Cold surge invading the Beijing 2022 Winter Olympic Competition Zones and the predictability in BCC-AGCM model

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Abstract
The 24th Olympic and Paralympic Winter Games will be held at three competition zones in North China. The cold surge is considered as the most dominant weather affecting the game schedule by the Organizing Committee of Beijing Olympic Games. In this article, both the frequency of 124 cold surge cases invading the competition zones and the corresponding atmospheric circulation during the winters of 1985–2020 are first analyzed. The results show that the frequency has not been reduced by the global warming. On the contrary, it has been increasing slightly in recent decade. By verifying the forecast skill of temperature drop at the zones in Beijing Climate Center-Atmospheric General Circulation Model (version 2.2), it is found that the average efficient forecast leading time with persistent temperature drop exceeding 1°C is about 7 days, but significant differences exist among the individual cases. The 20 best forecasts and the 20 worst forecasts were selected for further analysis. In the 20 worst forecasts, the cold surge processes cannot be forecasted even 1 day in advance. It is mainly due to the great deviation of the simulated circulation from the observation, especially the failure to forecast the enhancement of the Siberian High especially in its southeast part before the cold surge occurrence. While in the 20 best forecasts, the model can capture the cold surges 9 days before the occurrence, owing to its skill in forecasting the positive sea level pressure anomalies from the southern Barents Sea and the Kara Sea to eastern China. Above evaluations can provide useful information to the forecast of cold surge invading the competition zones beyond 1 week.

KEYWORDS
BCC-AGCM model, cold surge, competition zones of Beijing Olympic and Paralympic Winter Games, Siberian High
1 | INTRODUCTION

The cold surge is one of the most common disastrous weather in winter in the middle and high latitudes of the Northern Hemisphere. Its frequency decreased remarkably since the 1980s due to global warming. However, recent studies show that extreme cold events in the middle latitudes of the Northern Hemisphere have been increasing again since the early 21st century, when the global warming slows down. Both statistical results (Li et al., 2015; Johnson et al., 2018) and typical cases in Europe (Vries et al., 2013; Planchon et al., 2015), North America (Trenary et al., 2016; National Weather Service, 2019) and Asia (Ma and Zhu, 2019; Yamaguchi et al., 2019) indicate that the cold surges and cold winters in above regions occur more frequently in the latest decade than in the first decade of the 21st century, which can be partly attributed to the recent Arctic warming or the Arctic amplification caused by the rapid loss of the Arctic sea ice (Cohen et al., 2012, 2020; Liu J.P. et al., 2012; Tang et al., 2013; Mori et al., 2014; Ma et al., 2018; Dai et al., 2019). In China, the extremely strong cold surges are also more frequent during this period, resulting in severe low-temperature and freezing disasters, which badly harm the national economy and people’s lives (Zheng, 2019). For example, China experienced an unprecedented low-temperature and snowstorm disaster in early 2008 caused by four successive cold surges, resulting in 133 deaths and direct economic losses of over 20 billion dollars (Jiao and Qu, 2008; National Climate Center, 2008; Wen et al., 2009). In January 2016, the extreme “Boss-level” cold surge also caused similar economic losses (Liu et al., 2016; Sun et al., 2018; Ma and Zhu, 2019). Qin (2015) pointed out that five out of the seven regions in China will suffer from severe cold surges and freezing disasters in the future under the warming scenarios. Therefore, forecast of the cold surges is quite important in China.

In the 1950s, the pioneering studies of Gu (1956) and Tao (1959) revealed the sources and three tracks of the cold surges invading China. Zhu et al. (2010) also pointed out that the sources of cold air affecting China could be traced back to the Barents Sea, the Kara Sea and southern Iceland, with the strongest and the most frequent cold air from the Barents Sea. The cold air from the three sources converges in western Siberia and strengthens the Siberian High, which affects East Asia through three paths (Ding and Krishnamurti, 1987). These results provided synoptic basics for the cold surge forecasts in the 1980s and 1990s in China (Xu, 1985; Yu and Li, 1985; Yu et al., 1987; Li, 1996). In the 21st century, numerical models have become the primary tool for the forecast and early warning of cold surges. However, the numerical models perform poorly in directly forecasting the events with a leading time exceeding 1 week, even for the extreme case (Zhang et al., 2003; Tao et al., 2017).

