https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

Atmospheric Chemistry and Physics Discussions
Open Access
EGU

Comparison of influence between two types of cold surge on haze dispersion in Eastern China

Shiyue Zhang[1], Gang Zeng[1], Xiaoye Yang[1], Ruixi Wu[2], Zhicong Yin[1, 3]

[1] Key Laboratory of Meteorological Disaster of Ministry of Education (KLME), Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science and Technology, Nanjing, 210044, China

[2] Meteorological Bureau of Jiading District, Shanghai 201815, China

[3] Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, 519080, China

Correspondence to: Gang Zeng (zenggang@nuist.edu.cn)

Abstract. Cold surge (CS) is considered as a favorable weather process to improve air quality and is widely recognized. However, there is no detailed study on the differences in the dispersion ability of different types of CSs to haze days in eastern China (HD_{EC}). This paper uses the hierarchical clustering algorithm to classify the cool season (November to February of the following year) CSs across eastern China into blocking CSs and wave-train CSs and compares their influences on the number of HD_{EC} from 1980 to 2017. Results show that the wave-train CSs can significantly improve the visibility in eastern China and generally make the high air quality last for about 2 days longer than the blocking CSs, which indicates that the blocking CSs have a weaker ability to dissipate HD_{EC} compared with the wave-train CSs. The CSs affect the HD_{EC} by changing these meteorological elements like thermal inversion potential, horizontal surface wind, sea level pressure (SLP), and surface air temperature (SAT). 4 days after the CSs outbreak, the variations of thermal inversion potential and horizontal surface wind of two types of CSs tend to be consistent. However, the negative SAT anomalies, and the positive SLP anomalies caused by the blocking CSs lasted shorter than those caused by the wave-train CSs, which forms favorable conditions for the rapid growth of HD_{EC}. Furthermore, results show that in recent years, especially after the 1990s, the frequency of wave-train CSs has decreased significantly, while the frequency of blocking CSs has slightly increased, indicating that the overall ability of CSs to dissipate HD_{EC} has weakened in general.

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

1. Introduction

Haze can reduce visibility and affect traffic and ecological sustainability (Xu et al., 2013; Xie et al., 2014; Wang et al., 2016). Studies have shown that the haze in China is mainly concentrated in the eastern region of China (EC), and its peak is noticeable in winter and spring (Wang et al., 2015, 2016). During haze days, the concentration of aerosol particles increases and results in a wide range of visibility decline (Luo et al., 2001; Xu, 2001; Wu et al., 2012; Fu et al., 2013; Wu et al., 2014). For example, in the winter of 2015, severe haze in the Beijing-Tianjin-Hebei region affected more than 500,000 square kilometers, causing heavy pollution in 37 cities (Chang et al., 2016; Zhang et al., 2016). After this event, researchers and policymakers paid more attention to the studies related to haze events. Besides, strict control measures of air pollution and energy emissions have also been put in place.

Many studies indicated that the long-term trends of haze are closely related to fossil-fuel emissions (Shi et al., 2008; Wei et al., 2017). On the other hand, meteorological conditions also play an important role in determining regional air quality. In addition to the influence of human activities, the formation of haze is closely related to static and calm weather conditions, such as strong thermal inversion potential (TIP), negative sea level pressure (SLP) anomaly, and weak wind speed (Niu et al., 2010; Cai et al., 2017). In recent years, due to the decreased relative humidity, it is difficult for haze particles to transform into fog drops, making the number of haze days present a rising trend (Ding and Liu, 2014). In addition, the anomalies of atmospheric circulation caused by global warming may also enhance the stability of the lower atmosphere, which leads to more severe and frequent haze pollution (Cai et al., 2017). All these emphasize that the threat of haze to human society could be more serious in the near future.

Global warming leads to the decrease of cold days and cold surges (CSs) by raising the surface air temperature (SAT), which also provides favorable conditions for the increase of haze days (Lin et al., 2009). CS is a typical extreme weather process in East Asia, which significantly impacts the atmospheric circulation to improve the local air quality (Hu et al., 2000; Qu et al., 2015; Wang et al., 2016). With the outbreak of CSs, a series of abrupt variations of meteorological elements such as the positive SLP anomaly, the decrease of SAT, and the enhancement of north wind component will occur in the areas where the CSs pass (CCiM et al., 1999). When a CS occurs, the arrival of fresh and dry cold air can dissipate and reduce local air pollutants (Lin et al., 2008). Wang et al. (2016) proposed that the " early in the north and late in the south " feature of air quality improvement in mainland China results from the

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

cold air masses moving southward from high latitudes to low latitudes after the outbreak of CSs. Although some studies have shown that the weakening of East Asian Winter Monsoon and global warming leads to the decrease of CSs (Qu et al., 2015; Wang et al., 2006), extreme low-temperature events are still frequent (Park et al., 2011a), which makes the assessment of haze dispersion capacity of cold air activities still full of uncertainty.

Previous studies have shown that the outbreak of CSs has an obvious effect on haze dispersion (Lin et al., 2009; Hien et al., 2011; Ashfold et al., 2017). However, most of them analyzed the haze variation during the CSs based on case analyses or considering the interannual influence of CS frequency on haze. Studies have shown that there are large differences between individual cases of CSs in terms of circulation anomalies, influence path and range (Park et al., 2014; Cai et al., 2019). Therefore, it is necessary to consider the influence of classified CSs on haze. Based on this limitation, the following two questions are proposed in this paper: Are there different effects of CSs' types on the haze days in EC (HD_{EC})? If so, what is the physical mechanism that makes the difference? The solution to these issues will help us understand the mechanism of CSs in dissipating the haze and improving its predictability in the future.

The rest of this paper is organized as follows: Section 2 introduces the data and methods, while section 3 presents the study findings. The variation of HD_{EC} and its relationship with two types of CSs are shown in section 3.1. Section 3.2 explains the reason why different types of CSs have different abilities to dissipate HD_{EC}. The main conclusions and discussion are presented in section 4.

2. Data and Methods

2.1 Data

The datasets employed in this study were: (1) daily ERA-Interim atmospheric fields including SLP, air temperature at different levels, SAT, horizontal wind, and geopotential height (GPH) provided by the European Center for Medium-Range Weather Forecasts (ECMWF) (Dee et al., 2011). They have a horizontal resolution of 1.0°×1.0°. (2) daily observational datasets for 756 meteorological stations from 1980 to 2017 collected by the National Meteorological Information Center of China Meteorological Administration, including relative humidity, visibility, and weather phenomena. These datasets were observed four times per day (02:00, 08:00, 14:00, and 20:00LT). Stations with more than 5% missing

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

data were eliminated, while sporadic missing data were filled by cubic spline interpolation. Successive missing data were discarded.

