and Ding, 2006). In mainland China, Southeast China (105°-122°E, 20°-30°N; denoted in Fig. 1) is one of four major centers (Xinjiang, central North China, northeast China, and Southeast China) frequently influenced by cold surges (Ding *et al*., 2009). Although this region belongs to a subtropical climate zone, where the winter (November through March, NDJFM) climate is relatively mild (mean temperature is above 5°C), occasional occurrences of cold surges have tremendous impacts on socio-economical activities since a huge population (about 0.5 billion in year 2012) resides in this region. For example, a cold surge which occurred from 10 January to 5 February 2008, caused extremely damaging frosts, snow and ice storms in Southeast China (Lu *et al*., 2010; Yang *et al*., 2010), resulting in 4 billion US dollars of economic losses, the damage of 11867 kilo hectares of crops and killed 129 people (DCAS/NCC/CMA, 2008; Zhao *et al*., 2008). Following an eastward and southward propagation of the Siberian High (SH), very cold and dry continental air over the central and northern Eurasia is brought deep into Southeast China, causing a sudden temperature drop in this relatively lower-latitude region (Ding and Krishnamurti, 1987; Ding, 1990). In addition to temperature drop, cold surges often trigger strong convective activity with intense rainfall and massive snowfall as cold continental air masses interact with warmer and humid maritime air masses from the South China Sea (Chen and Ding, 2007; Lu *et al*., 2010; Yang *et al*., 2010).

Previous studies have suggested that from the early 1970s to early 2000s, both the SH and the EAWM showed significant weakening trends, accompanied by obvious increases in winter temperatures over East Asia (e.g., Gong and Ho, 2002; Chen *et al*., 2004; Panagiotopoulos *et al*., 2005; Wang and Ding, 2006; Wang *et al*., 2009). Correspondingly, the number of cold days has been continuously decreasing since the 1950s (Zhai and Pan, 2003; Zhou and Ren, 2011) and cold events, with spells of at least six consecutive cold days, have also decreased over the whole of China in the same period (Jiang *et al*., 2012). However, cold surge occurrences over East Asia have not shown any clear decreasing trends during the 1980s and 1990s (Chen *et al*., 2004): in fact a slight increase is found when extending the analyzed period into the 2000s (1980-2006). The implication is that the occurrence of cold surges may not change under future warmer condition (Park *et al*., 2011b). Focusing on China, Ding *et al*. (2009) noted that the occurrences of cold surges based on single station had significantly decreased over Northeast China, while no clear change was detectable over Southeast China.

It has been recognized that atmospheric blockings over the North Atlantic Ocean and Ural Mountains enhance cold

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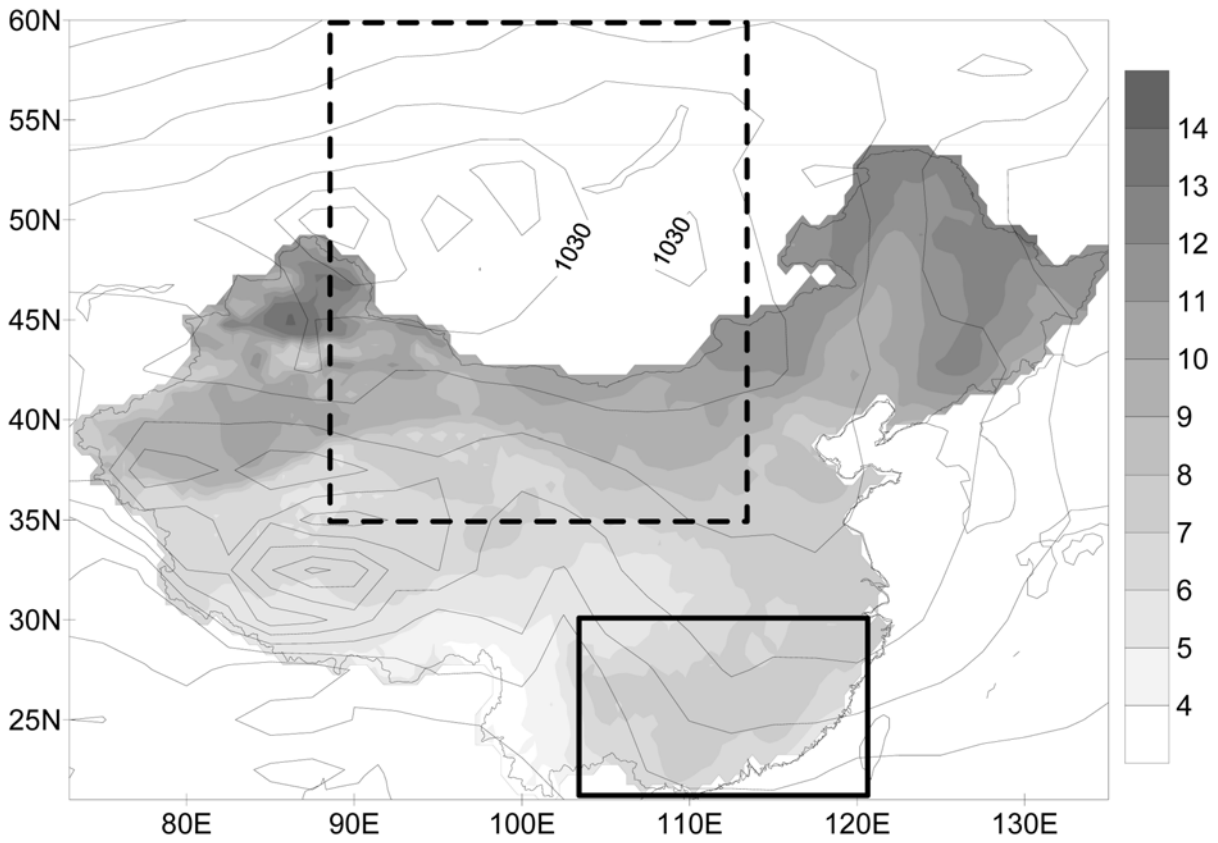

