Increase of wintertime fog in China: Potential impacts of weakening of the Eastern Asian monsoon circulation and increasing aerosol loading

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[1] Fog is a severe weather hazard that greatly influences traffic and daily life with potentially heavy economic loss. An increasing number of traffic accidents caused by fog have been reported in China in recent years. In this study, we show that the frequencies of fog events in wintertime over eastern-central China have doubled over the past three decades. For the same period, surface wind speeds have dropped from 3.7 m/s to about 3 m/s and the mean number of cold air outbreaks has decreased from 7 to around 5 times per winter; relative humidity and the frequency of light wind events have also increased significantly. Weakening of the East Asian winter monsoon system appears to be responsible for these changes. The weakened East Asian winter monsoon circulation brings less cold and dry air to the region, reduces wind speed, and favors the formation of fog. The regional increase in atmospheric aerosol loading may also change the regional circulation pattern, creating favorable conditions for fog. This hypothesis is tested using the National Centers for Environmental Prediction (NCEP) reanalysis data and model simulations with the National Center for Atmospheric Research Community Climate Model (NCAR/CCM3). The analyses show that the 500hPa trough in East Asia has shallowed over the past three decades. Meanwhile, the surface Siberian high has weakened which is likely the cause for the diminishment in speed of the prevailing northwesterly winds and the reduction in intrusions of dry and cold air from the northwest. The increase in atmospheric aerosols was shown to heat the atmosphere and generates a cyclonic circulation anomaly over eastern-central China. This circulation anomaly also leads to a reduction in the influx of dry and cold air over eastern-central China. These effects are responsible for the increased convergence of water vapor therein. All these changes favor the formation and maintenance of fog over this region.

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1. Introduction

[2] Heavy fog, which may extend over tens to hundreds of kilometers and last for several days, is a major weather hazard in winter in northern China. Not only does fog reduce visibility and cause accidents, it also affects human health, especially for people with respiratory problems. Fog is more likely to occur when wind speed is low, relative humidity is high and surface temperature is low [*Sachweh and Koepke*, 1995; *Niu et al.,* 2009]. Case studies [*Zhang et al.*, 2005; *Pu et al.*, 2008] also showed that in a stable boundary layer with temperature inversion, low-level warm air advection with sufficient water vapor makes fog persist for a longer time. These studies suggest that the change in the frequency of wintertime fog events may be highly related to meteorological conditions, which are greatly influenced by wintertime cold front activities and ultimately by the variation in the East Asia winter monsoon. Attempts have been made to discover the dynamic and thermodynamic conditions favoring the formation, maintenance and dissipation of fog in China [*Niu et al.*, 2009].

[3] The East Asian winter monsoon, characterized by strong winds from the northwest and outbreaks of cold air

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over northern China, has dramatically changed during the last several decades, which is the subject of a number of studies [*Guo*, 1994; *Xu et al.*, 1999; *Shi*, 1996]. Since the mid-1980s the East Asian winter monsoon has significantly weakened. In the meantime, winter surface temperatures in northern China have increased, resulting in 17 consecutive significantly warmer winters in China on record up to the year 2000 [*Wang*, 2006]. During the same period, both wind speed and the frequency of windy days decreased [*Xu et al.*, 2006]. These systematic changes are likely a response to the external forcings such as changes in tropical sea surface temperature (SST), global or regional scale warming, or aerosol forcing.

[4] Global warming is most significant in the middle to high latitudes during the Eurasian winter season [*Flato and Boer*, 2001]. The reduced thermal contrast between middle and high latitudes may lead to weak winter monsoon as revealed by several studies [*Hori and Ueda*, 2006; *Hu et al.*, 2000, 2003; *Kimoto*, 2005]. Meanwhile, in China, aerosol loading has increased dramatically since the 1970s [*Luo et al.*, 2001]. This increase has the potential to affect regional climate via its direct and indirect effects [*Ramanathan et al.*, 2001; *Li*, 2004; *Qian and Giorgi*, 1999; *Qian et al.*, 2003; *Li et al.*, 2007b; *Gu et al.*, 2010]. By reducing the amount of solar radiation reaching the ground that can amount to 25 Wm^{-2} on daily and monthly mean in China [e.g., *Li et al.*, 2007c] and diminishing the ocean-land temperature contrast, aerosols were found to spin-down the Asian monsoon circulation and water cycle [*Ramanathan et al.*, 2001]. Using coupled atmosphere-ocean general circulation models, *Ramanathan et al.* [2005] and *Lau et al.* [2008] demonstrated that aerosols have significantly changed the South Asian monsoon system during the summer although the mechanisms they proposed are somewhat different [*Lau and Kim*, 2006; *Chung and Ramanathan*, 2006]. *Menon et al.* [2002] showed that absorbing aerosols may enhance the upward motion in southern China and increase precipitation during the summer monsoon season. Less attention has been paid to changes in the East Asian monsoon during the winter season and the impact of aerosols on winter fog events. It is worth noting that other factors such as tropical ocean warming, forcing of the Tibetan plateau, and internal variability may also influence the East Asian monsoon system [*Zhou et al.*, 2009; *Lau et al.*, 2006; *Wu et al.*, 2009; *Li et al.*, 2010; *Wang et al.*, 2008; *Zhu and Wang*, 2002; *Jhun and Lee*, 2004]. Some observational results cannot be explained solely by aerosol effects [*Yu and Zhou*, 2007; *Yu et al.*, 2004]. This study does not rule out the influences of these factors, although we mainly focus the potential influences of aerosols and global scale warming.

[5] In this study, we analyze trends in the frequency of fog events, relative humidity, and the frequency of light winds, together with changes in the general circulation pattern, to examine how weakening of the East Asian winter monsoon and aerosols may influence winter fog over northern-central China. In the following section, data sets used are described. Section 3 presents results from the analysis of trends in fog occurrence and associated meteorological variables, as well as the pattern of regional general circulation. Based on these analyses, a hypothesis is made and tested by means of model simulations using the National Center for Atmospheric Research Community Climate Model (NCAR/CCM3) regarding the role of aerosols, which is given in Section 4. Section 5 summarizes the study.

2. Data

[6] The meteorological data used in this study were obtained from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA). This data set provides hourly meteorological records, including surface temperature, dew point temperature, wind speed and "present weather," from the 1950s to 2007. "Present weather" describes weather events such as rain, snow, fog, clouds and other important types of weather phenomena. Daytime data from 1976 to the present are used in this study because many gaps exist in earlier records due to instrument malfunctions [*Liu et al.*, 2004]. Three hundred and ninety sites with more than 20 years' worth of data were used in this study.

[7] Large-scale meteorological variables such as geopotential heights, sea level pressure, surface wind and water vapor were obtained from the National Centre for Environmental Prediction (NCEP) reanalysis which is a retroactive record of more than 50 years' worth of global analyses of atmospheric fields [*Kistler et al.*, 2001].

3. Trends in Fog Occurrence and Influential Factors

[8] Various trend analyses were conducted. The annual frequency of fog events is calculated by dividing the number of fog observations by the total number of observations in each year. The change of it during recent 30 years is then calculated using linear regression analysis. Trends in other quantities such as wind speed and occurrence of light winds are also obtained using the same methodology. Changes in the atmospheric circulation pattern are examined in order to investigate possible causes for the changes in the frequency of fog events. Changes in 500hPa geopotential heights, sea level pressure, 850hPa wind, and low-level water vapor transport divergence between the first 13 years and the last 13 years from 1976 to 2001 were calculated on the basis of monthly mean values from NCEP reanalysis data.

3.1. Frequency of Fog, Wind Speed, and Cold-Air Surges

[9] Figure 1a shows the mean fog frequency in winter over China at 390 sites from 1976 to 2007. The fog frequency is calculated by dividing the number of fog events by the total number of observations for each station. Fog events occurred more frequently over eastern-central China, especially along the Yangtze River corridor, than over other parts of China in the past three decades. Figure 1b shows changes in the frequency of fog events (percent per year) during wintertime obtained from linear regression analysis. Of the 390 sites, the frequency of fog events significantly decreased at 128 sites, increased at 110 sites and showed no significant change at the remaining sites. The most significant increase in the frequency of fog events, with a maximum value of about 0.3 percent per year, is over eastern-central China, the most heavily populated region of the country.

