Responses to Referee #1:

In their contribution, the authors presented potential roles of climate variability and change in recent increased haze pollution events in east China. This paper could be a welcome reference in the literature.

In recent years, haze pollution has been a particularly acute issue in east China. The reasons behind recent increase of haze pollution events are complex. A number of studies have discussed this problem from human activity perspective, i.e., increased emissions into atmosphere due to urban and industrial pollution. However, little attention has been paid to this issue from climate variability and change perspective. The authors showed decadal trends in haze day in northeast and southeast China and their relationships with Arctic sea ice extent, precipitation and surface winds. The results can improve our understanding of physical processes that influence haze variability in east China. Below I list some points, which the authors need to address.

Reply: Thanks for your suggestions, which have been addressed point by point in the following and the corresponding corrections have been presented in the manuscript.

1. Page 4/ Line9: Better outline the two regions (R1 and R2) in Figure 1. How many stations are used to calculate the averaged haze day in R1 and R2, respectively? Are the haze day trends sensitive to the number of stations used?

Reply: (1) These two regions have been shown in Figure 1 **[P14]** as the following. According to the statistics, there are 112 stations included in R1 and 104 in R2 **[P4 L11-12]**.

(2) As the suggested, further analysis is implemented and results indicate that the trends of haze days in these two regions show almost no sensitive to the number of stations used. However, a relative larger trend can be observed in southern China than that in northern China, which is also clear in Figure 1.

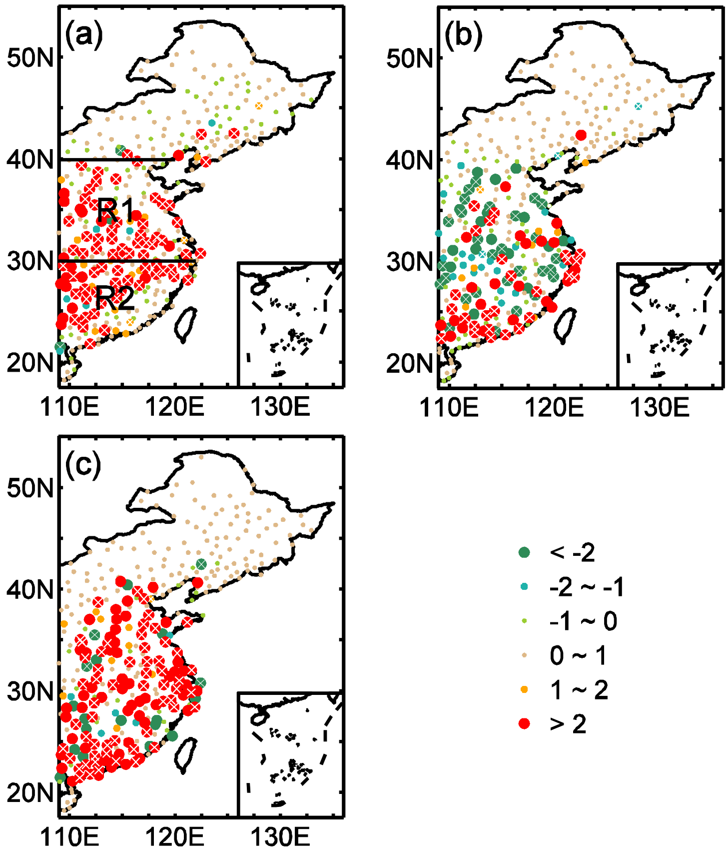

Figure 1. Linear trend of station winter haze days in the three periods: (a) 1960-1979, (b) 1980-1999, and (c) 2000-2012. R1 and R2 are the two regions that discussed in the text. The circle with cross means the change is significant at the 95% confidence level. Units: day·year^{-1}.

2. Page 4/Line 10: Explanation of the definition of haze day is needed.

Reply: [P4 L3-5] The numbers of the monthly haze days that used in this study are directly derived from the collections by the National Meteorological Information Center of China Meteorological Administration. The haze days are generally determined according to the immediately weather phenomenon by the sophisticated observers. Thus, the definition of haze day has not been shown in this study. Additionally, the measured haze occurrences are also defined based on the observations of visibility and relative humidity according to specified criteria, which vary between organizations (e.g., World Meteorological Organization and UK Met Office) and personal views (e.g., Vautard et al., 2009; Ding and Liu, 2014). In our early study, we adopted a comprehensive judgment method with visibility of less than

10 km, relative humidity at less than 90% and the wind speed lower than 7 m/s (Chen and Wang, 2015).

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 Earth Sci., 57, 36–46, 2014.

Vautard, R., Yiou, P., and Oldenborgh, G.: Decline of fog, mist and haze in Europe over the past 30 years, Nat. Geosci., 2, 115–119, doi:10.1038/NGEO414, 2009.

Chen, H. P., and Wang, H. J.: Haze Days in North China and the associated atmospheric circulations based on daily visibility data from 1960 to 2012, J. Geophys. Res. Atmos., 120, 5895–5909, doi:10.1002/2015JD023225, 2015.

3. Page 4/Line 13: “sea ice extent” should be “sea ice concentration”.

Reply: [P4 L15-16] Sorry for misleading and this sentence has been reworded as “The autumn ASI index is calculated as the total sea ice extent in the region of Arctic”.

4. Page 4/Line 14-16: Add “China Statistical Yearbook” in the reference list.

Reply: The ‘China Statistical Yearbook’ is published every year and there are at least 27 references from 1986 to 2012 which can be all found in the network. Thus, these references have not been listed in the manuscript.

5. Page 5/Line 17: It seems that for R2, the variability of winter haze day becomes larger in recent years as compared to the first and second periods.

Reply: It is actually true and it is apparent in Figure 2, which needs further studies in the future.

6. Page 6/Line 4: A little bit more discussion regarding the influence of Arctic sea ice loss on atmospheric circulation anomalies over east China is needed.