Recently, long-term forecasts of cold surge events in China based on the interpretation and application of the climate model products have been conducted. The climate models can well reproduce the basic characteristics of the East Asian winter monsoon (Hao et al., 2016; Li et al., 2017), and can also capture the East Asian cold surges 2 weeks in advance (Wei et al., 2019). However, the forecast skill differs greatly owing to different verification and evaluation criteria utilized in different studies. For example, Li et al. (2017) focused on the annual number of cold surge days and events in East Asia, which reflects the prediction skills for the seasonal large-scale circulation system rather than the synoptic cold surge process. Besides, the skill is also related to the cases selected and the predictability of the influencing circulation systems of cold surges. For example, Park et al. (2011) classified East Asian cold surges into wave-train type and blocking type. In both of the observation and climate models, the blocking cold surges tend to be more intense and last longer compared to the wave-train type. These researches suggest that the cold surge forecast should focus on not only the temperature itself but also the influencing circulations.

From 4 to 20 February and from 4 to 13 March 2022, the 24th Olympic and Paralympic Winter Games will be hosted in Beijing, China, respectively (BJ2022 in the following). According to the weather and wind analysis report issued by the Beijing Organizing Committee of the Olympic Games, there are six weather patterns notably affecting the game schedule in total, four of which are closely related to cold surges (Wang and Yu, 2019). Owing to the influence of the East Asian winter monsoon, the three competition zones of BJ2022 (Beijing, Yanqing and Zhangjiakou) are all vulnerable to the cold extremes. Recently, Ding et al. (2020a) explored that the pre-signal of cold surges invading the competition zones of BJ2022 from the Novaya Zemlya could have a leading influence exceeding 10 days. Therefore, forecast skills of influencing circulations should be considered when analyzing the intra-seasonal forecast skills of cold surges.

The Beijing Climate Center-Atmospheric General Circulation Model (BCC-AGCM) has become one of the main operational models for the sub-seasonal prediction in China. The simulation results well demonstrate the actual geographic distributions and the prominent annual cycle characteristics of the variables (Dong et al., 2009; Zuo et al., 2016). The model can reproduce the basic patterns of the winter circulations in the Northern Hemisphere and the dominant mode (Liu Y.Z. et al., 2012). It is also skillful in forecasting several
extreme temperature indices in China, including the daily minimum temperature associated with the cold surge (Dong et al., 2012). Therefore, in this article, we first evaluate the simulations of the latest version of the model (BCC-AGCM 2.2) for the 124 cold surge events at the BJ2022 competition zones during the winters of 1985–2020. Then we analyze the forecast skills for the influencing circulation in the cold surge events with a leading time from 1 day to 20 days, aiming to provide useful information of the cold surge forecast based on dynamic models.

2 | DATA AND METHOD

The BCC-AGCM 2.2 is an improved version of the Community Atmosphere Model Version 3 (CAM3) from the National Center for Atmospheric Research (NCAR) (Collins et al., 2006). Its simulation of intra-seasonal variations is significantly improved compared with CAM3. The model has a horizontal resolution of T106 and includes 26 vertical levels (Wu et al., 2014). The initial field of the model is derived from the T639 operational forecast model developed by the China National Meteorological Center. The optimal interpolated sea surface temperature (SST) data is adopted (Reynolds et al., 2002). The model hindcast starts from 1 January 1983, with the forecast length of 55 days in each simulation. On each day, the forecasts are conducted four times at 00Z, 06Z, 12Z and 18Z, respectively. The arithmetical average of all the four members is calculated as the daily average. In the analysis, the daily geopotential height (GPH) at 500 hPa, the sea level pressure (SLP) and the air temperature in the hindcast are applied. Daily data of SLP, 500 hPa GPH and 850 hPa horizontal winds are extracted from the NCEP/NCAR reanalysis project and used as the observation (Kalnay et al., 1996; Kistler et al., 2001).

In this article, three meteorological stations (WMO station code #54406, 54433 and 54401) are used to represent the three competition zones of BJ2022, respectively (Ding et al., 2020a). The daily average temperature data are used to calculate the temperature drop over two successive days in each winter. Here the winter of 1985 denotes December 1984–January 1985–February 1985.