Fig. 1. Spatial distribution of 1.5 standard deviation of daily mean 2meter temperature (T2m: shaded) and sea level pressure (SLP: contour, interval 2.5 hPa) during winter season (November to March, NDJFM hereafter) from 1962 to 2012 and the study region ([105°-122°E, 20°-30°N], enclosed by dark square) (dashed square indicates the domain of Siberian High: [35°N-60°N, 90°E-115°E]).

advection by northerly winds, and increase mass convergence in the upper troposphere. These effects lead to near surface cooling and strengthening of the SH (Ding, 1990; Wang *et al*., 2010; Cheung *et al*., 2012), which then can trigger occurrences of cold surges in East Asia. Actually, a higher frequency of blockings over the North Atlantic Ocean and Europe is found during the negative phase of North Atlantic Oscillation (NAO) compared to its positive phase (Shabbar *et al*., 2001). Moreover, the negative phase of the NAO is associated with a higher frequency of cold surges in Taiwan (Hong *et al*., 2008). Park *et al*. (2011a) pointed out that changes in the large-scale atmospheric circulation associated with the Arctic Oscillation (AO) might contribute to changes in the occurrences of cold surges over East Asia, but mainly in Korea and Japan rather than China. The occurrence of East Asian cold surges is also strongly linked with the interannual variation of the El Niño-Southern Oscillation (ENSO) cycle, with more (less) cold surges during warm (cold) ENSO winters (Chen *et al*., 2004). Other circulation system may also impact the occurrences of cold surges, such as Aleutian Low and the coupling with stratosphere (e.g., Hori and Ueda, 2006; Jeong *et al*., 2006; Kim *et al*., 2009). Until now, very few studies have focused on changes in the occurrence of winter cold surges over Southeast China despite their dynamical and practical importance.

This work investigates changes in the occurrence of spatially large winter cold surges over Southeast China from 1961 to 2012, and its connection to large-scale climate change. More specifically, the objectives of this study were to: 1) identify winter cold surges over Southeast China and classify these with regard to large-scale synoptic settings; 2) examine changes in the occurrence of cold surges from 1961 to 2012, especially after 1990; and 3) investigate the impact of global warming on changes in the occurrence of cold surges.

2. Data and method

a. Data

To detect winter (defined as November to March) cold surge occurrences over Southeast China, a daily mean $0.5^{\circ} \times 0.5^{\circ}$ gridded 2-meter air temperature (T2m) dataset, (1961 to 2012, compiled by the National Meteorological Information Center, China Meteorological Administration (http://cdc.cma.gov.cn/home.do)), was used. Daily mean sea level pressure (SLP), geopotential height (GPH) were taken from the National Centers for Environmental Prediction-National Center for At-

Table 1. 9 CMIP5 GCM used in this study.

Institution	Modeling Center	Model	Horizontal Dimensions (lons × lats)
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1	128 × 64
		BCC-CSM1.1(m)	320 × 160
College of Global Change and Earth System Science, Beijing Normal University	GCESS	BNU-ESM	128 × 64
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2	128 × 64
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC	CMCC-CMS	192 × 96
Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5	256 × 128
Max Planck Institute for Meteorology	MPI-M	MPI-ESM-LR	192 × 96
		MPI-ESM-MR	192 × 96
Norwegian Climate Centre	NCC	NorESM1-M	144 × 96

mospheric Research (NCEP-NCAR) reanalysis data set (Kalnay *et al*., 1996). By considering data availability and reliability, the analysis period was confined to the 51 winters from 1961/1962 to 2011/2012.

For the future projection, we used daily near surface air temperature (which were regarded as T2m in order to be comparable with instrument observation), SLP and GPH, taken from the historical simulation and RCP4.5 projection of Global Climate Models (GCMs), which participated in the phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor *et al*., 2012). We selected the nine CMIP5 GCMs with 1000 hPa pressure level data available for the Siberian region (Table 1). All the simulated data sets were regridded to a $2.5^{o} \times 2.5^{o}$ resolution to be comparable with the resolution of the NCEP-NCAR reanalysis data.

b. Definition of cold surges over Southeast China

In this study, cold surges over Southeast China were defined by several synoptic criteria representing an amplification of the Siberian High and temperature drops. Following Zhang *et al*. (1997), with some minor modifications considering characteristics of used data and studied region, we defined the occurrence of a cold surge over Southeast China when the following two specific conditions were satisfied.

1) A strong surface anticyclone over central Siberia [35°N-60°N, 90°E-115°E] should exist according to the criteria suggested by Zhang and Wang (1997). a) A maximum center of 1000 hPa GPH at the grid point relative to the eight surrounding points should exist, b) the magnitude of the SLP of this anticyclone center must be greater than 1035 hPa (same as the criteria used by Jeong and Ho (2005), Jeong *et al.* (2005) and Park *et al*. (2011)), c) the magnitude of the relative vorticity in this center should exceed a critical value of $1.0 \times 10^{-5}\ s^{-1}$ and last for more than 24 hours.

2) An abrupt drop in surface air temperature should be found over a large area in Southeast China. A drop in T2m value should exceed 1.5δ (where δ is the standard deviation of the daily winter T2m anomaly in 1961-2012) within 24-48 hours for at least 100 grid points ($0.5^{o} \times 0.5^{o}$ grid resolution for T2m dataset) using observational data and 4 grid points for GCMs simulated near surface air temperature (equal to $5^{o} \times 5^{o}$ as indicated by Park *et al*. (2011a)) in Southeast China. As can be seen from Fig. 1, the winter 1.5δ is generally larger than 7°C over the studied region. Wang and Ding (2006) used 7°C as a T2m criterion to define regional cold surges in Southeast China.