Reply: [P6 L6-11] Thanks for the suggestions. Actually, there are already some discussions can be found in section 4 for this perspective. As the suggestion, more discussion regarding this has been added in the current version of this study as "Early studies (e.g., Wang et al., 2015) have indicated that the reduction of autumn ASI can lead to positive sea level pressure anomalies in mid-latitude Eurasia, northward shift of track of cyclone activity in China and weak Rossby wave activity in eastern China during winter season. These atmospheric circulation changes favor less cyclone activity and more stable atmosphere in eastern China, resulting in more haze days there."

Wang, H. J., Chen, H. P., and Liu, J.: Arctic sea ice decline intensified haze pollution in eastern China. Atmos. Oceanic Sci. Lett., 8, 1-9, 2015.

7. Page 6/Line 14-15: I suggest the authors add some discussion about the possible factors contributing to increased precipitation during the first and second period and decreased precipitation during the third period.

Reply: Thanks for the suggestions. However, this article is mainly focused on the discussion about the influences of precipitation on the haze pollution, not the reasons for the precipitation changes. This suggestion as you proposed is beyond the scope of this article, thus the discussions about the precipitation changes have not been added in the current version.

8. It is not clear how the authors define ">" and "<" signs in Figure 6? Relative to what? Please clarify.

Reply: [P19] (1) ">" means "larger than" and "<" means "less than" in Figure 6, which have been clarified in the figure caption.

(2) The comparisons are implemented among these three periods that discussed in the paper, i.e. the second period is compared with the first period and the third period is compared with the second period.

9. Page 8/Line 15-21: I would like to suggest the authors to add more discussion

about the projected changes in precipitation and surface winds over east China in near term based on recent studies, CMIP5 model projections.

Reply: [P8 L22-27] Some discussions have been added as “Projections from CMIP5 models indicate that the low-level atmosphere tends to be more unstable and the atmosphere humidity will decrease in eastern China (Wang et al., 2015). Simultaneously, the winter precipitation in eastern China is projected to increase (Tian et al., 2015), but the surface winds decrease (Jiang et al., 2013). Thus there will be both favorable and unfavorable factors for haze occurrences in the near future based on the model projections. However, there is no doubt that, with the projected sea ice extent decrease (Kirtman et al., 2013), weakening of the winter East Asian monsoon wind (Wang et al., 2013) and total energy consumption increase, the haze pollution in eastern China may continue to be a serious problem in the near future. ”

Wang, H. J., Chen, H. P., and Liu, J.: Arctic sea ice decline intensified haze pollution in eastern China. Atmos. Oceanic Sci. Lett., 8, 1-9, 2015.

Tian, D., Guo, Y., and Dong, W. J.: Future changes and uncertainties in temperature and precipitation over China based on CMIP5 models. Adv. Atmos. Sci., 32(4), 487-496, doi:10.1007/s00376-014-4102-7, 2015.

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Understanding the Recent Trend of Haze Pollution in Eastern China: Roles of Climate Change

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Abstract

In this paper, the variation and trend of haze pollution in eastern China for winter of 1960-2012 were analyzed. With the overall increasing number of winter haze days in the period, the five decades were divided into three sub-periods based on the changes of winter haze days (WHD) in central North China (30°N-40°N) and eastern South China (south of 30°N) for east of 109°E mainland China. Results show that WHD kept gradual increasing during 1960-1979, overall stable during 1980-1999, and fast increasing during 2000-2012. The author identified the major climate forcing factors besides total energy consumption. Among all the possible climate factors, variability of the autumn Arctic sea ice extent, local precipitation and surface wind during winter is most influential to the haze pollution change. The joint effect of fast increase of total energy consumption, rapid decline of Arctic sea ice extent and reduced precipitation and surface winds intensified the haze pollution in central North China after 2000. There is similar conclusion for haze pollution in eastern South China after 2000, with the precipitation effect being smaller and spatially inconsistent.

1. Introduction

In recent years, China has suffered from increased severe haze events that have caused strongly impacts on society, ecosystem, and human health. For example, the eastern China was hit by a prolonged and heavy haze event in January 2013, which made Beijing reaching its highest level of air pollution and led to the first haze orange alert in Beijing's meteorological history (e.g. Ding and Liu, 2014; Zhang et al., 2014). Furthermore, serious health problems have been induced from respiratory illness to heart disease, premature death, and cancer with the intensification of air pollution (Wang and Mauzerall, 2006; Xu et al., 2013; Xie et al., 2014). Thus, increased attentions have been reported to the issue of haze both from the government bodies and the general publics, and some air pollution prevention actions have been implemented and have stipulated strict controls on coal consumption, industry production, vehicles, etc.

Early studies have documented that the haze days are generally increase in economically developed eastern China but decrease in the less economically developed regions in China (e.g. Niu et al., 2010; Wu et al., 2010; Ding and Liu, 2014), and this increasing trend of haze is reported to be more pronounced since 2001 (Sun et al., 2013). Thus, the human activities, such as rapid urbanization and economic development, are generally considered as the major contributors to this long-term increasing trend of haze in eastern China (Wang et al., 2013). For example, in Beijing, vehicles are reported to be the biggest source of particulate matter 2.5 ($PM_{2.5}$), accounting for 25% of the pollution, and the coal combustion and cross-regional transport are the second greatest source, both accounting for 19%, despite some debates still exist (He et al., 2013; Zhang et al., 2013). Similar phenomenon can be observed in the other regions in China, such as in Chengdu city over southwestern China in which the secondary inorganic aerosols and coal combustion can account for 37 ± 18% and 20 ± 12% of the air pollutants, respectively (Tao et al., 2014).