3 | COLD SURGE FREQUENCIES AT BJ2022 COMPETITION ZONES AND THE ATMOSPHERIC CIRCULATIONS

Intra-seasonal and interannual variations of the cold surge frequencies at BJ2022 competition zones during the winters of 1985–2020 are first analyzed. Due to their much high consistency of daily variability, here we use the average of air temperature at above three stations instead of individual station. Since the top 10% threshold of daily temperature drop magnitude is about 3.8°C, in the following analysis a cold surge event is identified if the drop is over 4°C, then 124 cold surge events are obtained (Figure 1). In the 124 cases, temperature drop (negative temperature change between two successive days) occurred in all stations, and the occurrence probability of cold surge events in each station was about 70–80%. Among the 124 events, the frequencies with temperature drop magnitude of 4–5°C, 5–6°C, 6–7°C and over 7°C are 65, 29, 15 and 15, respectively. The upper left panel of Figure 1 shows the 36-year cumulative frequency in each day. In the first half of winter (December to early January), the frequency demonstrates a slight decreasing change, while in the second half the frequency shows fluctuation. The annual frequency of cold surge events (right panel) shows an average number of 3.4 during 1985–2020. It displays a significant inter-annual variation, with the maximum number of 7 in 2009 and 2016, and the minimum number of 1 in 1989, 2002 and 2008. Moreover, the frequency has been increasing slightly since 2009. The average numbers during 1985–2008 and 2009–2020 are 3.2 and 4, respectively. This result is consistent with the cold surge frequency in North China (Ding et al., 2020b).

To better characterize the atmospheric circulation caused the cold surge event at the competition zones, a composition analysis on the occurring day of the 124 cases is performed (Figure 2). Before the composition, the correlation coefficients between different East Asian winter monsoon indices and the temperature changes in the competition zones are compared. The indices include the East Asian trough, the Siberian High and the westerly jet index. It could be found that the Siberian High has the strongest correlation with a leading time of 2 days (figures not shown). This also indicates that the Siberian High is a dominant factor, which is consistent with the result of Ding et al. (2020c). Therefore, only the SLP field is provided here. According to the climatological position, here the Siberian High is defined as the average SLP in (40–60°N, 80–120°E), as shown by the dashed box in Figure 2. The typical circulation pattern corresponding to the cold surge is characterized with two positive SLP anomaly centers from North China to Mongolia and from Novosibirsk to Barents Sea, accompanied with a negative anomaly center over Japan and its eastern ocean, that is, the west part of the Aleutian low pressure. In winter, the cold high dominates over Eurasia continent and the warm low dominates over the Pacific Ocean. Therefore, the SLP anomaly distribution in Figure 2 is favorable for
increasing the land-sea pressure contrast, contributing to the deepening of the East Asian trough in the middle troposphere and the enhancement of the strong northerly wind. Composition analysis of the 500 hPa GPH anomaly (figure not shown) indicates that the values between the negative and positive SLP anomaly centers shown in Figure 2 is less than $-80$ gpm. The location of this negative GPH anomaly center is consistent with that of the climatic East Asian trough. The average anomaly of the 850 hPa northwesterly wind in the west of the trough exceeds 3 m·s$^{-1}$ (figure not shown). This circulation pattern is favorable for the cold air invading the competition zones along the northwesterly airflow.

4 | VERIFICATION OF THE COLD SURGE EVENTS AT BJ2022 COMPETITION ZONES FORECASTED BY BCC–AGCM 2.2

Based on the selected 124 cases, the forecast skill of the BCC-AGCM 2.2 is evaluated with a leading time of 1–20 days. Figure 3 presents the forecast of the average daily temperature change for the 124 events, as well as the average of the 20 best and the 20 worst forecasts. The efficient leading forecast time is defined as the maximum leading days when the model can continuously forecast the cold surge events. Since the daily variability of the predictand in the model decreases rapidly with the increasing of the leading time (figure not shown), the threshold of temperature drop in the model is set to 1°C. For a cold surge event, if the model continuously forecasts a negative temperature change below $-1$°C (temperature drop over 1°C) with the leading time less than or equal to $N$ days, but forecasts a positive temperature change (temperature increase) or a slight temperature drop less than 1°C on the $N + 1$ days in advance, the efficient forecast leading time is $N$. Based on this method, the model forecast and efficient leading time for all the 124 events is calculated and ranked. The longer forecast efficiency indicates an earlier forecast of the cold surge,
FIGURE 3  Average daily temperature change for the 124 cold surge cases (histogram), the 20 best forecasts (solid line) and the 20 worst forecasts (dashed line) with the leading time of 1–20 days by the BCC-AGCM 2.2. The dotted line indicates −1°C (units: °C).