2.2 Methods

The visibility and relative humidity (Rhum) are routinely used in meteorology to distinguish the haze (Yin et al., 2017). After filtering the other weather parameters affecting visibility (i.e., dust, precipitation, sandstorm), we defined a haze day as a day with visibility lower than 10 km and the Rhum less than 90 % occurring at any of the four times (02:00, 08:00, 14:00, and 20:00LT) (Yin et al., 2019a). Figure S1 shows the climatology of haze days in China from 1980 to 2017. The haze days are mainly concentrated in the EC (22°N-37°N, 106°E-121°E), which is selected as the target area in the present study. The monthly average of HD_{EC} indicated that the HD_{EC} mainly peaks (Figure S1b) in the cool season (November to February of the following year (NDJF)). Consequently, we chose cool season as the study period for HD_{EC} in this research.

The CS is a cooling process superimposed on a cold day (Park et al., 2011a). The outbreak of the CSs in East Asia is closely related to the Siberian high, known as the Siberian high surge (Compo et al., 1999). In this study, we first divided EC into 5°×5° grid boxes as shown in Figure 1 and then calculated the average SAT for each box to avoid the extreme SAT anomaly in a single grid. To explore the impact of CSs on HD_{EC}, the selection of CS in this paper fulfil the following three criteria (Park et al., 2011b) : (1) the maximum pressure center in the domain of the Siberian high (Figure 1) should exceed 1,035 hPa on the day of the CS outbreak. (2) the daily temperature drop ($SAT_t - SAT_{t-1}$) and the SAT anomalies should exceed −1.5 standard deviation (i.e., the standard deviation of the SAT from 1980 to 2017) at least one box. (3) the haze day appeared in the box where the CS occurs from -2 days to 0 day related to the occurred CS. A total of 187 CSs were identified in this paper.

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

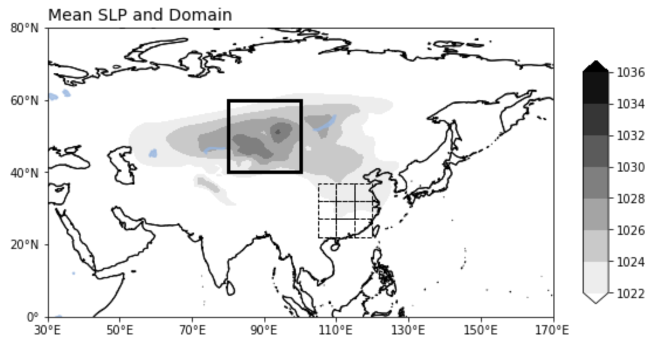


Figure 1. The domain of Siberian high (thick solid box; 40°N–60°N, 80°E–100°E) and EC (dotted box; 22°N-37°N, 106°E-121°E) divided into 5°× 5° grid boxes. Shadings indicate the cool season mean SLP.

3. Results

3.1 The influence of two types of CSs on HD_{EC}

The circulation evolution with different types of CSs is quite different (Park et al., 2013), which leads to the different distribution of surface meteorological conditions and haze. Here we display the evolutions of two typical CS events (Figure 2). These two events were selected because they belong to different types of CSs, referring to Park et al. (2008 and 2014), and have a large different effect on HD_{EC}. Figures 2a, 2e, 2i, 2m show a CS that occurred on December 31, 2000, with positive and negative GPH anomalies over the sub-arctic and East Asian coast, respectively, which meet the definition of the blocking CS (Park et al., 2015). The blocking structure has a relatively stable lifecycle, so the HD_{EC} only has a certain dispersion on the day of the CS outbreak, and heavy HD_{EC} begins to emerge 2 days after the CS outbreaks (Figures 2j and 2n). Figures 2c, 2g, 2k, 2o indicate a CS that occurred on January 7, 1983, which meets the definition of the wave-train CS (Chai et al., 2002; Park et al., 2015). The CS is associated with the wave-train structure of "-+ - +" at the upper troposphere. The cold air moves from west to east and invades EC along with this zonal wave-train (Yang et al., 2020a). The wave-train CS has a better ability to disperse HD_{EC}, and there is no new HD_{EC} appear for a long time after the wave-train CS erupts (Figures 2l and 2p).

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

Atmospheric Chemistry and Physics
Open Access
Discussions

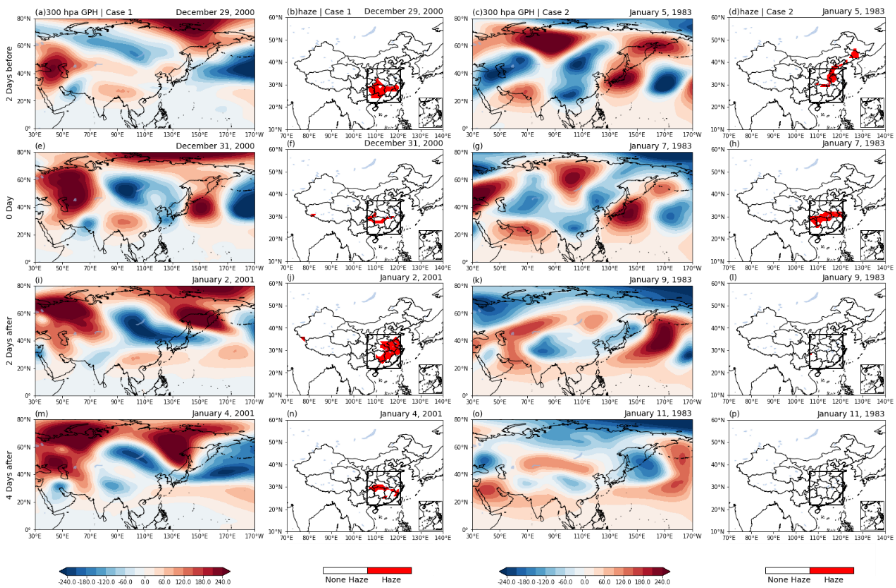


Figure 2. Composite of GPH anomalies (shading; gpm) at 300 hPa from -2 days to 4 days for case1 CS outbreak on December 31, 2000 (a, e, i, m), and case2 CS outbreak on January 7, 1983 (c, g, k, o), and the related spatial distribution of HD_{EC} (shading) (b, f, j, n and d, h, l, p).