Evidently, there is no doubt that there is a great role can be found from the human activities to the strongly increase of haze days in China. However, our deeply analysis in this study indicates that the variations of haze days show different trends in the past decades over eastern China, with increase in 1960-1979, no obvious change in 1980-1999 (even decrease over northern part of eastern China), and rapidly increase since 2000, which presents a disagreement with the persistently and rapidly increase of the total energy consumption over this region in the past. So, the impacts from the climate change must be considered when talking about the changes of haze events because the climate change can significantly influence the air pollution via variation of local atmospheric circulation. Some early studies have revealed that the increased haze days in eastern China may be associated with decreases of the surface wind speed (Xu et al., 2006; Gao et al., 2008; Niu et al., 2010) and the relative humidity in the atmosphere (Ding and Liu, 2014). Wu et al. (2008) indicate that the occurrences of heavy haze events in the Pearl River Delta region of China are generally concurrently with the stronger zonal circulations in the midtroposphere and weaker winds on the surface. Chen and Wang (2015) reveal that the severe haze events in boreal winter over northern China generally happen under a favorable atmospheric background, with the weakened northerly winds and the development of inversion anomalies in the lower troposphere, the weakened East Asian trough in the midtroposphere, and the northward East Asian jet in the high troposphere. Additionally, a recent study further reveals that the Arctic sea ice decline can intensify the haze pollution over eastern China and account for approximately 45-67% of the interannual to interdecadal variability of haze occurrences. However, the possible reasons for the different trends of haze days (varying from decades) over eastern China have not been revealed so far, although the ambient conditions of the haze occurrences have been well analyzed as well as the reason of its long-term increasing trend, which is thus to be our interest and topic in this study.

2. Data and Methods

The monthly haze day data for 756 meteorological stations in China during 1960-2013 have been collected by the National Meteorological Information Center of the China Meteorological Administration. The haze days from this dataset are generally determined according to the immediately weather phenomenon by the sophisticated observers. For the site-observation, it was rejected if there are miss values in time series. Thus a subset of total 542 stations is selected. We focus our analysis on haze pollution over eastern China (east of 109^{o}E, south of 40^{o}N, mainland China) in this study. As have been indicated, more than 40% haze pollution occurred in boreal winter (current year December and following year January-February), hence we focus on the winter season. We here after focus our analysis in two regions, R1 (east of 109^{o}E in 30^{o}N-40^{o}N, including 112 stations) and R2 (east of 109^{o}E~~,~~ and south of 30^{o}N, including 104 stations) in mainland China. Haze day is defined as the average in the region R1 or R2. The Arctic sea ice extent (ASI) is calculated from the Hadley Centre (HadISST1) with 1^{o} × 1^{o} resolution for 1870-2013 (Rayner et al, 2003). The autumn ASI index is calculated as the ~~area-averaged~~total sea ice extent in the region of ~~north 45^{o}N~~Arctic. The annual statistics of total energy consumption that providing for each province in China are obtained from the journal of ‘China Statistical Yearbook’ that published every year.

3. Results

Heavy haze events can not only strongly affect the traffic but also induce serious health problems from respiratory illnesses to heart disease, premature death and cancer (Pope and Docheru, 2006; Wang and Mauzerall, 2006). The intensified air pollution in China can be more or less attributed to the increased emissions of pollutants into the atmosphere as the result of rapid economic development thus fast increase of fossil fuel energy consumption and urbanization. Meanwhile, climate change can also significantly influence the air pollution via variation of local atmospheric circulation and precipitation.

As indicated by numerous studies, air pollution has generally been intensified in eastern China in past half-century, with more haze days and increased $PM_{2.5}$ concentration during winter and spring (e.g. Wang et al, 2015). However, based on our current studies, recent trend during 2000-2012 is different from that during 1980-1999 or 1960-1979 (Fig. 1). During 1960-1979, there is a general consistent increasing trend of winter haze days (WHD) in Beijing-Tianjin-Hebei area and in the lower reaches of Yangtze River Valley. There is no significant trend southeastern coastal region of China. In the second period (1980-1999), there are generally increasing trends south of 30^{o}N but some decreasing trends in regions between 30^{o}N and 40^{o}N in eastern China. During recent period (2000-2012) there are generally large increasing trends in the region south of 40^{o}N in eastern China. During all the three period, there is no significant trend in northeastern China and eastern Inner-Mongolia.

Thus, our first question is why there are some decreasing trends of WHD during the second period (1980-1999) when the rapid economy has been growing continuously from late 1970s up to present. We then plotted the WHD together with total energy consumption in R1 and R2 (Fig. 2). We found that WHD keeps gradual increasing during the first period, remains stable or slightly decreases during the second period, and then increases fast along with the rapid increase of total energy consumption during the recent period. Therefore, the contradiction between the no-increasing WHD and increasing energy consumption during the second period must be explained by other factors, most reasonably, some climate factors.

One of the possible major climate factors is the Arctic sea ice extent (Deser et al., 2010; Liu et al., 2012; Li and Wang, 2013; Li and Wang, 2014), whose relationship with the haze pollution in eastern China was first indicated by Wang et al. (2015). Here we show the apparent out-of-phase interannual relationship between the Autumn Arctic sea ice extent and WHD for both R1 and R2 in Fig. 3, with high correlation coefficients of -0.70 and -0.87 respectively during 1960-2012, -0.60 and -0.82 respectively during 1980-2012. Meanwhile the WHDs in R1 and R2 are temporally correlated each other at 0.75 during 1960-2012 in the interannual variability. With the significant impact of sea ice extent on the haze pollution, the fact that sea ice extent remains generally stable can largely explain the no-increase of WHD during the second period even along with economic development and total energy consumption increase. In addition, the rapid decline of the sea ice extent in recent two decades can also largely explain the fast increase of WHD in both northern and southern areas of eastern China. Early studies (e.g., Wang et al., 2015) have indicated that the reduction of autumn ASI can lead to positive sea level pressure anomalies in mid-latitude Eurasia, northward shift of track of cyclone activity in China and weak Rossby wave activity in eastern China during winter season. These atmospheric circulation changes favor less cyclone activity and more stable atmosphere in eastern China, resulting in more haze days there.