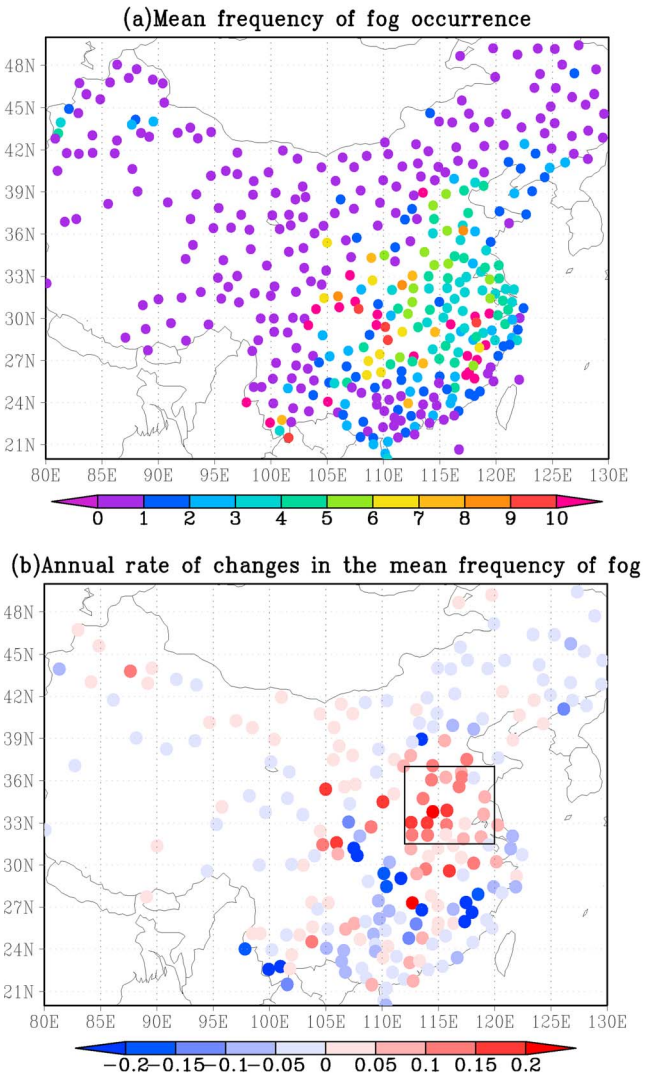

Figure 1. (a) The mean frequency of fog occurrence in winter (*100) and (b) the annual rate (percentage per year) of changes in the mean frequency of fog occurrence during wintertime over China at 390 sites from 1976 to 2007. Only stations with trends at the 5% significance level are shown in Figure 1b.

Data from the southeastern region and Sichuan basin area shows a decrease in the frequency of fog events over the same time period. There is no consistent pattern in other areas of the country.

[10] Fog usually forms over a plain under stable atmospheric conditions of light wind, sufficient moisture and low temperature [*Sachweh and Koepke*, 1995; *Zhang et al.*, 2005]. The common types of fog over eastern-central China are radiation-advection fog. Their formation requires sufficient water vapor, stable atmosphere which is often accompanied by temperature reversion, and cold land surface [*Niu et al.*, 2009]. The change in the frequency of fog events is very likely associated with changes in some, if not all, of these factors. Therefore, changes in relative humidity during this period are first examined. The geographical pattern of the change in relative humidity is very similar to that of Figure 1b, showing a significant increase over eastern-central China and a decrease over southern China (shown later in Figure 4b).

[11] During winter, the dry, cold air mass brought in by the prevailing northwesterly Siberian high pressure system is unfavorable for fog formation [*Zhang et al.*, 2005]. The time series of averaged frequency of fog events, averaged wind speed and the frequency of light winds are shown in Figure 2. The area-averaged frequency of fog events significantly increased from around 2% in 1976 to around 5% in 2007, more than doubling during the last 30 years. During the same period, the area-averaged wind speed reduced from about 3.7 m/s to about 3 m/s. Correspondingly, the frequency of light winds (wind speeds less than 1.6 m/s) increased from 9% in the 1970s to 14% in the beginning of the twenty-first century. The trends in Figure 2 are significant at larger than 95% confidence levels.

[12] The decrease in wind speed and increase in the occurrence of calm atmospheric conditions may suggest a weakening of the East Asian winter monsoon. As the East Asian winter monsoon weakened, the frequency of cold surges from the north also dropped. A variety of definitions for cold surges, such as changes in surface temperature, surface pressure, and wind speed, have been used [*Wang*, 2006]. The frequency of cold surges here is defined as the number of times in each winter season that the daily averaged surface temperature drops by more than 4°C from the previous day. Figure 2b shows the time series of the frequency of cold surges and averaged wind speed. The area-averaged frequency of cold surges decreased from about 7 to about 5 times per winter during the recent past 30 years. This trend also has a confidence level of over 95%.

3.2. Change in the General Circulation Pattern

[13] The decrease in wind speed over East Asia is corroborated by a similar decrease in various East Asian winter monsoon indices [*Gao*, 2007]. These indices include land and sea pressure differences [*Shi*, 1996], regionally averaged meridional winds in the lower troposphere [*Ji et al.*, 1997; *Chen et al.*, 2001], zonal winds in the higher troposphere [*Jhun and Lee*, 2004], and the strength of the East Asian trough [*Sun and Sun*, 1995]. These findings suggest that weakening of the East Asian winter monsoon may be associated with climate changes on a broader scale. General circulation pattern changes are examined by using NCEP reanalysis data from 1976 to 2001 in order to determine any relation between the frequency of fog events and the strength of the East Asian winter monsoon indices.

[14] As one of the most important atmospheric systems active in Eurasia during the winter months, the Siberian High has a direct and significant impact on the East Asian winter monsoon circulation, particularly on sea level pressure and northerly winds along the East Asian coast [*Wu and Wang*, 2002]. Figure 3a shows the mean sea level pressure and 850hPa wind vectors during winter seasons from 1976 to 2001. The winter monsoon circulation advects cold air masses from Siberia to the East Asian continent and more southerly regions. The prevailing weather episodes in winter in East Asia are outbreaks of cold-air surges which are marked by the invasion of extremely cold and dry air from the northwest [*Wang*, 2006].