Following these criteria, a total of 236 cold surges, with on average 4.6/winter, were identified for Southeast China during 1961-2012, which is lower than the 8.4/winter estimated for the whole of East Asia (Jeong and Ho, 2005).

c. Classification of cold surge types

The detected 236 cold surges were then classified into 3 major groups based on large-scale atmospheric circulation backgrounds or dynamical mechanisms involved. Park *et al*. (2008, 2011a) classified East Asian cold surges into two groups, one with cold surges associated with upper-level wave trains and the other with cold surges associated with blockings. The blocking type tends to occur more often during the negative phase of the AO, but the wave train type is observed during both positive and negative AO phases (Park *et al*., 2011a). There are two major paths of cold high pressure systems into East Asia related to the occurrence of cold surges; one is from west to east around 50°N and the other one is from northern Siberia to the Southeast Asia (Zhang and Chen, 1999). The cold surges over East Asia can be divided into two groups based on the source region, a north path group which originates from northwest of Lake Baikal and west path group which originates from north of Lake Balkhash (Zhang *et al*., 1997). This latter classification emphasizes the distinctive propagation paths of lower level high pressure systems for each category. On the other hand, the classification by Park *et al*. (2008, 2011a) mainly focus on the upper-tropospheric circulation patterns. By considering both the evolution of tropospheric circulation and local climate characteristics over

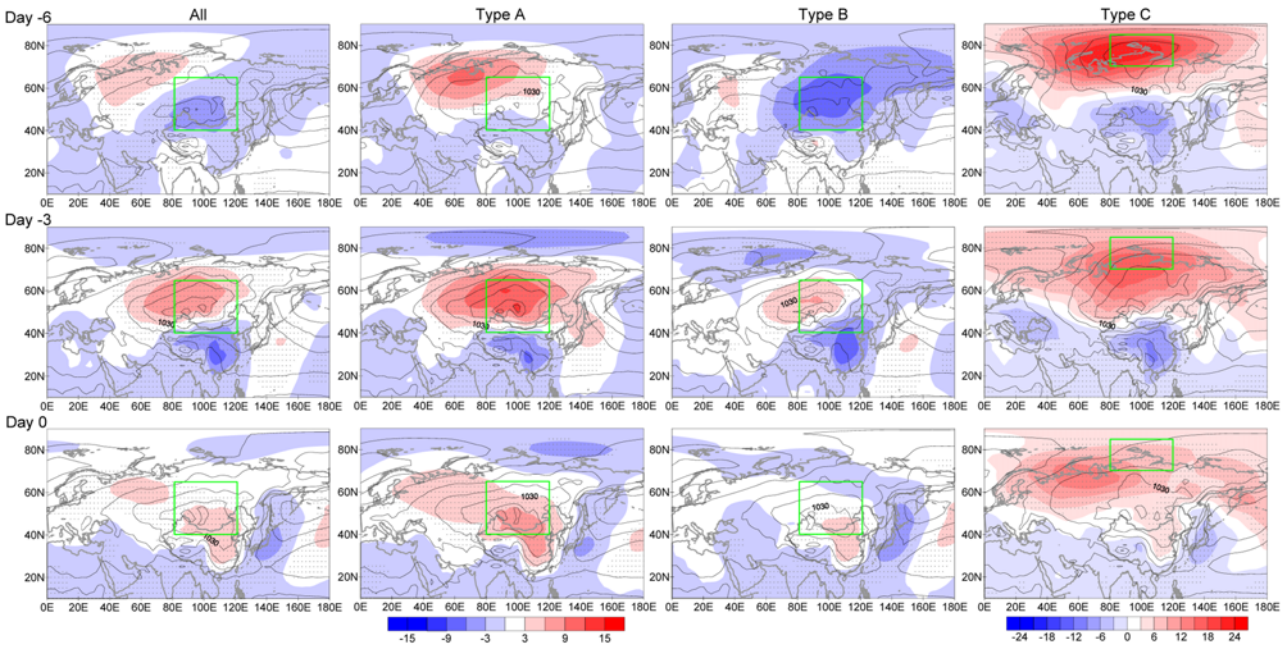

Fig. 2. Composite maps of sea level pressure (SLP) (contours, intervals 5 hPa) and its anomaly (shaded, with seasonal cycle removed) for all and three types of cold surges at 6 days (day -6) and 3 days (day -3) before and the cold surge day (day 0) (green rectangles in type A and B indicate the Siberian region [40°N-65°N, 80°E-120°E] to calculate the daily mean Siberian High index (SHI) and the green rectangles in type C indicate the Arctic high-pressure region [70°N-85°N, 80°E-120°E]) (region, where is significant at 0.05 level, is indicated by gray dots).

Southeast China, we classified cold surges over Southeast China into three main types. The classification is based on the daily evolution of high pressure systems over the central Siberian region ([40°N-65°N, 80°E-120°E]; shown in Fig. 2) and the Arctic [70°N-90°N, 80°E-120°E].

(1) Type A (a slowly amplifying, strong SH): a strong SH, with daily Siberian High intensity (SHI: SLP averaged over [40-65N, 80-120E] (Jeong *et al*., 2011)) stronger than 1030 hPa, is identified for more than 4 days 2 to 6 days prior to a cold surge occurrence (90 cases, 37.8%)

(2) Type B (a fast developing SH): at least 2 consecutive days 2 to 6 days prior to a cold surge occurrence with a daily SHI weaker than 1030 hPa (125 cases, 52.5%)

(3) Type C (Arctic high-pressure): a strong surface anticyclonic pressure anomalies can be identified over the Arctic region [70°N-85°N, 80°E-120°E] 4 to 6 days prior to a cold surge occurrence (the magnitude of the SLP of this anticyclone center must be greater than 1030 hPa); allow 1 day with no strong surface anticyclone identified; a cold surge will be classified to type C if the condition is satisfied even if it may also satisfy the criteria of type A or B (21 cases, 8.8%)

There are 2 cases which are not classified to the above three types, and they will not be further analyzed.

Previous studies classified the cold surges mainly into two types: wave train vs. blocking (Park *et al*., 2008, 2011). Here we divided the wave train type further into the type A and B cold surges. When we went through the evolution of large-scale circulation for all detected wave-train cold surges in Southeast China, it was found that about one third of them occur under slowly evolving circulation whereas the majority comes with a fast evolving system. The classified cold surge types have distinct upper level circulation pattern which will be discussed in the next section.