Precipitation change is another important factor that has significant impact on the haze pollution, via the wet removal effect of atmospheric pollutants. Here we plot the spatial distribution of the linear trend of station winter precipitation in eastern China for each of the three periods (Fig. 4). It is clear that R2 has generally increasing trend of precipitation during the first and second periods while R1 has apparent decreasing trend during the third period. Therefore, the precipitation trends favor WHD decreasing in R2 in the first and second periods and favor WHD increasing in R1 during the third period. In this regard, the impacts of both the sea ice extent and precipitation trends in R1 help to intensify the haze pollution in the central North China (R1) in recent period. While the precipitation trend in R2 (R1) is generally small in recent period (first two periods), thus has smaller impacts on WHD as compared to sea ice extent.

The simultaneous WHD-precipitation correlation coefficient is -0.11 and -0.16 respectively for R1 and R2 during 1961-2011. However, the WHD-precipitation correlation coefficient is -0.60 and -0.41 respectively for R1 and R2 during 1980-2011. Besides, we should not neglect the effect of changing surface winds. As shown in Fig. 5, there is generally weak reduction of surface winds in eastern China before year 2000, but spatially inconsistent trends of surface wind after 2000. Region R2 has the upward trend of surface wind after 2000, while R1 has upward and downward trends respectively in the north and south parts of the region.

Therefore, the precipitation trends in eastern China and the sea ice extent can explain larger proportion of WHD variance since 1980s in eastern China besides emission of pollutants by human beings. After the year 2000, from climate change perspective, the intensified WHD in R1 is a joint effect of sea ice decline and precipitation and surface wind decrease whereas the intensified WHD in R2 is mainly induced by the sea ice decline (the surface wind weak increase is not favorable to WHD increase).

Another widely concerned question is, has the governmental control on pollutant emissions received positive effect? Based on our analysis, the answer is affirmative. This can be demonstrated by comparing the PM2.5 content in large city like Beijing, Tianjin, Hangzhou, Xi'an, Changchun, Shanghai, and Guangzhou between 2003 and 2013, where all the cities have much reduced PM2.5 content in 2013 than 2003 during summer season (Cao et al., 2014). However, there has been no improvement of air quality for winter season. Then, how to understand such difference between air quality change between summer and winter? The key impact factor is the Artic sea ice extent. On one hand, the winter atmospheric circulation in eastern China is significantly modulated by the preceding autumn Arctic sea ice extent thus the sea ice decline can intensify the haze pollution in eastern China even though the total emission of pollutant into the atmosphere has been reduced. On the other hand, sea ice extent has no significant influence on the summer atmospheric circulation, thus the effect of cutting off the pollutant emission can be evidently observed. In other words, the winter haze pollution would be more serious if the government has not controlled the pollutant emission after the year 2000. Definitely, controls on the pollutant emission always have positive effects and should be always encouraged.

4. Conclusions and discussions

Based on our above analysis, the Arctic sea ice extent has the most apparent impacts on the haze pollution in eastern China among other climate factors including precipitation and surface wind since 1980s. After the year 2000, the sea ice decline and precipitation decrease in central North China jointly intensified the haze pollution, whereas the net effects of sea ice decline and surface wind increase also intensified the haze pollution in eastern South China. Our overall analysis and conclusions are schematically summarized in Fig. 6.

However, two other points should be addressed here. The first point relates the inter-correlation among sea ice extent, precipitation, and surface winds. Based on our previous study (Wang et al., 2015), the Arctic sea ice decline may favor the Rossby wave activity weakening in eastern China south of 40^{o}N thus leads to the precipitation decrease during winter season. Meanwhile, the change of sea ice extent may also have moderate impacts on both the zonal and meridional surface winds in eastern China. Secondly, recent trend after 2000 should be paid more attention. As we concluded above, both the Arctic sea ice decline and the precipitation decreasing in central North China, along with the total energy consumption increase, favors the haze pollution intensifying. In eastern South China, there are two apparent factors (sea ice decline and total energy consumption increasing) that help to intensifying the haze pollution except the precipitation. In addition, the surface wind keeps overall decreasing in central North China reflects the East Asian winter monsoon weakening after 1960 particularly after mid-1980s (Wang and He, 2012).

Projections from CMIP5 models indicate that the low-level atmosphere tends to be more unstable and the atmosphere humidity will decrease in eastern China (Wang et al., 2015). Simultaneously, the winter precipitation in eastern China is projected to increase (Tian et al., 2015), but the surface winds decrease (Jiang et al., 2013). Thus there will be both favorable and unfavorable factors for haze occurrences in the near future based on the model projections. However, there is no doubt that, ~~With~~ with the projected sea ice extent decrease (Kirtman et al., 2013), weakening of the winter East Asian monsoon wind (Wang et al., 2013) and total energy consumption increase, the haze pollution in eastern China may continue to be a serious problem in the near future. There are already series of governmental plans to address the air pollution issues in Beijing-Tianjin-Hebei area and Yangtze-River Delta as well as the Pearl River Delta even though the future climate change is not favorable to the air pollution reduction.

In Fig. 2, the year-to-year variation for summer haze days (SHD) is shown as well by the blue curve, indicating slight trend and rapid increase before and after 2000 for the two regions. Thus the intensification of the haze pollution in eastern China after 2000 is significant both in winter and summer. Changes of summer rainfall and near-surface wind should be directly associated with the SHD trend. Even though we did not find significant correlation between the SHD and the Arctic sea ice extent in the year-to-year variability, the SHD increase after 2000 may also be related to the Arctic sea ice. In addition, as shown in Zhu et al. (2011), the Pacific Decadal Oscillation (PDO) phase change in late 1990s may have impacts on the summer atmospheric circulation and precipitation changes in eastern China. Therefore understanding of the climate mechanisms for the SHD change calls more investigations from both local and remote perspectives.