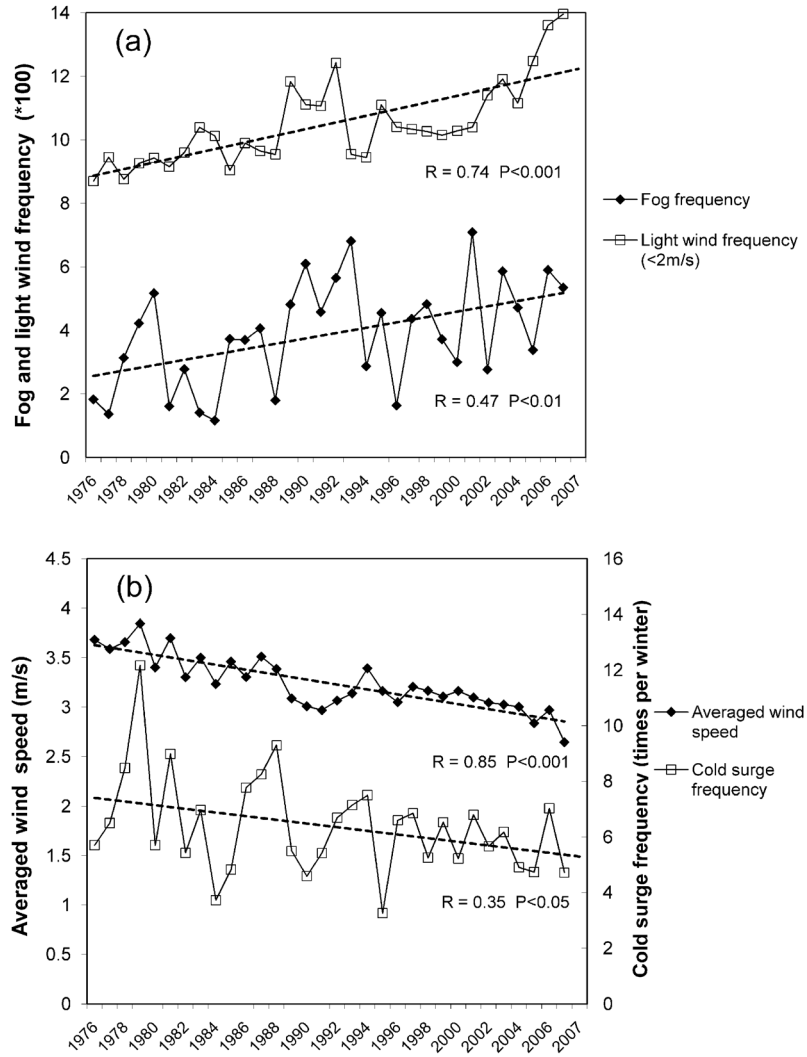

Figure 2. Time series of (a) mean frequencies of fog occurrence and light wind and (b) the frequencies of cold-air surges and mean wind speed over the boxed area in Figure 1b.

[15] Figure 3b shows the differences in mean sea level pressure and 850hPa wind (or anomalous flow) from 1976 to 2001 (the mean from 1989 to 2001 minus the mean from 1976 to 1988). The Siberian high appears to have weakened over the course of the past 26 years. In most areas, the anomaly wind vector is opposite to the prevailing wind which suppresses the prevailing wind; this is consistent with surface observations [*Xu et al.*, 2006]. Over the eastern-central China region, the change in sea level pressure is accompanied by a wind anomaly from the southeast direction along the eastern coastal area and a wind anomaly from the north in southern China. This results in the transport of less dry and cold air to eastern-central China but more to the southern parts of China. Such changes may explain the increase in relative humidity and fog frequencies over eastern-central China and the decrease of these quantities in the southeastern region.

[16] The above explanation is also corroborated by the change in water vapor transport divergence. Water vapor transport divergence is defined as $\nabla \cdot qv$, where q is the water vapor mixing ratio and v is the horizontal velocity of the air [*Houghton*, 1985]. Since fog and relative humidity are observed near the surface, only the water vapor transport divergence in the lower atmosphere from the surface to 850hPa was calculated. The rate of its change during the past 26 years is shown in Figure 4a (difference between 1989 and 2001 and 1976–1988). Note that a positive value means that water vapor has diverged and vice versa. Water vapor convergence over eastern-central China and water vapor divergence over southern China correspond to an increase and decrease in the frequency of fog events and in relative humidity in the two regions (Figure 4b), respectively. The above results suggest that the increase in the frequency of fog events in recent years is highly related to changes in wind speed and direction and water vapor fluxes due to the circulation change.

4. Ultimate Force Driving the Change

[17] While changes in the aforementioned variables are linked to the increasing trend of fog occurrence, they are not the ultimate forces driving the trend, as their own changes

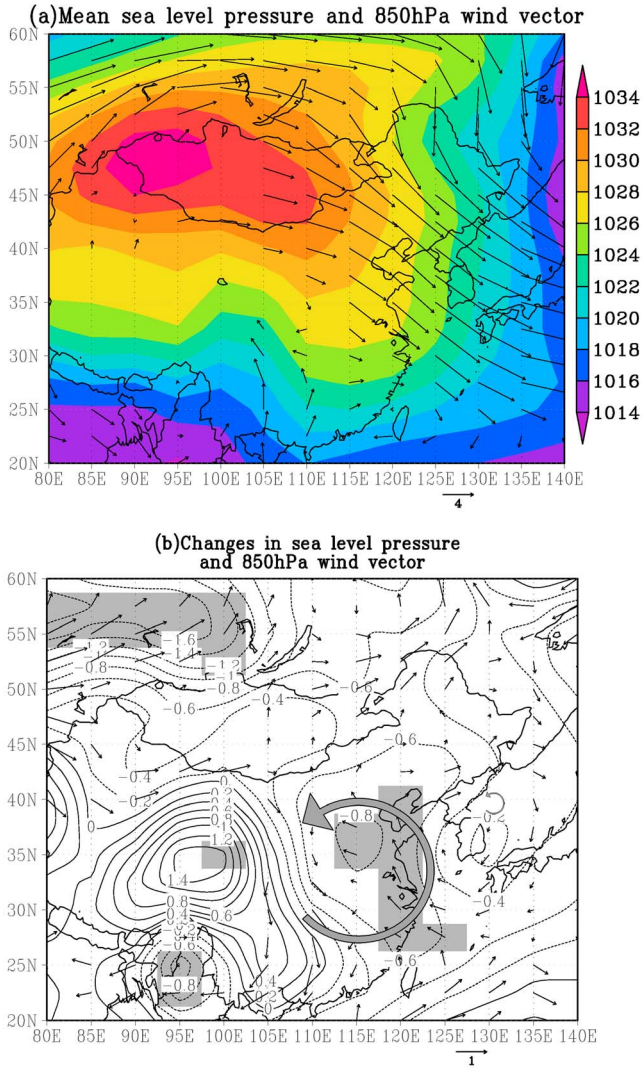

Figure 3. Wintertime sea level pressures (hPa) and 850hPa wind vectors (m/s) from the NCEP reanalysis: (a) mean values from 1976 to 2000, and (b) the difference (1989–2000 minus 1976–1988). Wind vectors over topography higher than 850hPa are masked out. Shaded areas are at the 5% significance level.

are likely responses to certain external forcings such as greenhouse gases and aerosols. This argument is reached after an extensive survey of previous global warming studies based both on models and observations and our own modeling results concerning the effect of aerosols on the factors that influence fog occurrence. Admittedly, we cannot rule out the possibility that these changes result from natural variations, but it is safe to point to the possibility that the changes were affected to some degree by the steady and dramatic increase of the two primary external forces in this region.

4.1. Global Warming Effect and Other Factors

[18] Previous model simulations and ground-based measurements demonstrated that global warming is more pronounced at high latitudes than at low latitudes [*Delworth and Knutson*, 2000; *Min et al.*, 2004; *Flato and Boer*, 2001]. The reduced thermal contrast between south and north diminishes the transport of energy through baroclinic waves and diminishes the strength of troughs and ridges as seen in the change of 500hPa geopotential heights shown in Figure 5. Geopotential heights in the trough region are increased. Behind the trough and near the surface, the associated high pressure system is weakened (Figure 3b). As a consequence, the transport of cold air originating from the East Asian trough at high latitudes becomes less powerful, which is a key indicator of the weakening winter monsoon in East Asia. Such arguments have been supported by many observational and modeling studies [*Hori and Ueda*, 2006; *Xu et al.*, 2006; *Hu et al.*, 2000, 2003; *Kimoto*, 2005]. Meteorological records from the past three decades [*Xu et al.*, 2006] reveal that surface wind speed has decreased steadily. Yet, the change is negatively correlated with near-surface air temperature, which suggests a possible relationship between wind speed