The case analysis results indicate that the ability of different types of CSs to haze dispersion is different. Referring to the research of Park et al. (2008) and Yang et al. (2020b), this paper uses the hierarchical clustering algorithm (HCA) to classify the CS types. The HCA (Rokach et al., 2005) creates a hierarchical nested clustering tree by calculating the similarity between different categories of data samples. In the clustering tree, the original data samples of different types are at the lowest level of the tree, and the top level of the tree is the root point of a cluster. This paper uses Euclidean distance to calculate the distance (similarity) between different samples. Here, we introduce the silhouette coefficient to determine the best classification number (Rousseeuw, 1987). For any sample i, the silhouette coefficient $s(i)$ is defined as:

$$s(i) = \frac{b(i)-a(i)}{max\{a(i),b(i)\}} \quad (1)$$

$a(i)$ means the average distance from sample i to all other samples in the cluster it belongs to, and $b(i)$ means the lowest average distance from sample i to all samples in any other cluster. The silhouette coefficient of the clustering result is the average of the silhouette coefficients of all samples. The range of silhouette coefficient is - 1 to 1. The closer to 1, the better the classification results.

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

According to the principle of maximum distance between clusters, the CSs from 1980-2017 can be classified into two categories (Figure 3a). The silhouette coefficient of the clustering model shows that when all CSs are divided into two types, the difference between them is the largest. Figures 3c and 3d show the composite GPH anomalies at 300 hPa that depict the blocking CSs and wave-train CSs. Such classification results are consistent with previous studies (Park et al., 2014, 2015). The cold air of the blocking CSs mainly moves in a north-south direction that invades from Siberia to EC, and the cold air of the wave-train CSs originating from the Ural Mountains converged near Lake Baikal then invaded EC.

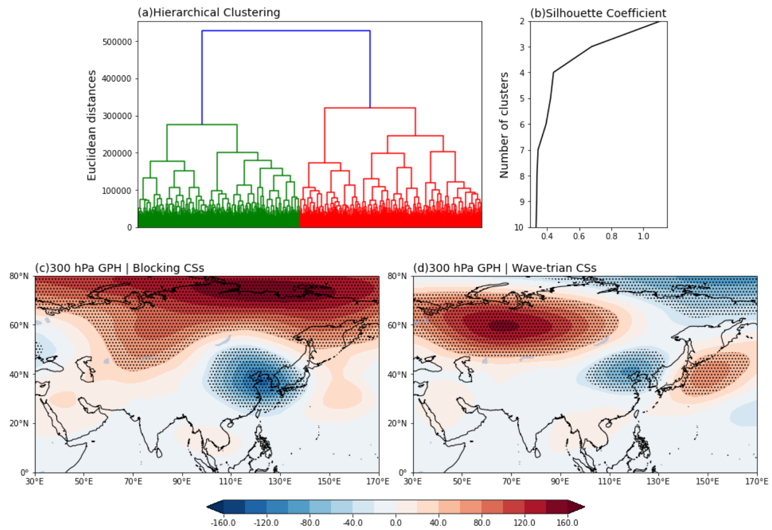


Figure 3. Hierarchical clustering tree (a) and silhouette coefficient (b) of cool season CSs in the EC. Composite of GPH anomalies at 300 hPa (shading; gpm) relative to blocking CSs (c) and wave-train CSs (d). Dotted areas are statistically significant at the 95% confidence level.

Figure 4 presents the circulation anomalies from -2 days to 6 days of the CSs events in the two types and the related evolution of HD_{EC}. For the blocking CSs, largely positive and negative GPH anomalies at 300 hPa are found over the Arctic and EC. The HD_{EC} tends to dissipate first and then increase rapidly after the CSs erupt. 6 days after the CSs erupt, the haze reaches a relatively large value (Figure 4i). For the wave-train CSs, a zonal wave-train structure of GPH anomalies can be seen in the midlatitude of the Eurasian. From -2 days to 6 days, the wave-train with northwest-eastern direction appears to move toward EC. With the movement of the wave-train, the haze dissipates rapidly, and EC can maintain high air quality weather for a longer time. Sporadic HD_{EC} does not appear until 6 days after, which is different

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

from the existence of HD_{EC} when the blocking CSs occur. It shows that blocking CSs have a weak ability to dissipate haze compared with wave-train CSs. This conclusion is also consistent with the individual cases mentioned above. In addition, we also used PM2.5 concentration data (acquired from the China National Environmental Monitoring Centre and were widely used in the research of PM2.5 in China, refer to Yin et al. (2021) and Wang et al. (2021)) together with NCEP/NCAR Reanalysis datasets (Kalnay et al., 1996) to verify the response of PM2.5 to the two types of CSs from 2014 to 2019, and the similar results were obtained (Figure S2). It shows that the selection of data sets does not affect the main conclusions of this paper.

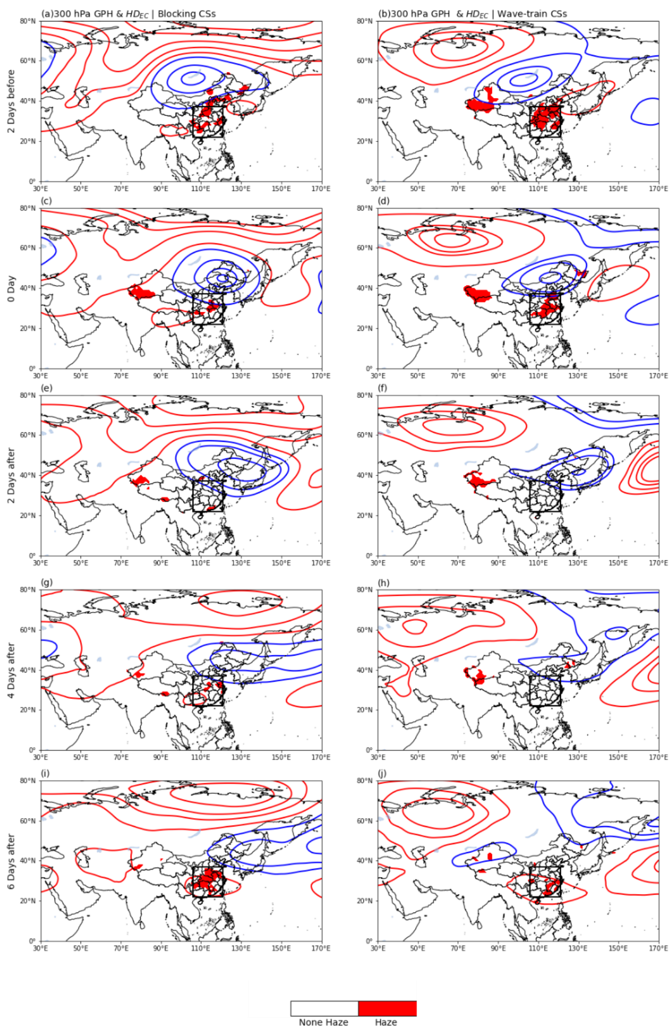


Figure 4. Composite of GPH anomalies at 300 hPa (contour; in intervals of 20 gpm) from -2 days to 6 days relative

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

to blocking CSs and the corresponding spatial distribution of HD_{EC} (shading, only shows the areas which are statistically significant at the 95% confidence level.) (a, c, e, g, i). b, d, f, h, and j are same as a, c, e, g, and i, but for wave-train CSs.