Acknowledgements

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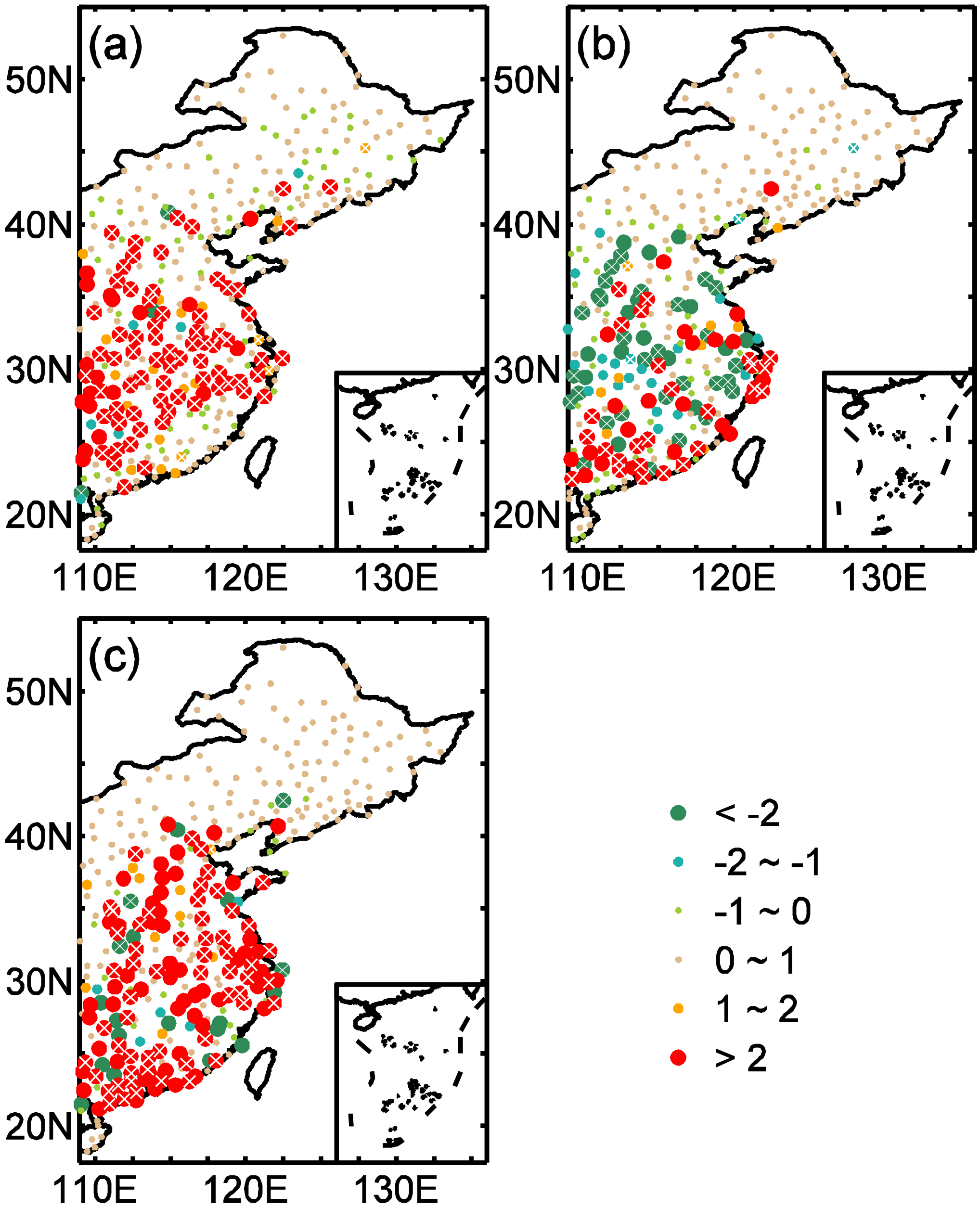
1 **Figures**


(a)
50N
40N
30N
20N
110E
120E
130E
(b)
50N
40N
30N
20N
110E
120E
130E
(c)
50N
40N
30N
20N
110E
120E
130E
< -2
-2 ~ -1
-1 ~ 0
0 ~ 1
1 ~ 2
> 2