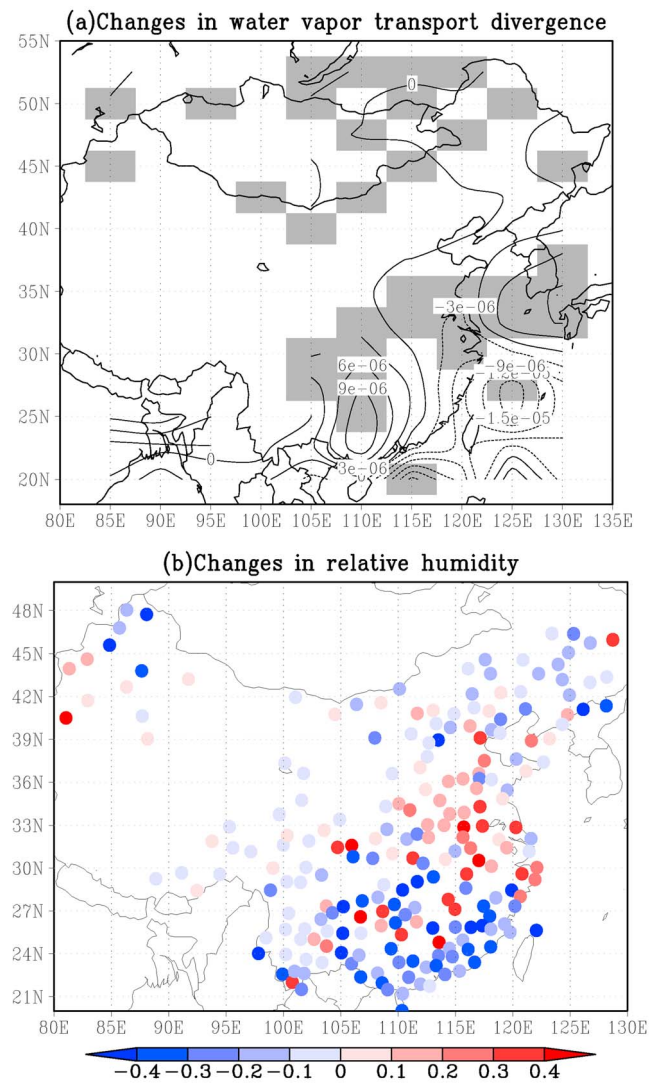

Figure 4. Changes in (a) water vapor transport divergence (contours, unit: kg/kg/m^2/s) below 850hPa and (b) relative humidity (%). Shaded areas are at the 5% significance level. Only stations with trends at the 5% significance level are shown in Figure 4b.

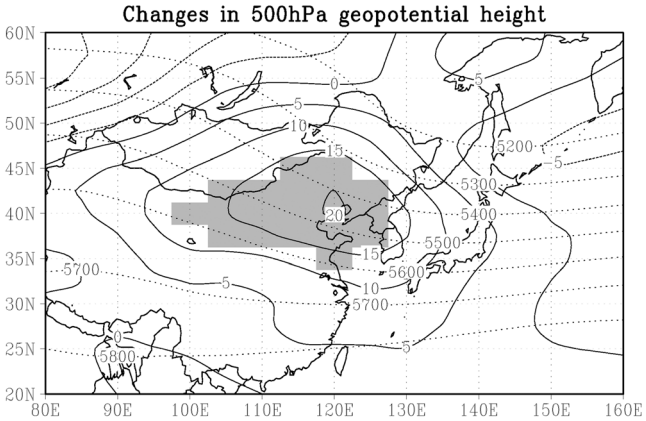

Figure 5. Changes in 500hPa geopotential height (contours, unit: m) from NCEP reanalysis (1989–2001 means minus 1976–1988 means). The dotted lines are averaged 500hPa geopotential heights from 1976 to 2001. Shaded areas are at the 5% significance level.

reduction and regional and global warming. The observed changes in surface temperature, wind speed and relative humidity in eastern-central China are generally consistent with the projected change under the global warming scenario [*Hu et al.*, 2000, 2003]. *Kimoto* [2005] showed that under the global warming scenario, the weakened winter monsoon is associated with the shallower and northeastwardly shifted planetary wave trough over the east coast of the Eurasian Continent. *Hori and Ueda* [2006] and *Hu et al.* [2000] showed that the weakening of the East Asian winter monsoon is a result of global warming. However, other factors such as the forcing of the Tibetan Plateau, snow cover over Eurasian continent, tropical SST, and the Arctic Oscillation were also shown to influence the East Asian winter monsoon [*Murakami*, 1987; *Watanabe and Nitta*, 1999; *Zhang et al.*, 1997; *Wang et al.*, 2000; *Gong et al.*, 2001]. These results indicate that planetary-scale features such as the tropical convective center near the western Pacific, the Siberian high, and the 500hPa trough and ridge over East Asia are inherently related to each other to influence the East Asian winter monsoon. Global warming together with these factors therefore appear to contribute to the change in the frequency of fog occurrence. There is no consensus on which one is dominant.

4.2. Regional Aerosol Effect

[19] Aerosol loading over China has increased since the 1960s, as inferred from ground-based radiation measurements [*Luo et al.*, 2001; *Kaiser and Qian*, 2002]. Figure 6a shows mean MODIS aerosol optical depths (AOD) during wintertime periods from 2000 to 2008. The large gray area represents bright surfaces over which there are no satellite retrievals. Most strikingly, AOD is largest in eastern China where the population density is highest and where economic growth is fastest in the country. Meteorological records showed that the frequency of clean atmospheric conditions in eastern-central China has continuously declined over the past 30 years (Figure 6b). Here, visibility is used as a proxy of clean atmospheric conditions: higher than a threshold corresponding to 75% of the maximum visibility observed at a particular location. Fog events, which also reduce visibility, are excluded in calculating the frequency of clean atmospheric conditions. The average frequency of clean atmospheric conditions over eastern-central China in winter decreased from around 26% to around 14% from 1976 to 2007. Moreover, the aerosols over eastern-central China are highly absorbing based on several studies on aerosol single scattering albedo (SSA) using a variety of retrieval methods [*Zhao and Li*, 2007; *Lee et al.*, 2007; *Xia et al.*, 2006]. For example, *Xia et al.* [2006] reported that the mean SSA in Beijing is around 0.9 at 550nm wavelength in all seasons and is even lower in winter based on 33 month observations by a CIMEL radiometer. The nationwide value of SSA retrieved from a Sun photometer network is 0.89 ± 0.04 according to the study of *Lee et al.* [2007]. Such high absorbing aerosols may heat the atmosphere, also generate a cyclonic circulation anomaly as shown in the NCEP reanalysis data, and therefore affect the fog formation.

[20] To quantify such aerosol effect, we employed the National Center for Atmospheric Research's Community Climate Model (CCM3), which is easy to use and performs soundly. It was run at the T42-L26 resolution of 2.8° by 2.8° with 26 vertical layers. The model contains an annually cyclic tropospheric aerosol climatology consisting of three-dimensional, monthly mean distributions of aerosol masses for sulfate, sea salt, black and organic carbon, and soil dust. It was generated using the Model for Atmospheric Chemistry and Transport (MATCH) which assimilates satellite-retrieved AOD from the NOAA Pathfinder II data set [*Stowe et al.*, 1997], integrated to present-day conditions [*Collins et al.*, 2001, 2002; *Rasch et al.*, 1997]. The mass concentrations of different aerosol species were modified by scaling the AOD climatology based on the MODIS Collection 5 AOD product whose quality has been validated in the region [*Li et al.*, 2007a; *Mi et al.*, 2007]. The original aerosol vertical distribution and aerosol components are retained. The climatological annual cycle of sea surface temperature was used in the model. Two types of model simulations were conducted: with and without anthropogenic aerosols over China as experimental and control runs, respectively. In the experiment without anthropogenic aerosols, the sulfate, black carbon and organic carbon aerosols were removed. In the experiment with anthropogenic aerosols, all types of aerosols were kept. In the model, the column mass concentration of BC accounts for about 4% of total column mass concentration of aerosols, while the column mass concentration of sulfate aerosols accounts for about 30% in all seasons. In winter, BC accounts for about 8% of the total column mass concentration and sulfate accounts for about 44%. The annual mean and wintertime aerosol single scattering albedo (SSA) over eastern China (105°E–120°E, 20°N–45°N) from model outputs are around 0.92 and 0.90, respectively. In both experiments, the sea surface temperature, green house gases and other forcing were the same. Each of the experiments was run for 20 years and the model outputs for the last 10 years (in equilibrium) were averaged. The differences of the outputs from these two experiments were used to demonstrate the changes caused by anthropogenic aerosols. Note that the model does not include aerosol indirect effects so any differences can only illustrate the potential impact of aerosols on atmospheric dynamics through radiative transfer processes.