3.2 Why are two types of CSs different in dispersing HD_{EC}?

According to the definition of HD_{EC}, which combines visibility and Rhum in this study, we composite the daily visibility anomalies and Rhum anomalies for 9 days before and after the outbreak of the blocking CSs and wave-train CSs, respectively (Figure 5). This helps to understand why the two types of CSs have different abilities to disperse HD_{EC}. According to our definition, haze is determined by visibility and Rhum. Considering two types of CSs, it was found that there is no significant difference in Rhum between the two kinds of CSs. However, the blocking CSs are generally less effective in improving visibility than the wave-train CSs. On the day when the blocking CSs outbreak, the visibility shows a rising trend; however, it begins to deteriorate continuously 3 days after. Though the visibility in EC has a noticeable downward trend 5 days before the outbreak of the wave-train CSs, it improves significantly on the day of the wave-train CSs outbreak and rapidly deteriorates again about 3 days after the wave-train CSs occur. Combined with the differences in the circulation evolution during the two types of CSs shown in Figure 4, the weak dissipating ability to block CSs during HD_{EC} may be related to the stable blocking anomalies, while the significant cyclical variations of visibility during the wave-train CSs may be related to the "+-+" wave-train structure anomalies transporting rapidly to the eastern.

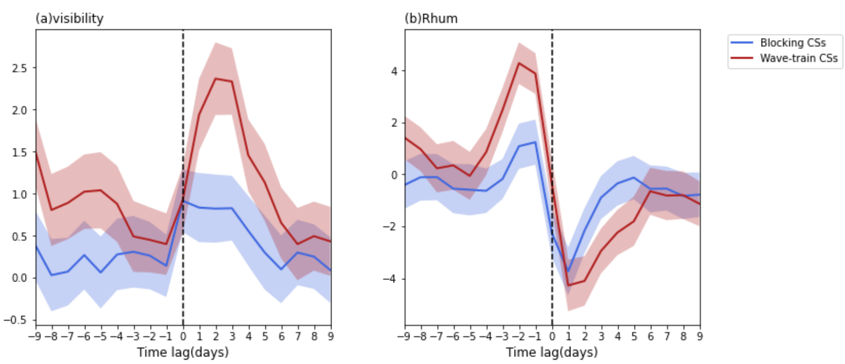


Figure 5. Mean (a) visibility anomalies (km), and (b) Rhum anomalies (%) in EC during 9 days before and after the outbreak of the blocking CSs (blue lines) and wave-train CSs (red lines), respectively. Shading represents plus/minus one standard deviation among the CSs.

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

Previous studies show that haze is influenced by surface meteorological conditions (Wang et al., 2015a; Yin et al., 2019a), which have significant variations after the outbreak of CSs (Park et al., 2014). Figure 6 reveals the thermal inversion potential anomalies (TIP, defined as the air temperature at 850 hPa minus SAT referring to Yin et al. (2019b)), surface horizontal wind speed (UV_sfc) anomalies, SAT anomalies, and SLP anomalies for 4 days before and after the outbreak of the blocking CSs and wave-train CSs, respectively. The results show that the high variations of meteorological elements reached the strongest on the day of the CSs outbreak, and their anomalies weakened in the next 4 days. Compared with the blocking CSs, the variation of meteorological elements related to wave-train CSs is stronger. 4 days after the outbreak of the two types of CSs, the difference of TIP and UV_sfc between the two types of CSs tended to be the same. However, the negative SAT anomalies and the positive SLP anomalies caused by the wave-train CSs lasted longer than those caused by the blocking CSs. This is in line with the difference in HD_{EC} dispersion ability between the two types of CSs.

It should be noted that the SAT and SLP anomalies caused by the two types of CSs in this paper are different from those of Park et al. (2014). It is due to the regions they selected to identified CSs included the northern part of Northeast Asia. The invasion of cold air is generally from north to south, so their research covers more CSs in Northeast Asia, while our study only focuses on CSs in eastern China with heavy haze. If we choose the same region to identify, similar results can be obtained (Figure S3).

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

Atmospheric Chemistry and Physics Discussions
Open Access
EGU

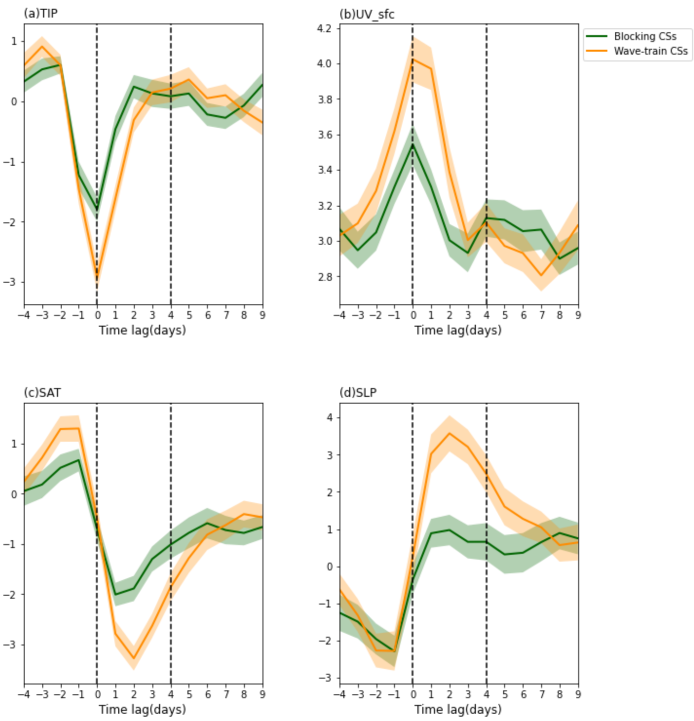
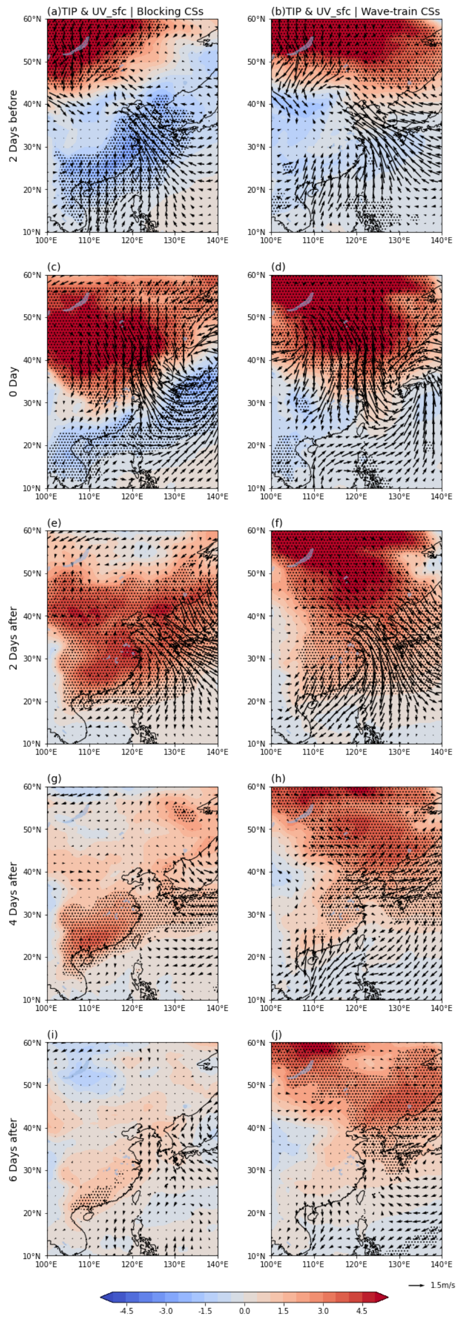