2

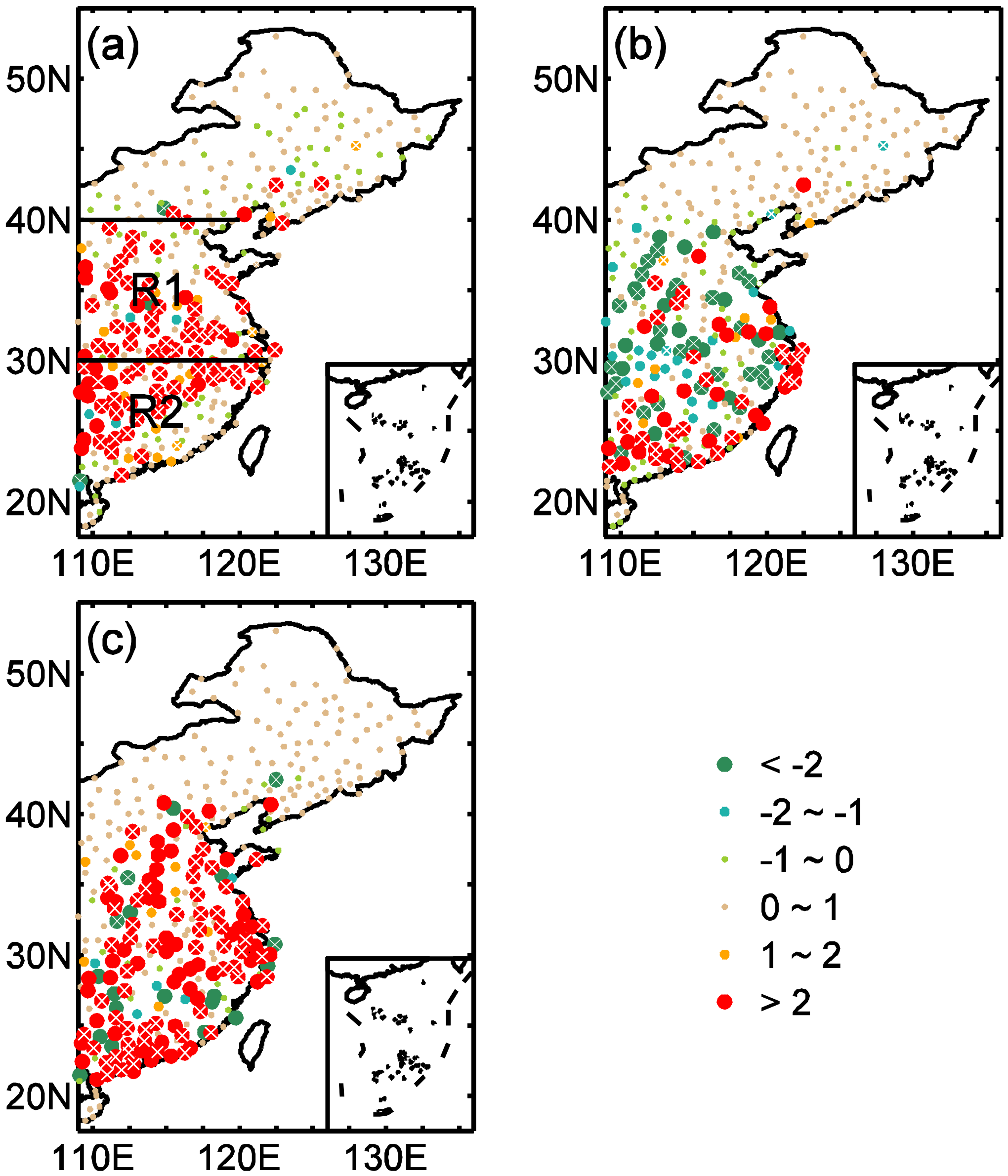


Figure 1. Linear trend of station winter haze days in the three periods: (a) 1960-1979, (b) 1980-1999, and (c) 2000-2012. R1 and R2 are the two regions that discussed in the text. The circle with cross means the change is significant at the 95% confidence level. Units: day·year^{-1}.

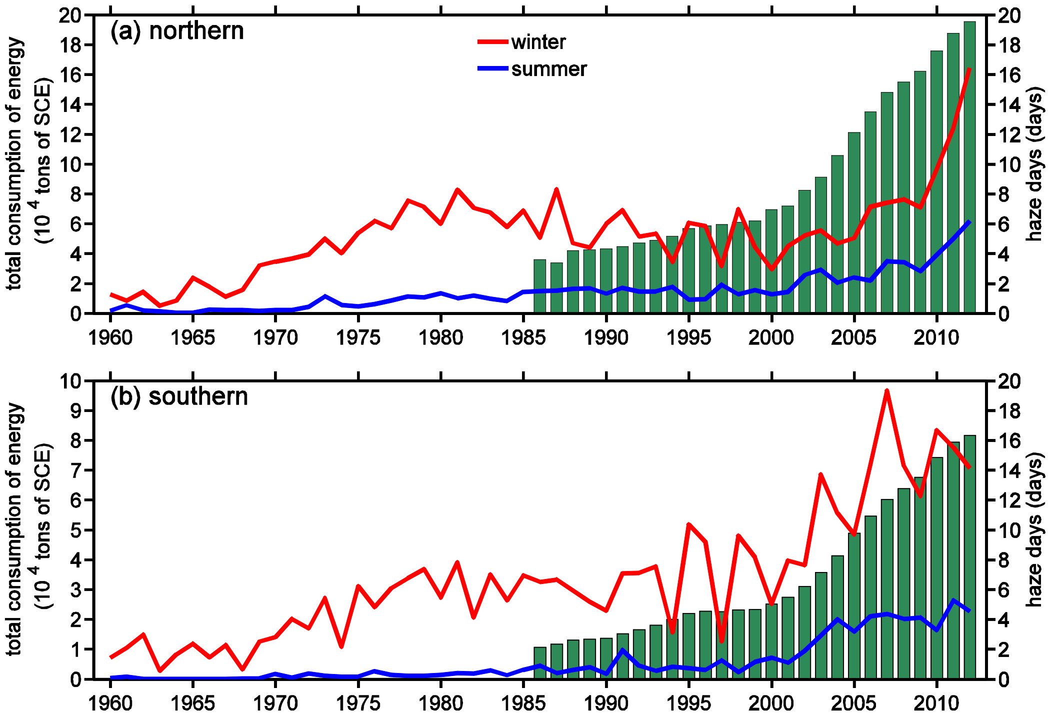


Figure 2. Time series for winter haze days (red curve), summer haze days (blue curve) and total energy consumption (bar) for (a) region R1 (30^{o}N-40^{o}N) and (b) region R2 (south of 30^{o}N) in east of 109^{o}E of mainland China.