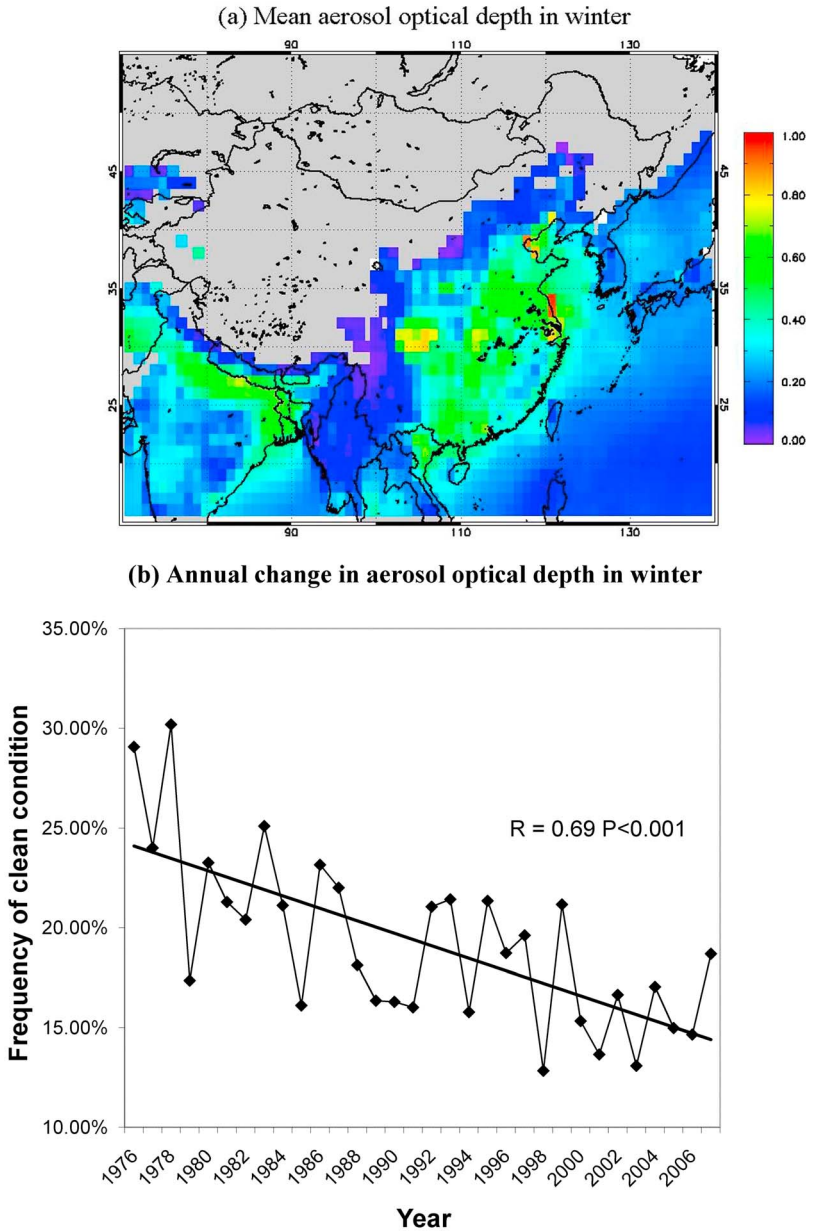

Figure 6. (a) Mean MODIS AOD in winter and (b) the change in the frequency of clean atmospheric conditions in eastern-central China from 1976 to 2007.

[21] All meteorological variables (temperature, pressure, precipitation, radiation, etc.) are output and analyzed, but only those variables that are of direct importance to fog occurrence and maintenance are presented and discussed here, as illustrated in Figure 7. Figure 7a shows the annual mean of AOD from MODIS during 2000–2008. AOD is very high at several locations including eastern-central China, the Sichuan basin, and the southern coastal region. The blank areas without MODIS retrievals are substituted by data from the original data set in the CAM model. Figure 7b shows the mean sea level pressure and 850hPa winds from the model simulation. The pattern is very similar to Figure 3a with the Siberian high located over the Mongolia region and the prevailing northwest wind over eastern-central China. This indicates the model captures the most important feature of the winter monsoon circulation. However, a discrepancy in wind direction over southern China is noted between the model simulation and the NCEP reanalysis data, implying some detailed features missing in the model. The comparison of the mean surface temperature between the model (in which surface temperature means radiative surface temperature) and reanalysis is presented in Figures 7c and 7d. The model simulated surface temperature very well with only slight overestimations over the Mongolia and the Tibetan regions. The magnitudes of the standard deviations of them are almost the same. However, the simulated specific humidity is not as good as the surface temperature. The model overestimates specific humidity in the south over ocean but underestimate it in the south over land (Figures 7e and 7f).

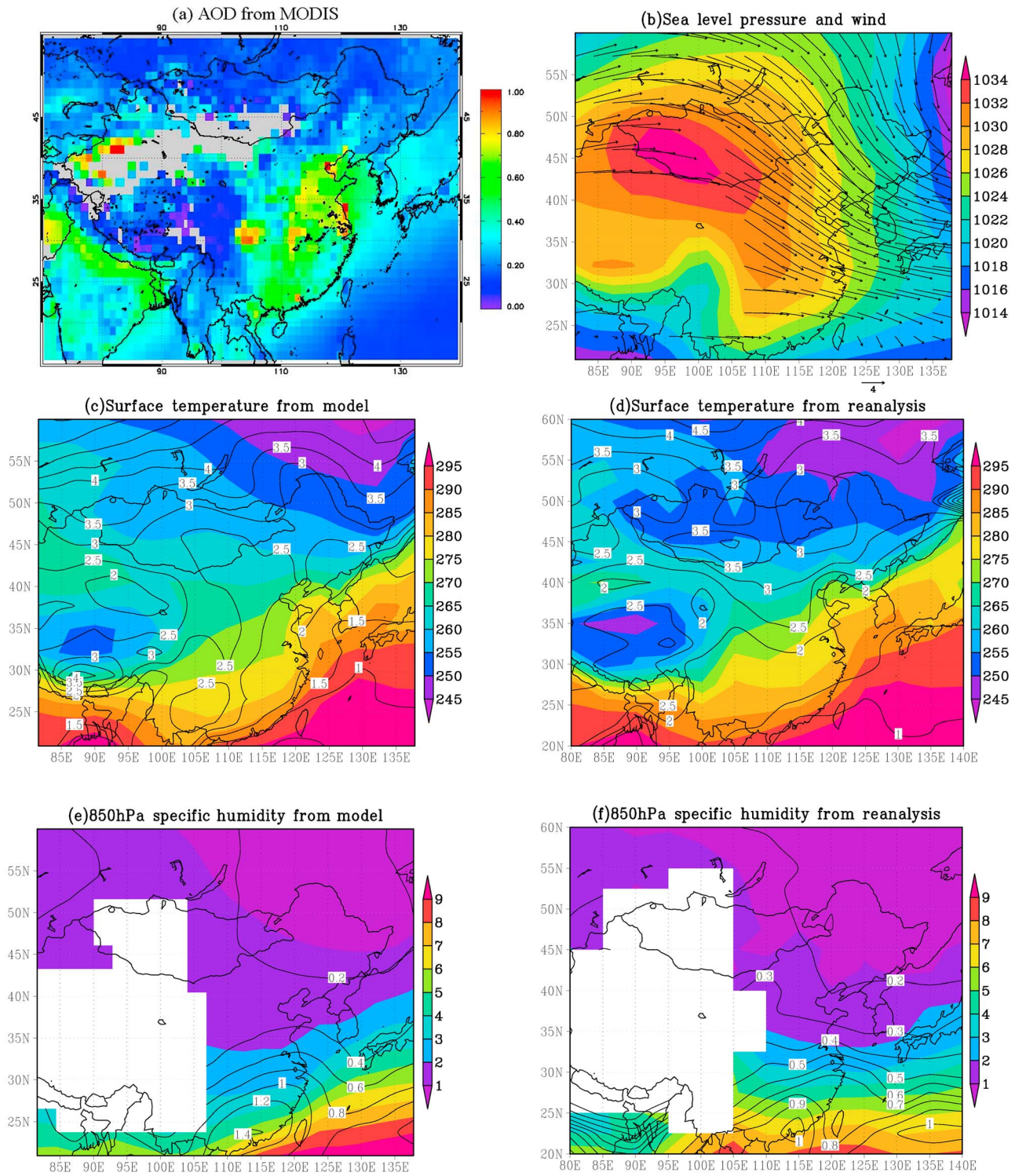

Figure 7. Mean states of (a) AOD used in forcing the model from MODIS in all seasons during 2000–2008; (b) the sea level pressure (hPa) and 850hPa wind vectors (m/s) from the model simulation; surface temperature (K) from (c) the model simulation and (d) NCEP reanalysis data; and 850hPa specific humidity (kg/kg*1E3) from (e) the model simulation and (f) NCEP reanalysis data in winter. All the model results are from the simulation with anthropogenic aerosols. The contours are the standard deviations of the means. Values over topography higher than 850hPa were masked out in Figures 7e and 7f.