Figure 6. Mean (a) TIP anomalies (K), (b) UV_sfc anomalies (m s^{-1}), (c) SAT anomalies (K), and (d) SLP anomalies (hPa) in EC during 9 days before and after the outbreak of the blocking CSs (blue lines) and wave-train CSs (red lines), respectively. Shading represents plus/minus one standard deviation among the CSs.

CSs invade EC would cause a sharp drop in temperature, which may strengthen the TIP in the lower atmosphere (Lin et al., 2009). The strong TIP is unfavorable for the vertical dispersion of haze, making the cold, dry, and clear air difficult to spread (Chen et al., 2015; Zhong et al., 2019). Figure 7 indicates that the cold front will lead the TIP to control EC, forming a conducive condition to HD_{EC}, which may also be a reason for the rapid decline of visibility in EC 2 days after the outbreak of CSs. Compared with the wave-train CSs, the TIP after the outbreak of blocking CSs maintained for a longer time and a larger control region, which may cause the weak dispersion ability to HD_{EC}. From the perspective of UV_sfc, the cold air was limited to the north, and the warm and humid conditions in EC were maintained before the outbreak of the CSs. The CSs cause the airflow with the northern wind component to invade EC, rapidly dispersing the haze and causing the visibility to rise. However, after the outbreak of the CSs, the anomalies of UV_sfc in EC decrease abnormally, providing conducive conditions to the generation and

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

maintenance of haze. The anomalies of UV_sfc in EC after the outbreak of blocking CSs are weaker and have a shorter duration than wave-train CSs.



https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

Figure 7. Composite anomalies of TIP (shading; K; dotted areas are statistically significant at the 95% confidence level) and UV_sfc (vectors; m s^{-1}) from -2 days to 6 days relative to the outbreak of blocking CSs (a, c, e, g, i) and the wave-train CSs (b, d, f, h, j).

The increase of Siberian high accompanies the outbreak of CSs and the splitting and southward movement of the Siberian high leads cold air into EC. Comparatively speaking, the distribution of SLP anomalies in Eurasia before the blocking CSs form a pattern similar to the negative phase of the Arctic oscillation. Figure 8 shows that when the blocking CSs occur, the positive SLP anomalies and the negative SAT anomalies in the high-latitudes move southward, and the positive SLP anomalies control EC. 2 days after the outbreak of the blocking CSs, the positive SLP anomalies, and the negative SAT anomalies in the EC decline rapidly, providing favorable conditions for the accumulation of pollutants. The occurrence of wave-train CSs is accompanied by the eastward movement of significant positive SLP anomalies and negative SAT anomalies. 2 days after, the positive SLP anomalies affect EC continuously, resulting in a longer period of high visibility in EC.

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

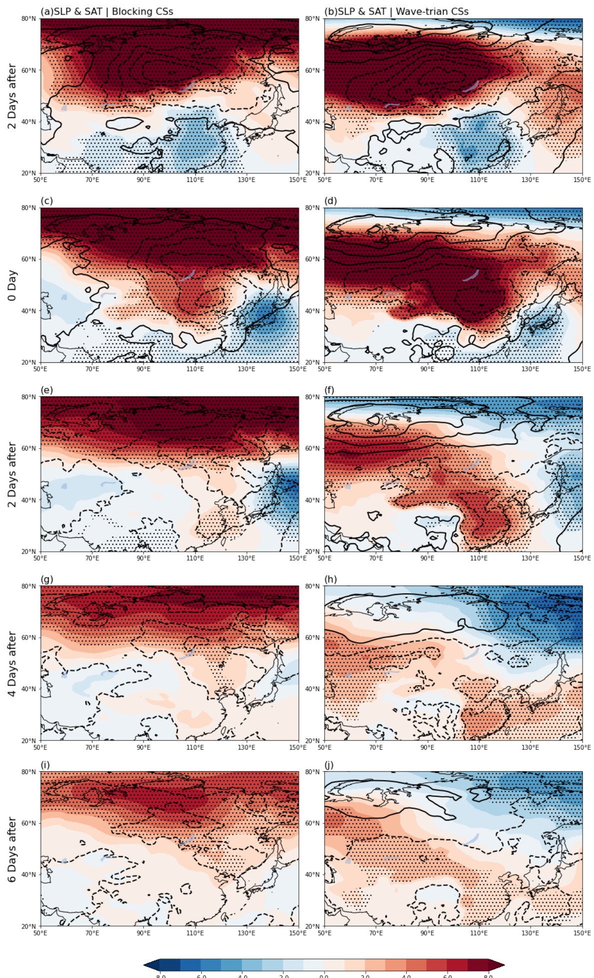


Figure 8. Composite anomalies of SLP (shading; hPa; dotted areas are statistically significant at the 95% confidence level) and SAT (contour; K) from -2 days to 6 days relative to the blocking CSs (a, c, e, g, i) and the wave-train CSs (b, d, f, h, j).