3. Results

The general patterns of SLP and atmospheric circulation anomalies representing the three types are shown in Fig. 2. The type A cold surges occur with the amplification and south-eastward extension of the SH. A distinct feature is that high pressure anomalies centered over the Ural Mountains (day -6) propagates into central Siberia (day -3) and further expands to East Asia. Following the expansion of the SH, cold air moves into northern China and then to southeast China leading to a steep temperature drop, causing a cold surge occurrence in southeast China (Fig. 3). Previous work has suggested that large-scale negative GPH anomalies in the lower stratosphere are precursory signals prior to cold surge occurrences in East Asia (Jeong *et al*., 2006; Kim *et al*., 2009). A similar evolution pattern is found for type A cold surges in our study (Fig. 4). Its upper-tropospheric (300 hPa) and lower stratospheric (50 hPa) GPH pattern (Fig. 4) suggests that the amplification of the SH is initiated from a quasi-stationary high-pressure anomalies over the Ural Mountains and a subsequent development of baroclinic wave propagating to East Asia within about a week (Fig. 5). The upper level atmospheric circulation pattern associated with type A clearly illustrates the Ural-Siberian

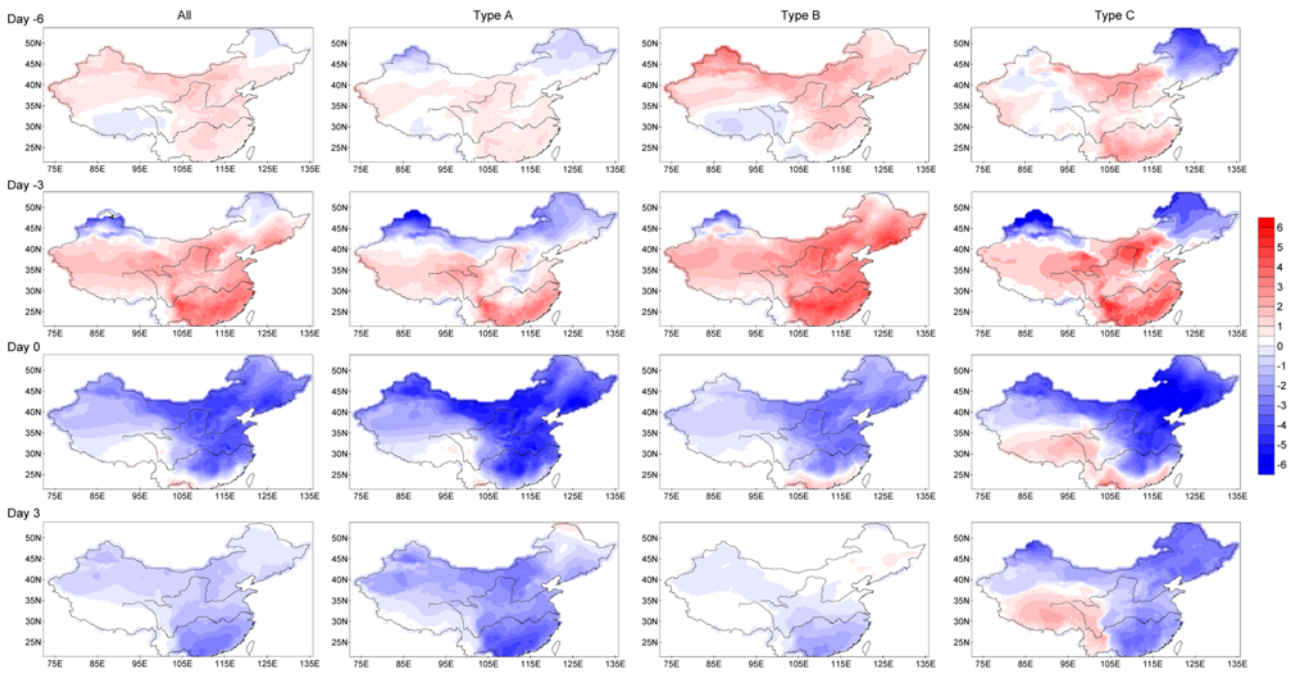

Fig. 3. Composite maps of 2-meter air temperature anomaly for all and three types of cold surges at 6 days (day -6) and 3 days (day -3) before, the cold surge day (day 0), and 3 days after the outbreak of cold surge over mainland of China.