FIGURE 4  The SLP (contours) and its anomalies (shading) in (a) the 20 worst and (b) the 20 best forecasts with the leading time of 1 day. The dashed box shows the climatic location of the Siberian High in winter. The thick black and red line means the 1,030-hPa contour in the model and in the observation, respectively (units: hPa).
which can provide an earlier warning for the possible future impacts. Conversely, the shorter forecast leading time means a later response of the model to the cold surge. The 20 cases with the longest forecast leading time are defined as best forecasts and the 20 cases with the shortest leading time are defined as worst forecasts.

The histogram in Figure 3 shows the average daily temperature change for all the 124 cold surge events forecasted by the model. It is noted that the temperature change in the model generally decreases with the increasing of the leading time in the first 10 days, at a decreasing rate of 0.45°C−day−1. The model can continuously forecast the 2°C temperature drop within 5 days in advance and the 1°C drop within 7 days. This is generally consistent with previous studies (Zhang et al., 2003; Tao et al., 2017). Beyond 10 days, although the forecasted average temperature change of the 124 cases is still negative, its intensity is significantly weaker than that within 10 days. In the 20 best forecasts, the model produces significantly stronger temperature change. The temperature drop magnitude decreases slowly within the first 9 days compared with the 124-case mean. In the 20 best forecast type, the average forecast leading time for the 1°C temperature drop can be up to 15 days. Conversely, the 20 worst forecasts demonstrate warming even when the leading time is 1 day. The most extreme cases with the 30 greatest temperature drops are also analyzed. The average leading time in these cases is 7 days, which is similar with the 124-case average.

The circulations in the good forecasts and the poor forecasts are analyzed to figure out the reasons for the significant difference in their forecasts. Figure 4 presents the SLP and its anomalies averaged in the 20 worst forecasts and the 20 best forecasts with the leading time of 1 day. Comparing it with Figure 2, we can find a significant difference in the SLP between the two types of forecasts. There are negative anomalies over most regions of East Asia in the 20 worst forecasts. Specifically, the anomaly is below −4 hPa on the east of the Siberian High, which is the most dominant atmospheric circulation affecting the cold surge at the zones. This anomaly pattern weakens and even reverses the land-sea pressure gradient in the middle latitudes of East Asia in winter, which is not favorable for the southward movement of the cold air. It is the reason for the incorrect forecast even 1 day in advance. On the contrary to Figure 4a, the SLP anomalies in the 20 best forecasts are all positive over the north of 40°N in Eurasia (Figure 4b). The pressure anomaly exceeds 4 hPa in the central Siberian High, which is higher than the observation in Figure 2. The negative SLP anomaly to the east of the Sea of Japan in the observation is not forecasted in Figure 4b, suggesting that the accurate forecast of the Siberian High is the key for forecasting the cold surge at the zone.

Figure 5 presents the SLP and its anomalies in the 20 best forecasts, with the leading time of 5, 7, 9 and 11 days. The forecasted circulation anomalies with the leading time of 5 and 7 days are comparable to those in Figure 4b, demonstrating positive SLP anomalies dominant from the Ural Mountains to Lake Baikal. The SLP anomaly exceeds 4 hPa in the eastern part of the Siberian High. The forecast field with the leading time of 9 days shows that the area of positive SLP anomalies is located significantly more northwestward than the observation, so the Siberian High is weaker than the observed high. Since the land-sea pressure contrast corresponding to the cold surge in winter is mainly determined by the Siberian High, the temperature drop magnitude is weakened in the model due to the northwestward movement of the high pressure and the intensity decrease in its eastern part. Even in the best forecasts, the average temperature drop magnitude is only 1.5°C (Figure 3). In the forecasted circulation with the leading time of 11 days, the SLP anomalies to the east of Lake Baikal transform from positive to negative, and the Siberian High is nearly normal. From Figure 5, it could also be found that the SLP over the south of Barents Sea has a 4-day leading influence on the Siberian High. That means the high SLP center has a southeastward propagation from the south of Barents Sea, which is similar with the 500-hPa cyclone center in Ding et al. (2020a). Statistical results of the paths of all the 124 cases indicate that the northwest and west paths can account for about 78.5%, which also demonstrates the importance of the Siberian High in causing the cold surges invading the zones. Forecast skill of the Siberian High is also assessed between the 20 best and 20 worst forecasts. In the 20 best cases, the model can well capture the positive daily pressure change (> 1 hPa) since 9 days before the cold surge occurrence (figure not shown). However, in the 20 worst cases, the intensity of the Siberian High in the model is quite weak even with a leading time of 1 day. Thus, the forecast skill of the model for the cold surge at BJ2022 competition zone depends on its ability to predict the strength of the eastern Siberian High. So it could be considered that the forecast of Siberian High rather than other circulation members determines the efficient skill or leading time of the cold surges in BCC-AGCM 2.2.