The results discussed earlier indicate that the blocking CSs have a weak ability to dissipate the HD_{EC}, while the outbreak of wave-train CSs can make EC maintain high air quality for a longer time. Thus, the frequency variations of the two types of CSs may also affect the trend of HD_{EC} in recent years. Figure 9a displays the time series of the frequency of blocking CSs and wave-train CSs. The results show that the wave-train CSs have an obvious downward trend, and the blocking CSs have a slight upward trend. To get a better sense of the variation of the two types of CSs, the ratio of blocking CSs to wave-

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

Atmospheric Chemistry and Physics Discussions
Open Access

train CSs is shown in Figure 9b, which has a visible upward trend, and its 9-year moving average exhibits a significant interdecadal variation. It means that in recent years, the ability of CSs to dissipate HD_{EC} has decreased in general.

We further calculated the partial correlation coefficients between the frequency of blocking CSs (wave-train CSs) and HD_{EC} to exclude the influence of another type of CSs. It can be found that there is a significant positive correlation between blocking CSs and HD_{EC} (Figure 9c). It should be noted that this does not mean that more blocking CSs cause more haze but reflects the weak dispersion ability of blocking CSs to HD_{EC}, resulting in relatively more HD_{EC}. The negative correlation between wave-train CSs and HD_{EC} is significant (Figure 9d), which is consistent with the result above. Furthermore, previous studies have shown that with the appearance of a warm Arctic-cold Eurasian pattern, there will be more blocking high maintained in the winter (Cohen et al., 2014; Luo et al., 2016), causing more blocking CSs to invade East Asia, and the phenomenon is further intensified under global warming (Yang et al., 2020b). It can be considered that ability of CSs to dissipate haze in East Asia weakened in the future, and policymakers are required to consider the problem of air pollutions.

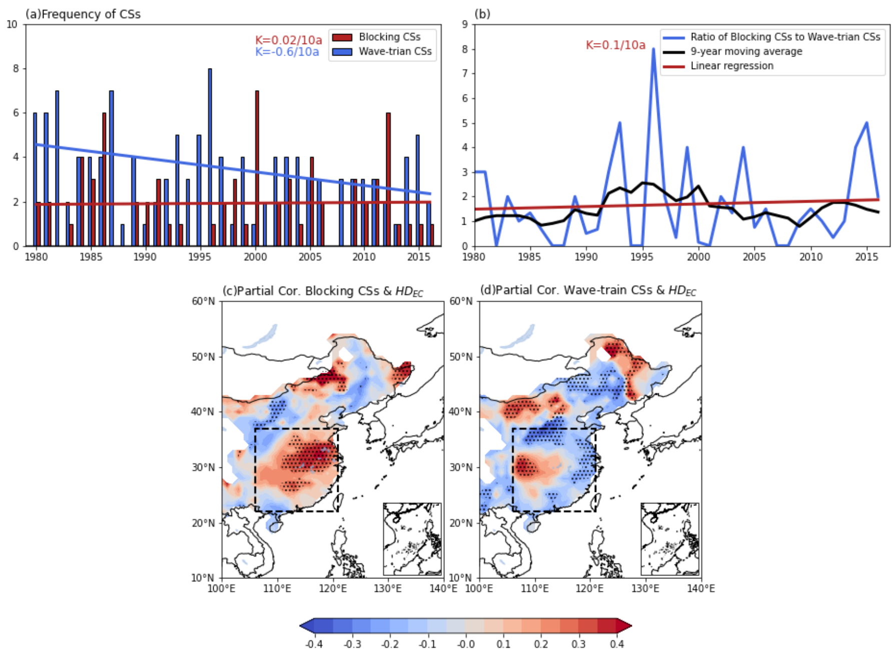


Figure 9. (a) Time series of the blocking CSs and the wave-train CSs (The solid line is the linear regression of the time series, and the text in the upper right corner indicates the trend of the solid lines). (b) Time series of the ratio of

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

blocking CSs to wave-train CSs (blue), 9-year moving average (black), and linear regression (red). The partial correlation coefficient between HD_{EC} and the frequency of blocking CSs (c) and the wave-train CSs (d). Dotted areas are statistically significant at the 95% confidence level.

4. Conclusions and discussion

In this paper, the connection between the CSs and the cool season haze over the EC is investigated based on the observational and reanalysis datasets from 1980 to 2017. The 187 CSs over EC are classified into two types by HCA, blocking CSs and wave-train CSs. Usually, the blocking CSs are accompanied by a meridional dipole in the upper-tropospheric GPH anomalies, which consists of a stable blocking structure. The blocking structure tends to control the EC for a long time and forms a relatively stable meteorological condition, which has the disadvantage to dissipate the HD_{EC}. Correspondingly, the local meteorological conditions, especially TIP and the quiescent wind band, rapidly appear after the blocking CSs outbreak, provide a haze-prone background. In addition, the positive SLP anomalies induced by the outbreak of the blocking CSs can rapidly restore to normal, and the SAT warm up under the influence of the weakening of the north wind component. Therefore, the ability to block CSs to dissipate HD_{EC} is limited. On the contrary, high air quality in EC can last longer due to the shorter duration of TIP and longer duration of positive SLP anomalies. In general, HD_{EC} can remain at a low level for a shorter (longer) time after the outbreak of blocking (wave-train) CSs. It is confirmed that blocking CSs has been increased over the past few years (Park et al., 2011a; Luo et al., 2018). Furthermore, the increasing trend of blocking CSs is likely to continue in the future, which may weaken the dispersion of haze and worsen the HD_{EC}. This reminds us that the problem of air pollution is still very serious and needs more attention.

Finally, it should be noted that the lack of meteorological station information in the observed data limits the accuracy of the haze distribution to some extent. Previous studies documented that the CSs outbreak greatly affected the dispersion of haze (Lin et al., 2009 and Wang et al., 2016). However, it can be seen that the visibility anomalies from -5 days to the day of the wave-train CSs outbreak have a sharp decline trend. Whether the CSs aggravate the haze before the outbreak deserves our attention in future research. In addition, to better understand the formation of haze and improve the predictability of haze, more research is needed to explore the possible impacts of meteorological elements on haze pollution in China.

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

Atmospheric Chemistry and Physics Discussions

Data availability

The ground observations are from the website: http://data.cma.cn. Daily mean meteorological data are obtained from the ERA-Interim reanalysis data archive: http://www.ecmwf.int/en/research/climate-reanalysis/era-interim.

Author contributions

SZ and GZ put forward the idea and design research, RW provided observational data including relative humidity, visibility, and weather phenomena. SZ and XY performed research, and ZY provided valuable suggestions. SZ wrote the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

This research is supported by the National Key Research and Development Program of China (2017YFA0603804) and the National Natural Science Foundation of China (41575085).