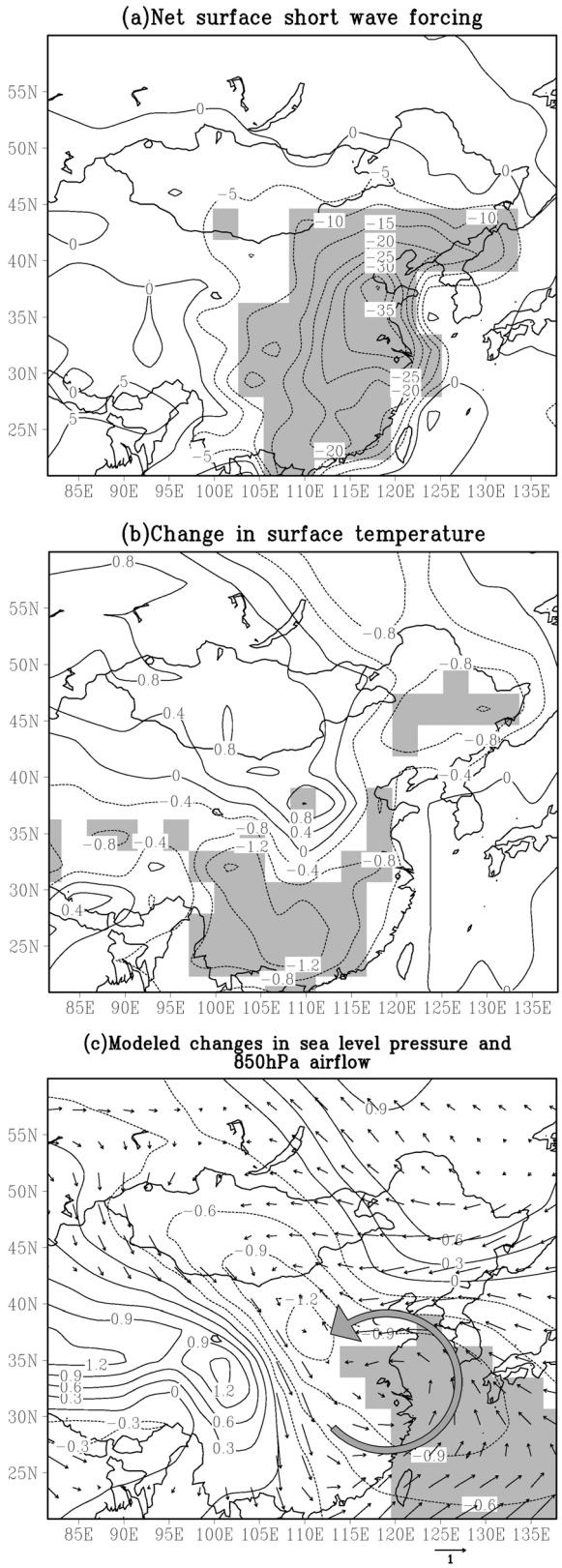

Figure 8. (a) Net surface shortwave forcing (W/m^2) and changes in (b) surface temperature (°C) and (c) sea level pressure (contours, unit: hPa) and 850hPa wind (arrows, unit: m/s) in winter caused by anthropogenic aerosols. Shaded areas are at the 10% significance level.

[22] Figure 8 presents the changes in surface short wave fluxes (8a), surface temperature (8b), sea level pressure, and 850hPa wind (8c). The differences between the two experiments with and without anthropogenic aerosols are used to show the changes caused by anthropogenic aerosols. As expected, aerosols greatly reduce the amount of shortwave radiation reaching the surface. The maximum reduction is greater than 30 W/m^2 over eastern-central China where the aerosol optical thicknesses are high (Figure 6a). However, the change in surface temperature does not follow exactly the pattern of the change in shortwave flux reaching the ground. Surface temperature is lowered more in southern China than in northern China and is presumably caused by an aerosol-induced circulation change (discussed later), as well as the amount of solar radiation that is higher in the south than the north. As a result, the reduction in solar radiation by the same amount of aerosol loading is larger in the south than in the north. The maximum reduction is over 1.5°C in the Sichuan

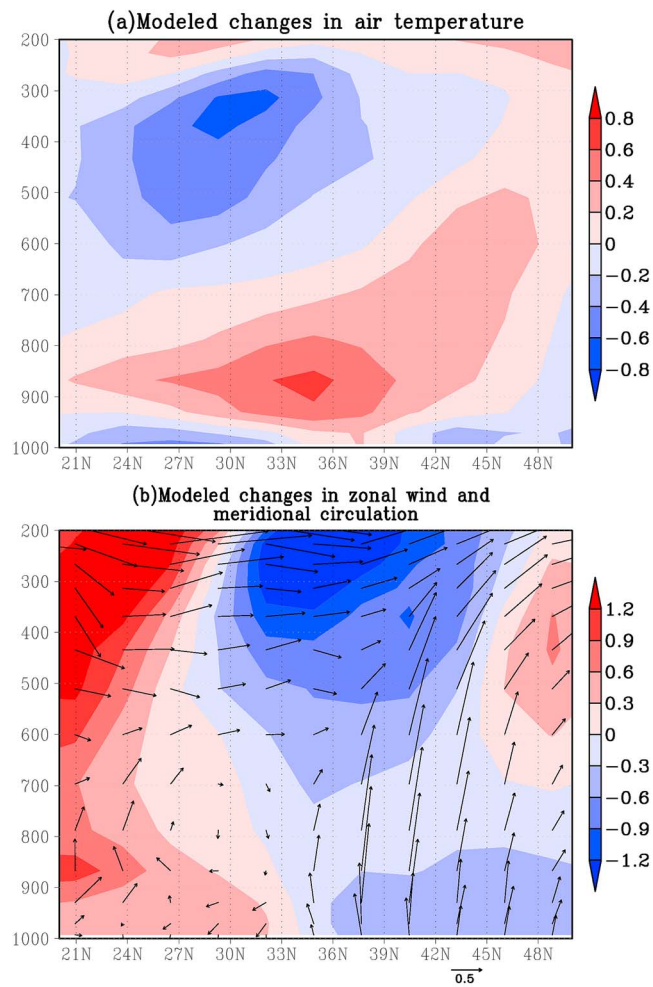

Figure 9. (a) Changes in air temperature and (b) zonal wind (shaded areas, unit: m/s) and meridional circulation (arrows, unit: 10^{-4} hPa/s for pressure velocity and m/s for meridional wind speed) averaged from 110°E to 120°E in winter from model simulations.