5 CONCLUSIONS AND DISCUSSION

According to the weather report issued by the Beijing Organizing Committee of BJ2022, six weather patterns can notably affect the game schedule in total, four of which are closely related to cold surge events (Wang and Yu, 2019). It has great importance to analyze the
predictability of cold surge events at the BJ2022 competition zones by dynamic models. Therefore, the intra-seasonal and interannual variations of the cold surge frequency during 1985–2020 at the competition zones and the corresponding atmospheric circulation are first analyzed. It can be found that the cold surge frequency in winter has not been reduced with the global warming. On the contrary, it has been increasing slightly since 2009, with the average frequency increasing from 3.2 during 1985–2008 to 4.0 after 2009. When a cold surge event occurs at the zones, positive SLP anomalies dominate from the Barents Sea and the southern Kara Sea to eastern China, while negative SLP anomalies dominate to the east of Japan. In the middle troposphere the geopotential height anomalies usually demonstrate a positive center in Central Siberia and a negative center over the Sea of Japan. The circulation pattern is favorable for a further increase of the land-sea pressure gradient in winter, thereby prompting the high-latitude northerly wind to invade southward to China and inducing cold surge at the zones.

By further analyzing the efficient forecast leading time of the BCC-AGCM 2.2 for the cold surges at the zones, we found that the average forecast leading time in the model for the temperature drop exceeding 1°C is about 7 days, but there are significant differences among the individual cases. In the 20 worst forecasts, the cold surge processes cannot be forecasted even 1 day in advance. It is mainly due to the great deviation of the simulated circulation from the observation, especially the failure to forecast the strengthening of the SLP in the southeastern side of Siberian High before the cold surge. In the 20 best forecasts, the drop over 1°C can be forecasted 15 days in advance, and the 2°C drop can be forecasted 8 days in advance. In the good forecasts, the model well captures the positive SLP anomalies from the southern Barents Sea and the Kara Sea to eastern China. These circulation anomalies can originate and persist 9 days in advance, which is probably the main reason. The above evaluations can be the reference for the model-based forecasts of cold surge on the leading time over a week. Further analysis reveals that, even in the 20 best forecasts, the model fails to reproduce the distribution of geopotential height anomalies at middle levels. It falsely distributes the positive and negative anomaly centers, especially the East Asian trough.

The cold surge invading northern China has complex paths and different duration length (Ding et al., 2020c). Due to the limited area of the BJ2022 competition zones, the cold surge influence usually lasts only 1 day and then

**FIGURE 5** Same as Figure 4b, but with the leading time of (a) 5 days, (b) 7 days, (c) 9 days and (d) 11 days.
moves eastward or southward. Thus, only the occurring day of cold surge invasion is considered in this article. In the future study, we will evaluate the forecast of the cold surge process from northwestern China to southern China based on the BCC-AGCM 2.2. Although the Siberian High is the dominant factor for the cold events in northern China including the competition zones, the cold surges are also influenced by other circulation systems, such as the blocking high (Bueh and Xie, 2015; Xie and Bueh, 2017), the East Asian jet stream (Wu and Sun, 2017) and the polar jet (Liao and Zhang, 2013). For example, Xie and Bueh (2017) revealed the common features and the differences of the blocking activities between ordinary and extensive cold surge. For the ordinary type, the blocking is limited in the Ural Mountains and exhibits a regional feature, while for the extensive type the blocking can extend eastward into Northeast Asia. Besides, the position or the shape of the Siberian High especially its spatial extension also has significant impacts to the temperature besides the intensity. Liu and Zhu (2020) explored that a stronger Siberian High with an expanding eastern edge is coupled with the East Asian trough and results in a colder winter in Northeast China. Results also indicate that the horizontal extent of the Siberian High corresponds well with the zonal extents of the large-scale tilted ridge and trough, and the latter could be caused by the abnormal blocking high (Bueh and Xie, 2015). But compared with the intensity, the skillful forecast of the Siberian High shape is still a big challenge in almost all the climate models. These will also be analyzed in the future to obtain a more comprehensive understanding of the circulation patterns under which the model can better forecast the cold surge invading the competition zones.

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CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

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