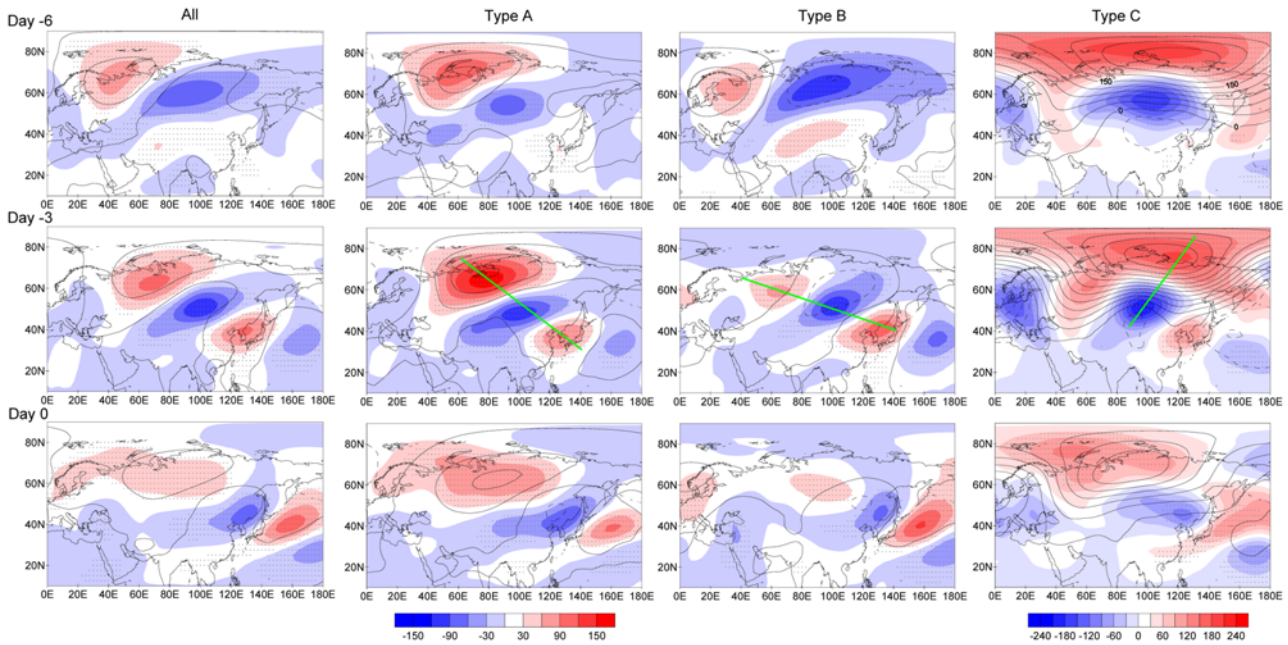

Fig. 4. Same as Fig. 2 but for geopotential height (GPH) anomaly at 300 hPa (shaded; region, where is significant at 0.05 level, is indicated by gray dots) and 50 hPa (contour, intervals 30 gpm).

Blocking pattern (Cheung *et al*., 2012), which exhibits quasi-barotropic feature in the high-latitudes. Cheung *et al*. (2012) suggested that under such conditions, there is stronger meridional flow along its downstream edge that enhances cold advection toward Siberia. Because of the strong cold advection coupled to the large-scale circulation, the SH amplifies greatly prior to the type A outbreaks as seen in the composite map of SLP in Fig. 2.

Type B cold surges are associated with an upper-level wave-train travelling from northwestern Russia to East Asia, but the

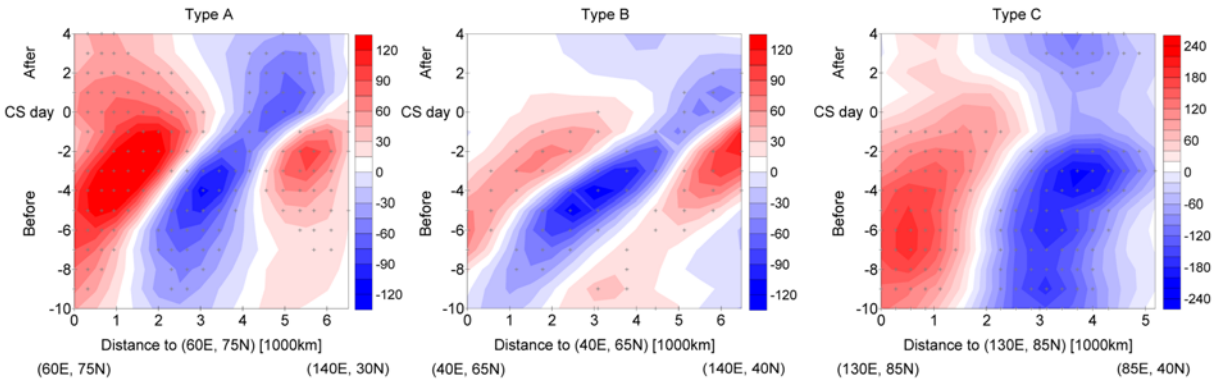

Fig. 5. Time evolution of geopotential height anomaly at 300 hPa along the lines in Fig. 4 for three cold surge types from 10 days (day -10) before to 4 day (day 4) after the cold surge day (day 0) (region, where is significant at 0.05 level, is indicated by gray cross).

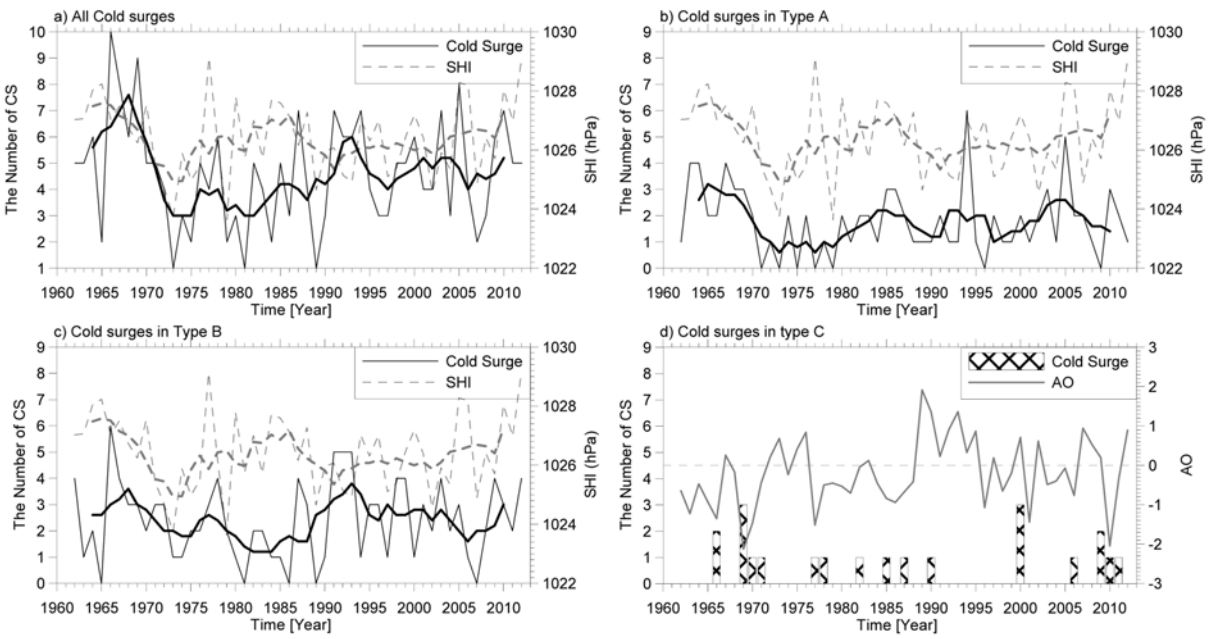

Fig. 6. a) Variation in the occurrence of the winter (NDJFM) cold surges (CS) over Southeast China, and winter mean Siberian High intensity (SHI) (thick lines indicate 5-year running average), b) same as a) but for cold surges in type A, c) same as a) but for cold surges in type B and d) cold surges in type C and winter mean Arctic Oscillation (AO) index (obtained from the Climate Prediction center (CPC), http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml).