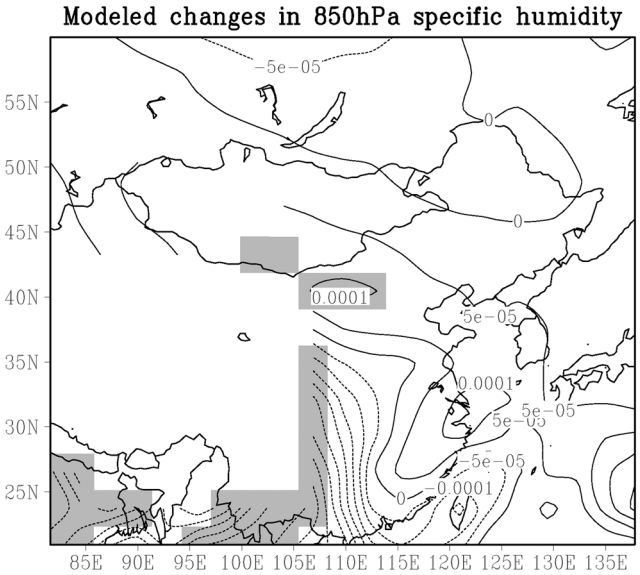

Figure 10. Changes in 850hPa specific humidity (kg/kg) in winter caused by anthropogenic aerosols. Shaded areas are at the 10% significance level.

basin region where AOD is always high (Figures 6a and 7a). It is worth noting that China's industrialization and modernization dated back to the turn of the 1970s/1980s. Prior to this period, industrial activities were not as prevalent and thus less anthropogenic aerosols, especially secondary aerosols, would have been generated. Such a regional impact of anthropogenic aerosols on the East Asian monsoon circulation could be significant over the past several decades. A cyclonic anomaly flow is induced by aerosols over eastern-central China (Figure 8c). The anomaly flow along the eastern coastal region from the southeast weakens the invasion of dry and cold air from the north. But the anomaly flow in central China from the northwest brings more cold air to the south. This is also one reason why the surface temperature decreases greatly over this region. Again, the distribution of the pressure anomaly (difference in sea surface pressure between the control and experimental runs) grossly resembles the difference in NCEP pressure fields between the same two periods (1989–2001 minus 1976–1988) (Figure 3b), although the Siberian high does not change as much as that from the NCEP reanalysis data.

[23] To further explore the causes for such changes, the mean latitude-height distributions of the temperature change, the meridional circulation anomaly and the zonal wind change over 110°E–120°E longitude regions are shown in Figure 9. It is seen that aerosols greatly heat atmosphere in the lower troposphere centered around 35°N but cool the surface (Figure 9a). Significant heating takes place between 900hPa and 800hPa with the maximum increase of air temperature over 0.8°C. This leads to the upward motion in the north of 34°N and a cyclonic circulation anomaly as shown in Figure 8c. The cyclonic circulation anomaly weakens the prevailing northwesterly wind over eastern-central China but enhance the northerly wind over southern China. The large temperature drop over southern China is caused by such enhanced northerly wind. Correspondingly, the zonal wind speed also decreases in the north but increases in the south (Figure 9b). Such a circulation change favors the formation of fog in the north but not in the south. The change in 850hPa specific humidity is also shown in Figure 10. As expected, the specific humidity increase over eastern-central China but decreases over southern China. However, the changes over these regions are not very significant (at ~10% significance level) since the mean state of the specific humidity simulated by the model has relatively large standard deviations compared with the NCEP reanalysis data as shown before.

5. Summary

[24] The frequency of fog events during winter over eastern-central China has significantly increased during the past 30 years. Meanwhile, wind speed and the frequency of cold-air surges dropped but the frequency of light wind events increased. The surface relative humidity also increased dramatically over the region with a similar pattern to the change in fog frequency. These changes attest to the weakening of the East Asian winter monsoon which may be induced by several important factors such as global warming, the tropical SST anomaly, and a change in snow cover over the Eurasian region. Global-scale warming may reduce the thermal contrast between high and midlatitudes, weaken troughs and ridges of midlatitude waves, and diminish the strength of the Siberian high and the East Asian winter monsoon. This leads to less invasion of dry and cold air from the northwest (cold fronts) and lower wind speed, creating a favorable background for fog. Other factors influencing the East Asian winter monsoon are pointed out but not elaborated in detail here. The increase in atmospheric aerosols was shown to change the regional circulation as well in the same direction. High loading absorbing aerosols over China reduce the radiation at the surface but heat the atmosphere, generating a cyclonic circulation anomaly over eastern-central China, a similar pattern to that revealed from the NCEP reanalysis data. The anomaly circulation weakens the northwesterly wind over eastern-central China, but enhances the northerly wind over southern China. As such, fog is easier to form over eastern-central China than over southern China. A major difference between the observed trend from the NCEP reanalysis data and model results is the change of the Siberian high. The increased AOD over the East Asian region does not lead to the weakening of the Siberian high as observed in the reanalysis data. This result indicates that the increase of aerosols over this region may only have regional influences rather than global-scale influences such as those induced by global warming. However, the effects of global warming and aerosols may still work in harmony to explain the changes in fog frequency over eastern-central and southern China in recent three decades, although the two effects are often thought to offset each other in the context of global warming in general.

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References

Chen, W., H. F. Graf, and R. Huang (2001), The interannual variability of East Asian winter monsoon and its relation to the summer monsoon, *Adv. Atmos. Sci.*, *17*(1), 48–60.

Chung, C. E., and V. Ramanathan (2006), Weakening of North Indian SST gradients and the monsoon rainfall in India and the Sahel, *J. Clim.*, *19*, 2036–2045, doi:10.1175/JCLI3820.1.

Collins, W. D., P. J. Rasch, B. E. Eaton, B. V. Khattatov, J.-F. Lamarque, and C. S. Zender (2001), Simulating aerosols using a chemical transport model with assimilation of satellite aerosol retrievals: Methodology for INDOEX, *J. Geophys. Res.*, *106*(D7), 7313–7336, doi:10.1029/2000JD900507.

Collins, W. D., P. J. Rasch, B. E. Eaton, D. W. Fillmore, J. T. Kiehl, C. T. Beck, and C. S. Zender (2002), Simulation of aerosol distributions and radiative forcing for INDOEX: Regional climate impacts, *J. Geophys. Res.*, *107*(D19), 8028, doi:10.1029/2000JD000032.

Delworth, T. L., and T. R. Knutson (2000), Simulation of early 20th century global warming, *Science*, *287*, 2246–2250, doi:10.1126/science.287.5461.2246.

Flato, G., and G. J. Boer (2001), Warming asymmetry in climate change simulations, *Geophys. Res. Lett.*, *28*, 195–198, doi:10.1029/2000GL012121.

Gao, H. (2007), Comparison of East Asian winter monsoon indices, *Adv. Geosci.*, *10*, 31–37, doi:10.5194/adgeo-10-31-2007.

Gong, D., S. Wang, and J. Zhu (2001), East Asian winter monsoon and Arctic oscillation, *Geophys. Res. Lett.*, *28*, 2073–2076, doi:10.1029/2000GL012311.

Gu, Y., K. N. Liou, W. Chen, and H. Liao (2010), Direct climate effect of black carbon in China and its impact on dust storms, *J. Geophys. Res.*, *115*, D00K14, doi:10.1029/2009JD013427.

Guo, Q. Y. (1994), Relationship between the variability of East Asia winter monsoon and temperature anomalies in China, *Q. J. Appl. Meteorol.*, *5*, 218–225.

Hori, M. E., and H. Ueda (2006), Impact of global warming on the East Asian winter monsoon as revealed by nine coupled atmosphere-ocean GCMs, *Geophys. Res. Lett.*, *33*, L03713, doi:10.1029/2005GL024961.

Houghton, J. T. (1985), *The Global Climate*, 256 pp., Cambridge Univ. Press, Cambridge, U. K.

Hu, Z.-Z., L. Bengtsson, and K. Arpe (2000), Impact of global warming on the Asian winter monsoon in a coupled GCM, *J. Geophys. Res.*, *105*(D4), 4607–4624, doi:10.1029/1999JD901031.

Hu, Z.-Z., S. Yang, and R. Wu (2003), Long-term climate variations in China and global warming signals, *J. Geophys. Res.*, *108*(D19), 4614, doi:10.1029/2003JD003651.

Jhun, J., and E. Lee (2004), A new East Asian winter monsoon index and associated characteristics of the winter monsoon, *J. Clim.*, *17*, 711–726, doi:10.1175/1520-0442(2004)017<0711:ANEAWM>2.0.CO;2.

Ji, L., S. Sun, K. Arpe, and L. Bengtsson (1997), Model study on the interannual variability of Asian winter monsoon and its influence, *Adv. Atmos. Sci.*, *14*(1), 1–22, doi:10.1007/s00376-997-0039-4.