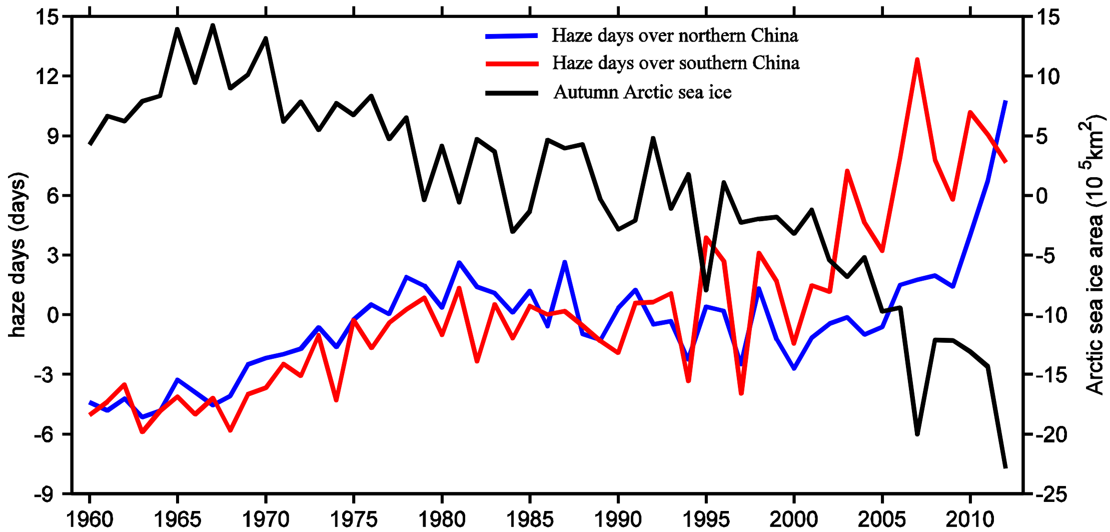


Figure 3. Temporal variations of winter haze days (WHD) for R1 (blue) and R2 (red), and autumn Arctic sea ice extent (ASI) (black). The results of correlation coefficient (CC) analysis are: CC(WHD-R1, WHD-R2)=0.75 in 1960-2012 and 0.58 in 1980-2012; CC(WHD-R1, ASI)= -0.70 in 1960-2012 and -0.60 in 1980-2012; CC(WHD-R2, ASI)= -0.87 in 1960-2012 and -0.82 in 1980-2012.

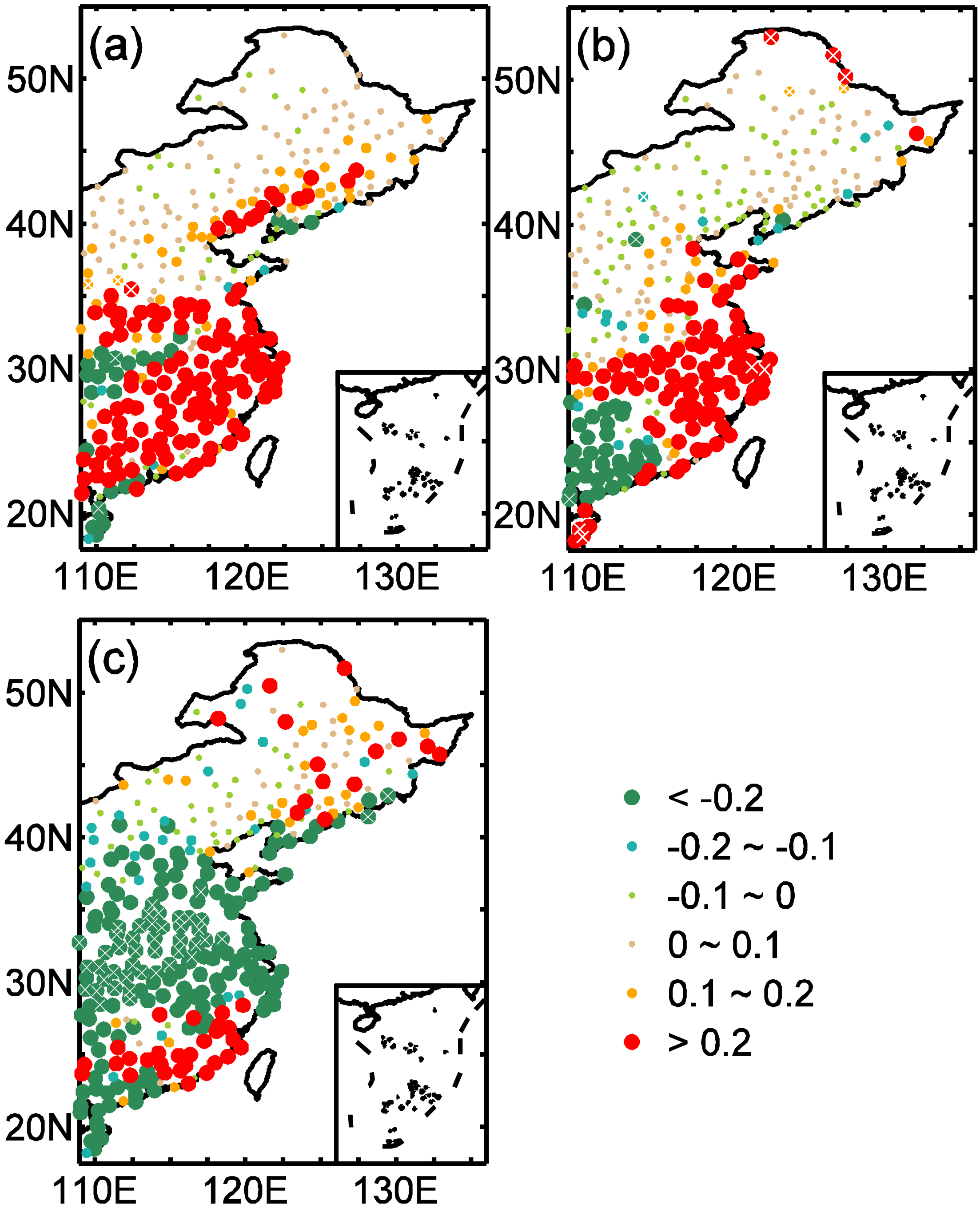


Figure 4. Linear trend of station winter precipitation (mm/day) in the three periods: (a) 1961-1979, (b) 1980-1999, and (c) 2000-2011. The circle with cross means the change is significant at the 95% confidence level.