amplification of the SH emerges later, at day -3, and the SH is weaker than in type A. The horizontal scale of the upper-level wave-train is smaller than type A, and the travel speed of this wave-train is faster than that during type A events (Fig. 5). The upper level atmospheric circulation pattern corresponding to type B (at day -6) is similar to the Eastern Europe Blocking pattern suggested by Cheung *et al*. (2012). The northerly wind is stronger near the Ural Mountains which bring more intense cold air masses toward western Siberia. The temperature is well below normal over the western and northern part of Siberia. However, the temperature is close to normal over southern and eastern of Siberia. The associated SHI is relatively weaker for cold surges in type B compare to that of type A, which corresponds to the findings of Cheung *et al*. (2012).

For type C, a strong high pressure anomaly is located in the Arctic, centered over the Kara, Latev, and East Siberian Seas at day -6. The positive anomalies maintains a quasi-stationary and equivalent barotropic feature during the occurrence and development stages, but its southernmost part extends into central Siberia at day -3 resulting in a cold surge occurrence over northeastern China (Fig. 5). Its upper-level signature suggests that the positive pressure anomalies are coupled to the lower stratosphere, showing a typical anomalous GPH pattern of the negative phase of the AO (Thompson and Wallace,

1998). The composite circulation patterns for all cold surges reflect Type B mostly (Figs. 2 and 4), but the evolution pattern before day -6 significantly differ from that of type A and C. There are few cases with the two high pressure systems coexist over both Arctic region and Siberian region. Under this condition the type C is classified into type A or B depending on the lasting periods of intensive SH days. Type A and B cold surges can be regarded as subgroups of the wave train cold surges and the type C cold surges can be regarded as the Arctic high-pressure type which was suggested as blocking type of cold surges by Park *et al*. (2011a).

a. Long-term changes in the occurrence of cold surges

Cold surges of different dynamic origin may have different interdecadal variation, so it is important to investigate long-term variation of total occurrences as well as for the different types. Figure 6 shows the temporal variation of cold surge occurrences and the SHI in 1961 to 2012. The number of cold surges/winter shows considerable interannual variability (standard deviation: 2.1) and interdecadal fluctuation. The interdecadal variation of all cold surge occurrences (Fig. 6a) mainly shows an in-phase relationship with the SHI until the late 1980s, which is in line with the findings of Wang and Ding (2006). However, this association has weakened during the last two decades (1990s to 2000s), showing instead a weak negative relationship.

We found that this in-phase and out-of-phase is dependent on the contribution of the different types. The type A cold surges, with a slowly amplifying strong SH, mostly contribute to the in-phase relationship with the SHI, especially at the interdecadal time-scale (correlation coefficient is 0.393 which is significant at 0.05 level) (Fig. 6b). The type A cold surges are thought to be a typical cold surge in East Asia, and shows good dynamical links with EAWM circulation (e.g., Zhang *et al*., 1997; Jeong and Ho, 2005). Type B cold surges, accounting for more than half of total identified cold surges, shows rather an out-of-phase relationship with the SHI. Especially, it seems that the type B mainly contributed to the cold surges occurrences in the last two decades when winter SHI was relatively weaker compared to the first half of the studied period. Type C cold surges, associated with the negative phase of the AO (Fig. 6d), became more frequent during the latest decade when the AO index frequently displayed very strong negative values. However, there are too few type C occurrences to draw any firm conclusions. The type A and B cold surges show weak linear association with the AO variation (correlation coefficients are −0.158 and 0.047 respectively).

We can also see from Fig. 6 that the total occurrence of cold surge showed a sharp decreasing trend in the early 1970s, followed by a weak but steady increasing trend since the early 1980s. This trend is mainly due to the variability in type B cold surges. There is no clear trend in the occurrence of type A cold surge. The occurrence of type B cold surges has increased during the last two decades along with the weakening of the SHI may indicate that the occurrence of cold surges over Southeast China, especially the type B cold surge, may not decrease in a future warmer climate with a continuous weakening winter SHI (Jeong *et al*., 2011). These findings are robust independent of T2m drop thresholds. The general finding of this work remains unchanged with 1δ and 1.5δ thresholds. There is some change in the long-term trend under 2δ threshold, which is mostly due to too small number of events detected. The results are not significantly affected by the choice of the magnitude of the SLP of this anticyclone center (1035 hPa) either. Previous work also suggested that cold surge frequency in East Asia is associated with an interannual variation of the El Niño-Southern Oscillation (ENSO) cycle (Chen *et al*., 2004). In this work the relationship between Niño 3.4 sea surface temperature (SST) and the occurrence of cold surges in southeast China was also examined. Results shown (figure not shown) that the interannual variation of all and type B cold surge occurrence was highly correlated with the ENSO cycle (correlation coefficients was 0.28 and 0.35, respectively, both were significant at 0.05 level). No correlation was found between ENSO cycle and cold surge occurrence of type A and C. The link between ENSO cycle and cold surge occurrence is mostly on interannual scale other than on interdecadal scale. The long term trend of cold surge occurrence was less affected by the variation of ENSO cycle.

b. Projected change in the occurrence of cold surges

Previous studies suggested that the number of cold days in East Asia has decreased since 1980 (e.g., Zhai and Pan, 2003; Choi *et al*., 2009) and it is projected to decrease continuously under future warmer conditions (IPCC 2012). However, as shown above, this has not lead to a decrease of cold surges in East Asia, but rather a slight increase, may remain unchanged under future warmer conditions (Park *et al*., 2011b). The occurrence of cold surges over Southeast China has also increased since early 1980s (Fig. 6a). How about the possible future change of the occurrence of cold surges over Southeast China?