References

Ashfold, M. J., Latif, M. T., Samah, A. A., Mead, M. I., Harris, N. R. P.: Influence of Northeast Monsoon cold surges on air quality in Eastern Asia, Atmospheric Environment, 166, 498-509, https://doi.org/10.1016/j.atmosenv.2017.07.047, 2017.

Cai, B., Zeng, G., Zhang, G. and Li, Z.: Autumn cold surge paths over North China and the associated atmospheric circulation, Atmosphere, 10, 134, https://doi.org/10.3390/atmos10030134, 2019.

Cai, W. J., Li, K., Liao, H., Wang, H. J., and Wu, L. X.: Weather Conditions Conducive to Beijing Severe Haze More Frequent under Climate Change, Nat. Clim. Change, 7, 257–262, https://doi.org/10.1038/nclimate3249, 2017.

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

CCiM, G.R.: The horizontal and vertical structure of East Asia winter monsoon pressure surges, QJR Meteorol. Soc, 125, 29–54, https://doi.org/10.1002/qj.49712555304, 1999.

Chai, D. H., Wu, M. H., Li, J. X., Zhao, Y. Q.: Analysis of greenhouse effect of cold wave low temperature on different structures in 2000 (in Chinese), Meteorological Science, 2002(03), 367-371, 2002.

Chang, L. Y., Xu, J. M., Tie, X. X., and Wu, J. B.: Impact of the 2015 El Nino event on winter air quality in China, Sci. Rep., 6, 34275, https://doi.org/10.1038/srep34275, 2016.

Chen, H. P., Wang, H.J.: Haze Days in North China and the associated atmospheric circulations based on daily visibility data from 1960 to 2012, Journal of Geophysical Research: Atmospheres, 120(12), 5895–5909, https://doi.org/10.1002/2015JD023225, 2015.

Cohen, J., Screen, J., Furtado, J., et al.: Recent Arctic amplification and extreme mid-latitude weather, Nature Geoscience, 7, 627–637. https://doi.org/10.1038/ngeo2234, 2014.

Compo, G. P., Kiladis, G. N., and Webster, P. J.: The horizontal and vertical structure of east Asian winter monsoon pressure surges, Q. J. R. Meteorol. Soc., 125, 29–54, https://doi.org/10.1002/qj.49712555304, 1999.

Dee, D., and Coauthors.: The ERA-interim reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, https://doi.org/10.1002/qj.828, 2011.

Ding, Y. H., and Liu, Y. J.: Analysis of long-term variations of fog and haze in China in recent 50 years and their relations with atmospheric humidity, Sci. China Ser. D: Earth Sci., 57, 36–46, https://doi.org/10.1007/s11430-013-4792-1, 2014.

Fu, C. B., Wu, J., Gao, Y. C., Zhao, D. M., Han, Z.W.: ConECutive extreme visibility events in China during1960–2009, Atmos. Environ., 68, 1–7, https://doi.org/10.1016/j.atmosenv.2012.11.035, 2013.

Han, S. Q., Bian, H., Tie, X., Xie, Y., Sun, M., Liu, A.: Impact measurements of nocturnal planetary boundary layer on urban air pollutants: From a 250-m tower over Tianjin, China. J. Hazard. Mater., 162, 264–269,2009.

Hien, P.D., Loc, P.D., Dao, N.V.: Air pollution episodes associated with East Asian winter monsoons, Sci. Total. Environ, 409, 5063–5068, https://doi.org/10.1016/j.scitotenv.2011.08.049, 2011.

Hu, Z.Z., Bengtsson, L., Arpe, K.: Impact of global warming on the Asian winter monsoon in a coupled GCM, J. Geophys. Res., 05, 4607–4624, https://doi.org/10.1029/1999JD901031, 2000.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D.,Gandin, L., Iredell, M., Saha, S., White, G.,Woollen, J., Zhu, Y.,Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki,W., Higgins,W., Janowiak, J., Mo, K. C., Ropelewski, C.,Wang, J., Jenne, R.,and Joseph, D.: The NCEP/NCAR 40-year reanalysis project, B.Am. Meteorol. Soc., 77, 437–471, https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2, 1996.

Lin, C. Y., Lung, S. C.C., Guo, H. R. et al.: Climate variability of cold surge and its impact on the air quality of Taiwan, Climatic Change 94, 457–471, https://doi.org/10.1007/s10584-008-9495-9, 2009.

Luo, D. H., Chen, X. D., Dai, A. G et al.: Changes in Atmospheric Blocking Circulations Linked with Winter Arctic Warming: A New Perspective, Journal of Climate, 31 (18), 7661-7678, https://doi.org/10.1175/JCLI-D-18-0040.1, 2018.

Luo, D. H., Xiao, Y. Q., Yao, Y., Dai, A. G. et al.: Impact of Ural Blocking on Winter Warm Arctic–Cold Eurasian Anomalies. Part I: Blocking-Induced Amplification, Journal of Climate, 29 (11), 3925-3947, https://doi.org/10.1175/JCLI-D-15-0611.1, 2016.

Luo, Y. F., Lu, D., Zhou, X. J.; Li, W. L.: Characteristics of the spatial distribution and yearly variation of aerosol optical depth over China in last 30 years, J. Geophys. Res., 106(D13), 14,501–14,513, https://doi.org/10.1029/2001JD900030, 2001.

Niu, F., Li, Z. Q., Li, C., Lee, K.-H., Wang, M. Y.: Increase of wintertime fog in China: Potential impacts of weakening of the eastern Asian monsoon circulation and increasing aerosol loading, J. Geophys. Res., 115, D00K20, https://doi.org/10.1029/2009JD013484, 2010.

Park, T. W., Ho, C. H., Jeong, J. H., et al.: Different characteristics of cold day and cold surge frequency over East Asia in a global warming situation, Journal of Geophysical Research: Atmospheres, 116(D12), D12118, https://doi.org/10.1029/2010JD015369, 2011a.

Park, T. W., Ho, C. H., Yang, S.: Relationship between the Arctic Oscillation and Cold Surges over East Asia, J Clim, 24(1), 68–83, https://doi.org/10.1175/2010jcli3529.1, 2011b.

Park, T. W., Jeong, J.H., Ho, C.H., et al.: Characteristics of atmospheric circulation associated with cold surge occurrences in East Asia: A case study during 2005/06 winter, Adv. Atmos. Sci, 25, 791–804, https://doi.org/10.1007/s00376-008-0791-0, 2008.