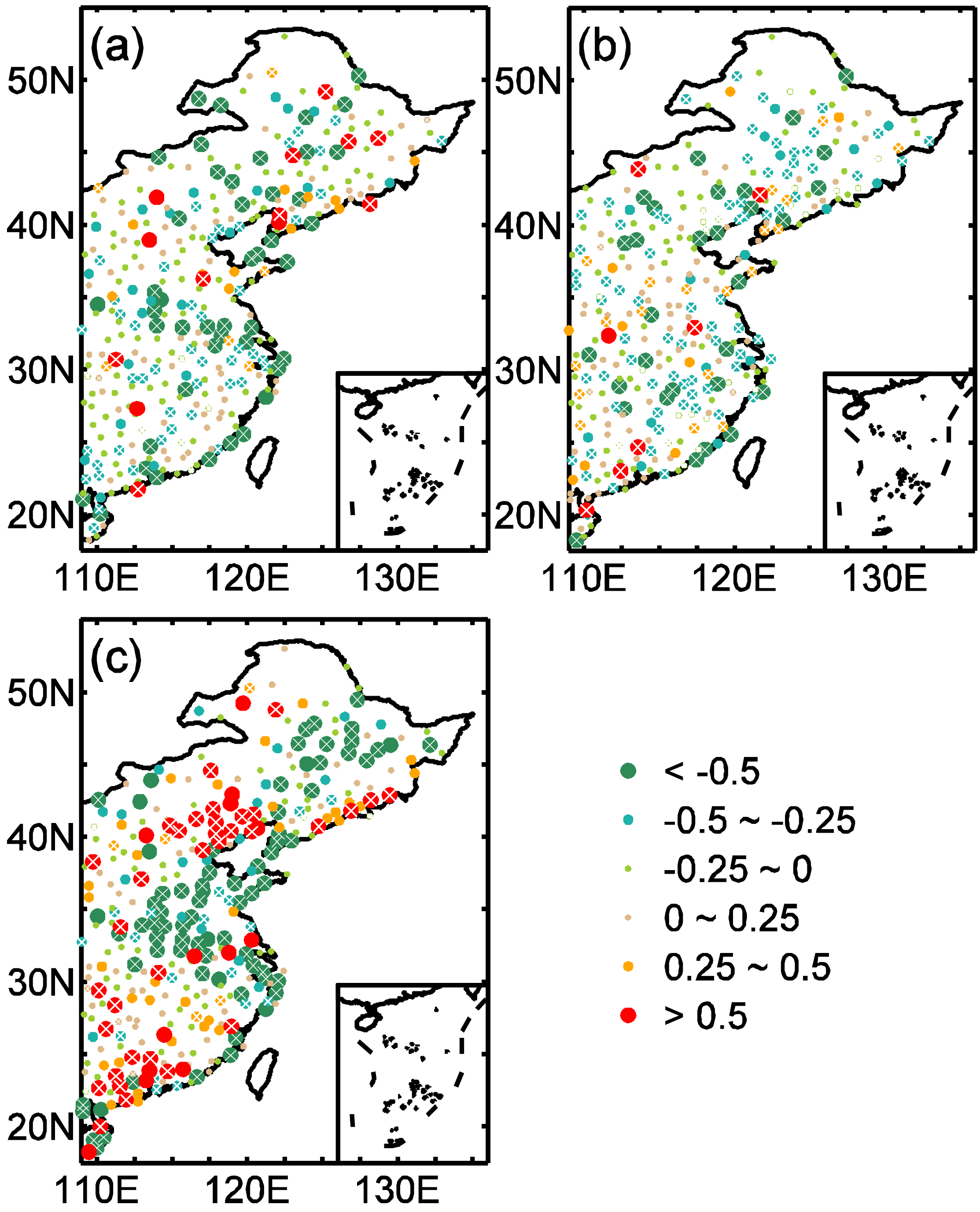


Figure 5. Same as in Figure 4 but for the winter surface wind speed (m/s).

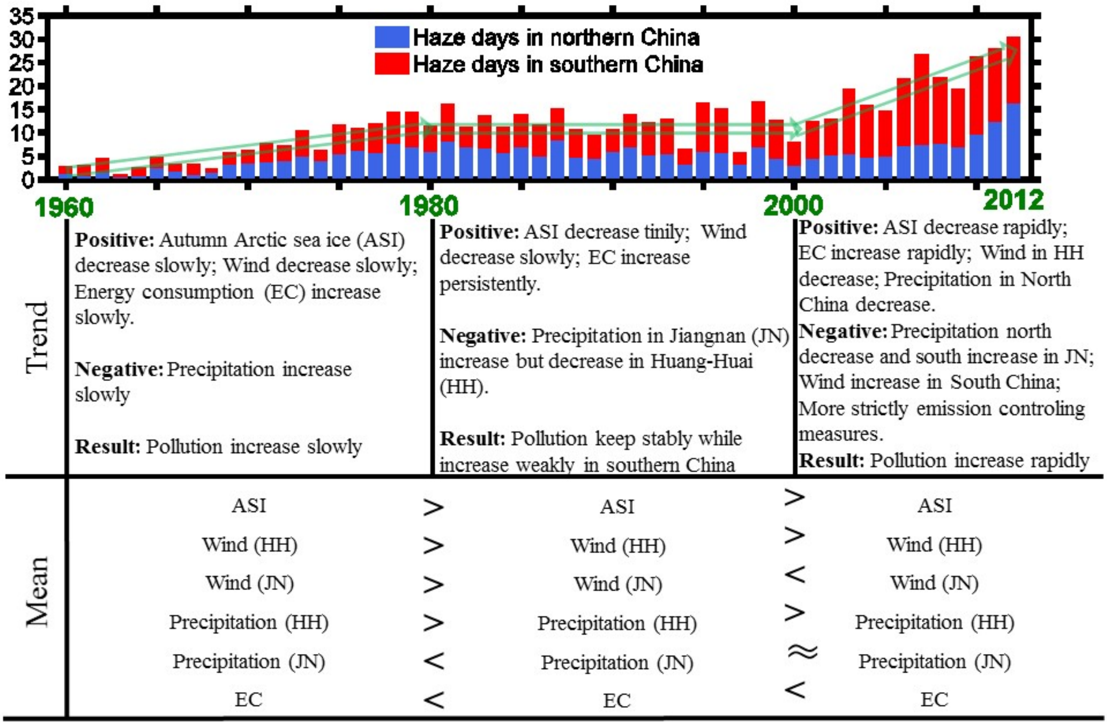


Figure 6. Summary of the haze pollution change in eastern China and various influencing factors including climate change. The time series for winter haze days and their linear trends are plotted on the top. The signs of “>” mean “larger than”, “<” mean “less than”, and “≈” mean “equivalent”. The comparisons are implemented among these three periods, i.e. the second period is relative to the first period and the third period is relative to the second period.