To investigate the possible future change in cold surge occurrences, projected change in the occurrence of cold surges for 9 GCMs from CMIP5 under RCP4.5 are illustrated in Fig. 7, in which two periods, 2046-2065 and 2076-2095, are used to indicate the middle-term and long-term change. Here we can see that the occurrence of cold surges is likely to increase in the future compared to the mean condition during 1981-2000 from historical simulations. This is in line with the results from the phase 3 of the CMIP (CMIP3) (Park *et al*. 2011b). We did the same detection and classification of cold surges with the CMIP5 data as with the observational data (described in section 2). Overall, the models historical simulations exhibit more occurrences of cold surges than those observed, but the relative fraction of each type of cold surges is relatively well reproduced (Table 2). The model results suggest that the

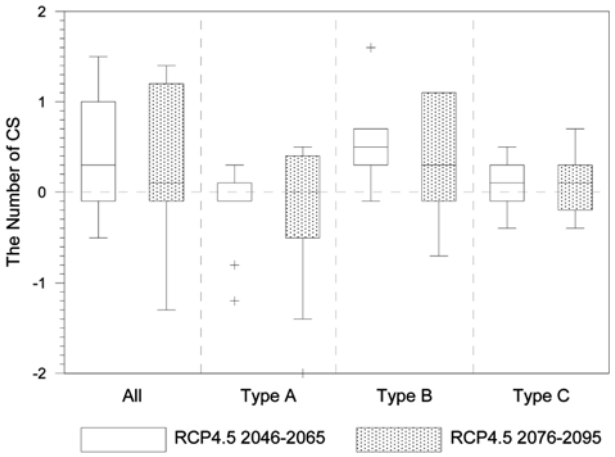

Fig. 7. Project change in the occurrence of cold surge during 2046-2065 and 2076-2095 under RCP4.5 scenario with respect to the mean during 1981-2000 under Historical simulation for the selected CMIP5 models.

Table 2. Average, standard deviation, and linear trend of cold surge occurrence in southeast China during 1981-2000 for observation and 9-model ensemble mean under historic simulation.

	Average		Standard deviation		Linear trend	
	Obs	ESM	Obs	ESM	Obs	ESM
Total	4.4	7.9	1.8	0.7	0.1	0.0
Type A	1.7	2.9	1.2	0.6	0.0	0.0
Type B	2.3	4.2	1.7	0.7	0.1	0.0
Type C	0.4	0.8	0.7	0.4	0.0	0.0

occurrence of type A cold surges is likely to remain unchanged till then end of 21th century, while type B cold surges are likely to increase, even if there is larger uncertainty in the later period, and this is the major reason for the increase in the total occurrences of cold surges (Fig. 7). This is possibly in association with a declining SHI: the SH becomes unstable with more fast-developing and decaying cases which may lead to more type B cold surges the end of 21th century. This is consistent with the cold surge evolution during the last two decades. The occurrence of type C cold surges may also increase in the future, which highlights the importance of type C cold surges as suggested from observation during the last two decades. Thus, the occurrence of wave-train related cold surges will likely not change much in a warmer climate. But cold surges with high frequency wave activities (type B) and stratospheric coupling over the Arctic region (type C) may become more pronounced in a warmer future.

4. Conclusions

Based on daily variations of SHI prior to the occurrence of a cold surge, the cold surges identified over Southeast China can be classified into three types: a stationary SH (type A), a developing SH (type B) and Arctic high-pressure (type C). The classification identifies distinctive synoptic patterns prior to a cold surge, which has implications for the understanding of past changes and for predicting future cold surges.

The occurrence of cold surges decreased in the 1960s and early 1970s, after which a slightly increasing trend is observed. The interdecadal variation in the occurrence of type A cold surges follows the change in SHI, which also accounts for most of the change in total cold surge occurrences before 1990. The type B cold surges, which accounts for half of the total winter cold surges, slightly increased during 1961-2012, especially in the second half of the period when the SHI was relatively weaker than the first half of the study period. The contribution of the type B cold surges to the interdecadal variation of total winter cold surges has increased since the early 1980s, becoming the dominant type after 1990. The contribution of the type C events, which generally occur when the winter AO is negative or weak, to the total number of cold urges is relatively small, but became more frequent in the latest decade when AO changed into a negative phase.

The occurrence of cold surges is projected to be unchanged till the end of 21 century, even if there is increasing uncertainty regarding the decline in SHI. The occurrence of type A cold surges is likely to remain unchanged. The increase in the total occurrence is mostly due to an increasing occurrence of type B cold surges. The occurrence of type C cold surges may also increase in the future. Possibly in association with a declining SHI, the SH becomes unstable with more fast-developing and decaying cases which may lead to more type B cold surges the end of 21th century, which is consistent with the cold surge evolution during the last two decades.

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REFERENCES

Chen, T. C., W. R. Huang, and J. Yoon, 2004: Interannual variation of the east Asian cold surge activity. *J. Climate*, **17**, 401-413.

Chen, Y., and Y. H. Ding, 2007: Cold air activities in July 2004 and its impact on intense rainfalls over Southwest China. *Acta. Meteorol. Sin.*, **21**, 302-319.

Cheung, H. N., W. Zhou, H. Y. Mok, and M. C. Wu, 2012: Relationship between Ural-Siberian blocking and the East Asian winter monsoon in relation to the Arctic Oscillation and the El Niño-Southern Oscillation. *J. Climate*, **25**, 4242-4257.

Choi, G., and Coauthors, 2009: Changes in means and extreme events of temperature and precipitation in the Asia-Pacific Network region, 1955-2007. *Int. J. Climatol.*, **29**, 1906-1925.

DCAS/NCC/CMA (Division of Climate Application and Service, National

Climate Center China Meteorological Administration), 2008: *Climate Events and Impacts in February of 2008*. (Available online at http://ncc.cma.gov.cn/influ/yxpj.php).

Ding, T., W.-H. Qian, and Z.-W. Yan, 2009: Characteristics and changes of cold surge events over China during 1960-2007. *Atmos. Oceanic Sci. Lett.*, **2**, 339-344.

Ding, Y., and T. N. Krishnamurti, 1987: Heat-budget of the Siberian high and the winter monsoon. *Mon. Wea. Rev.*, **115**, 2428-2449.