Park, T.W, Ho, C.H, Jeong, J.H, et al.: A new dynamical index for classification of cold surge types over East Asia, Climate dynamics, 45(9): 2469-2484, https://doi.org/10.1007/s00382-015-2483-7, 2015.

Park, T.W., Ho, C.H., Deng, Y.: A synoptic and dynamical characterization of wave-train and blocking cold surge over East Asia, Clim Dyn 43, 753–770, https://doi.org/10.1007/s00382-013-1817-6, 2014.

Qian, Y., Leung, L. R., Ghan, S. J. Giorgi, F.: Regional climate effects of aerosols over China: Modeling and observation, Tellus, 55B, 914–934, https://doi.org/10.3402/tellusb.v55i4.16379, 2003.

Qu, W., Wang, J., Zhang, X., Yang, Z., Gao, S.: Effect of cold wave on winter visibility over eastern China, J. Geophys. Res, 120, 2394–2406, https://doi.org/10.1002/2014JD021958, 2015.

Rokach, L., Maimon, O.: Clustering methods. Data mining and knowledge discovery handbook, Springer US, 321-352, 2005.

Rousseeuw, P.: Silhouettes: A graphical aid to the interpretation and validation of cluster analysis. Journal of Computational and Applied Mathematics, 20, 5365, https://doi.org/10.1016/0377-0427(87)90125-7, 1987.

Shi, C., Zhang, H., Roth, M., Li, Z.: Impacts of urbanization on long-term fog variation in Anhui Province, China. Atmos. Environ, 42, 8484–8492, https://doi.org/10.1016/j.atmosenv.2008.08.002, 2008.

Wang, H. J., and Chen, H. P.: Understanding the recent trend of haze pollution in eastern China: roles of climate change, Atmos. Chem. Phys., 16, 4205–4211, https://doi.org/10.5194/acp-16-4205-2016, 2016.

Wang, H. J., Chen, H. P., Liu, J. P.: Arctic Sea Ice Decline Intensified Haze Pollution in Eastern China, Atmospheric and Oceanic Science Letters, 8:1, 1-9, https://doi.org/10.3878/AOSL20140081, 2015.

Wang, X, Zhang, R, Tan, Y, et al.: Dominant synoptic patterns associated with the decay process of PM 2.5 pollution episodes around Beijing, Atmospheric Chemistry and Physics, 21(4): 2491-2508, https://doi.org/10.5194/acp-21-2491-2021, 2021.

Wang, Z. S., Liu, X. D., Xie, X. N.: Effects of Strong East Asian Cold Surges on Improving the Air Quality over Mainland China, Atmosphere, 7, 38, https://doi.org/10.3390/atmos7030038, 2016.

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

Wei, Y., Li, J., Wang, Z., Chem, H., Wu, Q., Li, J., Wang, Y., and Wang, W.: Trends of surface PM2:5 over Beijing–Tianjin–Hebei in 2013–2015 and their causes: emission controls vs. meteorological conditions, Atmos. Oceanic Sci. Lett., 10, 276–283, https://doi.org/10.1080/16742834.2017.1315631, 2017.

Wu, J., Fu, C. B., Zhang, L. Y., Tang, J. P.: Trends of visibility on sunny days in China in the recent 50 years, Atmos. Environ., 55, 339–342, https://doi.org/10.1016/j.atmosenv.2012.03.037, 2012.

Wu, J., Luo, J. G., Zhang, L. Y., Xia, L., Zhao, D. M., Tang, J. P.: Improvement of aerosol optical depth retrieval using visibility data in China during the past 50 years, J. Geophys. Res. Atmos., 119, 13,370–

https://doi.org/10.5194/acp-2021-436
Preprint. Discussion started: 28 June 2021

13,387, https://doi.org/10.1002/2014JD021550, 2014.

Xie, Y. B., Chen, J., and Li, W.: An assessment of PM2:5 related health risks and impaired values of Beijing residents in a consecutive high-level exposure during heavy haze days, Environ. Sci., 35, 1–8, 2014.

Xu, P., Chen, Y. F., and Ye, X. J.: Haze, air pollution, and health in China, Lancet, 382, 2067, https://doi.org/10.1016/S0140-6736(13)62693-8, 2013.

Xu, Q.: Abrupt change of themid-summer climate in central east China by the influence of atmospheric pollution, Atmos. Environ., 35, 5029–5040, https://doi.org/10.1016/S1352-2310(01)00315-6, 2001.

Yang, X. Y., Zeng, G., Zhang, G. W., Li, Z.X.: Interdecadal Variation of Winter Cold Surge Path in East Asia and Its Relationship with Arctic Sea Ice, Journal of Climate, 33(11), 4907–4925, https://doi.org/10.1175/JCLI-D-19-0751.1, 2020a.

Yang, X. Y., Zeng, G., Zhang, G. W., Vedaste, I., Xu, Y.: Future projections of winter cold surge paths over East Asia from CMIP6 models, International Journal of Climatology, 1-16, https://doi.org/10.1002/joc.6797, 2020b.

Yin, Z, Zhang, Y, Wang, H, et al.: Evident PM 2.5 drops in the east of China due to the COVID-19 quarantine measures in February, Atmospheric Chemistry and Physics, 21(3): 1581-1592, https://doi.org/10.5194/acp-21-1581-2021, 2021.

Yin, Z. C., Wang, H. J.: Possible Relationship between the Chukchi Sea Ice in the Early Winter and the February Haze Pollution in the North China Plain., 32(16), 5179-5190, https://doi.org/10.1175/JCLI-D-18-0634.1, 2019b.

Yin, Z.C., Li, Y. Y., Wang, H. J.: Response of early winter haze in the North China Plain to autumn Beaufort sea ice, Atmos. Chem. Phys., 19, 1439–1453, https://doi.org/10.5194/acp-19-1439-2019, 2019a.

Yin, Z.C., Wang, H.J., and Chen, H. P.: Understanding severe winter haze events in the North China Plain in 2014: Roles of climate anomalies, Atmos. Chem. Phys., 17, 1641–1651, https://doi.org/10.5194/acp-17-1641-2017, 2017.

Zhang, L. Y., Lu, X. B., Yang, L. L., Ding, F., Zhu, Z. F., and Rui, D. M.: Study on the Effects of the Strong El Nino Event on Air Quality of Eastern China in Winter, The Administration and Technique of Environmental Monitoring, 28, 23–27, 2016.

Zhong, W. G., Yin, Z. C., Wang, H. J.: The relationship between anticyclonic anomalies in northeastern

Asia and severe haze in the Beijing–Tianjin–Hebei region, Atmos. Chem. Phys., 19, 5941-5957, https://doi.org/10.5194/acp-19-5941-2019, 2019.