Ding, Y. H., 1990: Buildup, air-mass transformation and propagation of Siberian high and its relations to cold surge in East-Asia. *Meteor. Atmos. Phys.*, **44**, 281-292.

Gong, D. Y., and C. H. Ho, 2002: The Siberian high and climate change over middle to high latitude Asia. *Theor. Appl. Climatol.*, **72**, 1-9.

Hong, C. C., H. H. Hsu, H. H. Chia, and C. Y. Wu, 2008: Decadal relationship between the North Atlantic Oscillation and cold surge frequency in Taiwan. *Geophys. Res. Lett.*, **35**, L24707.

Hori, M. E., and H. Ueda, 2006: Impact of global warming on the East Asian winter monsoon as revealed by nine coupled atmosphere-ocean GCMs. *Geophys. Res. Lett.*, **33**, L03713.

IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

Jeong, J. H., and C. H. Ho, 2005: Changes in occurrence of cold surges over east Asia in association with Arctic Oscillation. *Geophys. Res. Lett.*, **32**, L14704.

_____, _____, B. M. Kim, and W. T. Kwon, 2005: Influence of the Madden-Julian Oscillation on wintertime surface air temperature and cold surges in east Asia. *J. Geophys. Res.-Atmos.*, **110**, D1104.

_____, B. M. Kim, C. H. Ho, D. L. Chen, and G. H. Lim, 2006: Stratospheric origin of cold surge occurrence in East Asia. *Geophys Res Lett*, **33**, L14710.

_____, T. H. Ou, H. W. Linderholm, B. M. Kim, S. J. Kim, J. S. Kug, and D. L. Chen, 2011: Recent recovery of the Siberian high intensity. *J. Geophys. Res.-Atmos.*, **116**.

Jiang, Z., T. Ma, and Z. Wu, 2012: China coldwave duration in a warming winter: change of the leading mode. *Theor. Appl. Climatol.*, **110**, 65-75.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437-471.

Kim, B. M., J. H. Jeong, and S. J. Kim, 2009: Investigation of stratospheric precursor for the East Asian cold surge using the potential vorticity inversion technique. *Asia-Pac. J. Atmos. Sci.*, **45**, 513-522.

Lu, Q. F., W. J. Zhang, P. Zhang, X. B. Wu, F. Y. Zhang, Z. Q. Liu, and M. B. Dale, 2010: Monitoring the 2008 cold surge and frozen disasters snowstorm in South China based on regional ATOVS data assimilation. *Sci. China Earth Sci.*, **53**, 1216-1228.

Panagiotopoulos, F., M. Shahgedanova, A. Hannachi, and D. B. Stephenson, 2005: Observed trends and teleconnections of the Siberian high: A recently declining center of action. *J. Climate*, **18**, 1411-1422.

Park, T. W., C. H. Ho, and S. Yang, 2011a: Relationship between the Arctic Oscillation and cold surges over East Asia. *J. Climate*, **24**, 68-83.

_____, _____, S. J. Jeong, Y. S. Choi, S. K. Park, and C. K. Song, 2011b: Different characteristics of cold day and cold surge frequency over East Asia in a global warming situation. *J. Geophys. Res.-Atmos.*, **116**.

Shabbar, A., J. P. Huang, and K. Higuchi, 2001: The relationship between the wintertime North Atlantic Oscillation and blocking episodes in the North Atlantic. *Int. J. Climatol.*, **21**, 355-369.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.*, **93**, 485-498.

Thompson, D. W. J., and J. M. Wallace, 1998: The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.*, **25**, 1297-1300.

Wang, L., R. H. Huang, L. Gu, W. Chen, and L. H. Kang, 2009: Interdecadal variations of the East Asian winter monsoon and their association with quasi-stationary planetary wave activity. *J. Climate*, **22**, 4860-4872.

_____, W. Chen, W. Zhou, J. C. L. Chan, D. Barriopedro, and R. Huang, 2010: Effect of the climate shift around mid 1970s on the relationship between wintertime Ural blocking circulation and East Asian climate. *Int. J. Climatol.*, **30**, 153-158.

Wang, Z., and Y. Ding, 2006: Climate change of cold wave frequency of China in the last 53 years and the possible reasons. *Chinese J. Atmos. Sci.*, **30**, 1068-1076. (In Chinese with English abstract)

Wu, M. C., and J. C. L. Chan, 1995: Surface-features of winter monsoon surges over South China. *Mon. Wea. Rev.*, **123**, 662-680.

_____, _____, 1997: Upper-level features associated with winter monsoon surges over south China. *Mon. Wea. Rev.*, **125**, 317-340.

Yang, G. M., Q. Kong, D. Y. Mao, F. H. Zhang, Z. M. Kang, and Z. P. Zong, 2010: Analysis on the long-lasting freezing rain and snowstorm event at the beginning of 2008. *Acta. Meteorol. Sin.*, **24**, 380-396.

Zhai, P. M., and X. H. Pan, 2003: Trends in temperature extremes during 1951-1999 in China. *Geophys. Res. Lett.*, **30**.

Zhang, P. Z., and G. M. Chen, 1999: A statistical analysis of the cold wave high which influences on China. *Acta. Meteorol. Sin.*, **57**, 493-501. (in Chinese with English abstract)

Zhang, Y., and W. C. Wang, 1997: Model-simulated northern winter cyclone and anticyclone activity under a greenhouse warming scenario. *J. Climate*, **10**, 1616-1634.

_____, K. R. Sperber, and J. S. Boyle, 1997: Climatology and interannual variation of the East Asian winter monsoon: Results from the 1979-95 NCEP/NCAR reanalysis. *Mon. Wea. Rev.*, **125**, 2605-2619.

Zhou, Y. Q., and G. Y. Ren, 2011: Change in extreme temperature event frequency over mainland China, 1961-2008. *Clim. Res.*, **50**, 125-139.

Zhao, L. N., and Coauthors, 2008: Disasters and its impact of a sever snow storm and freezing rain over southern China in January 2008. *Climatic Environ. Res.*, 13, 556-566. (in Chinese with English abstract).