Kaiser, D. P., and Y. Qian (2002), Decreasing trends in sunshine duration over China for 1954–1998: Indication of increased haze pollution?, *Geophys. Res. Lett.*, *29*(21), 2042, doi:10.1029/2002GL016057.

Kimoto, M. (2005), Simulated change of the East Asian circulation under global warming scenario, *Geophys. Res. Lett.*, *32*, L16701, doi:10.1029/2005GL023383.

Kistler, R., et al. (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*, 247–267, doi:10.1175/1520-0477(2001)082<0247:TNNYRM>2.3.CO;2.

Lau, K.-M., and K.-M. Kim (2006), Observational relationships between aerosol and Asian monsoon rainfall, and circulation, *Geophys. Res. Lett.*, *33*, L21810, doi:10.1029/2006GL027546.

Lau, K.-M., et al. (2008), The Joint Aerosol-Monsoon Experiment: A new challenge in monsoon climate research, *Bull. Am. Meteorol. Soc.*, *89*, 369–383, doi:10.1175/BAMS-89-3-369.

Lau, N. C., A. Leetmaa, and M. J. Nath (2006), Attribution of atmospheric variations in the 1997–2003 period to SST anomalies in the Pacific and Indian Ocean Basins, *J. Clim.*, *19*, 3607–3628, doi:10.1175/JCLI3813.1.

Lee, K. H., Z. Li, M. S. Wong, J. Xin, Y. Wang, W.-M. Hao, and F. Zhao (2007), Aerosol single scattering albedo estimated across China from a combination of ground and satellite measurements, *J. Geophys. Res.*, *112*, D22S15, doi:10.1029/2007JD009077.

Li, H., A. Dai, T. Zhou, and J. Lu (2010), Responses of East Asian summer monsoon to historical SST and atmospheric forcing during 1950–2000, *Clim. Dyn.*, *34*, 501–514, doi:10.1007/s00382-008-0482-7.

Li, Z. (2004), Aerosol and climate: A perspective from East Asia, in *Observation, Theory and Modeling of Atmospheric Variability*, edited by X. Zhu, pp. 501–525, World Sci., New York.

Li, Z., F. Niu, K.-H. Lee, J. Xin, W.-M. Hao, B. Nordgren, Y. Wang, and P. Wang (2007a), Validation and understanding of Moderate Resolution Imaging Spectroradiometer aerosol products (C5) using ground-based measurements from the handheld Sun photometer network in China, *J. Geophys. Res.*, *112*, D22S07, doi:10.1029/2007JD008479.

Li, Z., et al. (2007b), Preface to special section on East Asian Studies of Tropospheric Aerosols: An International Regional Experiment (EAST-AIRE), *J. Geophys. Res.*, *112*, D22S00, doi:10.1029/2007JD008853.

Li, Z., et al. (2007c), Aerosol optical properties and their radiative effects in northern China, *J. Geophys. Res.*, *112*, D22S01, doi:10.1029/2006JD007382.

Liu, B., M. Xu, M. Henderson, Y. Qi, and Y. Li (2004), Taking China's temperature: Daily range, warming trends, and regional variations, 1955–2000, *J. Clim.*, *17*, 4453–4462, doi:10.1175/3230.1.

Luo, Y., D. Lu, X. Zhou, W. Li, and Q. He (2001), 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, doi:10.1029/2001JD900030.

Menon, S., J. Hansen, L. Nazarenko, and Y. Luo (2002), Climate effects of black carbon aerosols in China and India, *Science*, *297*, 2250–2253, doi:10.1126/science.1075159.

Mi, W., Z. Li, X. Xia, B. Holben, R. Levy, F. Zhao, H. Chen, and M. Cribb (2007), Evaluation of the Moderate Resolution Imaging Spectroradiometer aerosol products at two Aerosol Robotic Network stations in China, *J. Geophys. Res.*, *112*, D22S08, doi:10.1029/2007JD008474.

Min, S. K., E. H. Park, and W. T. Kwon (2004), Future projections of East Asian climate change from multi-AOGCM ensembles of IPCC SRES scenario simulations, *J. Meteorol. Soc. Jpn.*, *82*, 1187–1211, doi:10.2151/jmsj.2004.1187.

Murakami, T. (1987), Effects of the Tibetan Plateau, in *Monsoon Meteorology*, edited by C. Chang and T. Krishnamurti, pp. 235–270, Oxford Univ. Press, New York.

Niu, S., C. Lu, H. Yu, L. Zhao, and J. Lu (2009), Fog research in China: An overview, *Adv. Atmos. Sci.*, *27*(3), 639-662, doi:10.1007/s00376-009-8174-8.

Pu, M. J., G. Z. Zhang, W. L. Yan, and Z. H. Li (2008), Features of a rare advection-radiation fog event, *Sci. China Ser. D*, *51*(7), 1044–1052, doi:10.1007/s11430-008-0071-y.

Qian, Y., and F. Giorgi (1999), Interactive coupling of regional climate and sulfate aerosol models over eastern Asia, *J. Geophys. Res.*, *104*(D6), 6477–6499, doi:10.1029/98JD02347.

Qian, Y., L. R. Leung, S. J. Ghan, and F. Giorgi (2003), Regional climate effects of aerosols over China: Modeling and observation, *Tellus Ser. B*, *55*(4), 914–934, doi:10.1046/j.1435-6935.2003.00070.x.

Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld (2001), Aerosols, climate and the hydrological cycle, *Science*, *294*, 2119–2124, doi:10.1126/science.1064034.

Ramanathan, V., et al. (2005), Atmospheric brown clouds: Impact on South Asian climate and hydrologic cycle, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 5326–5333, doi:10.1073/pnas.0500656102.

Rasch, P. J., N. M. Mahowald, and B. E. Eaton (1997), Representations of transport, convection, and the hydrologic cycle in chemical transport models: Implications for the modeling of short-lived and soluble species, *J. Geophys. Res.*, *102*(D23), 28,127–28,138, doi:10.1029/97JD02087.

Sachweh, M., and P. Koepke (1995), Radiation fog and urban climate, *Geophys. Res. Lett.*, *22*, 1073–1076, doi:10.1029/95GL00907.

Shi, N. (1996), Features of the East Asian winter monsoon intensity on multiple timescale in recent 40 years and their relation to climate, *J. Appl. Meteorol. Sci.*, *7*(2), 175–182.

Stowe, L. L., A. M. Ignatov, and R. R. Singh (1997), Development, validation and potential enhancements to the second generation operational aerosol product at NOAA/NESDIS, *J. Geophys. Res.*, *102*(D14), 16,923–16,934, doi:10.1029/96JD02132.

Sun, S., and B. Sun (1995), The relationship between the anomalous winter monsoon circulation over East Asia and summer drought/flooding in the Yangtze and Huaihe River valley, *Acta Meteorol. Sin.*, *57*(4), 513–522.

Wang, B. (2006), *The Asian Monsoon*, 189 pp., Springer, New York.

Wang, B., R. Wu, and X. Fu (2000), Pacific-East Asian teleconnection: How does ENSO affect East Asian climate?, *J. Clim.*, *13*, 1517–1536, doi:10.1175/1520-0442(2000)013<1517:PEATHD>2.0.CO;2.

Wang, B., Q. Bao, B. Hoskins, G. Wu, and Y. Liu (2008), Tibetan Plateau warming and precipitation changes in East Asia, *Geophys. Res. Lett.*, *35*, L14702, doi:10.1029/2008GL034330.

Watanabe, M., and T. Nitta (1999), Decadal change in the atmospheric circulation and associated surface climate variations in the Northern Hemispheric winter, *J. Clim.*, *12*, 494–510, doi:10.1175/1520-0442(1999)012<0494:DCITAC>2.0.CO;2.

Wu, B., and J. Wang (2002), Winter Arctic Oscillation, Siberian High and East Asian Winter Monsoon, *Geophys. Res. Lett.*, *29*(19), 1897, doi:10.1029/2002GL015373.

Wu, B., T. Zhou, and T. Li (2009), Seasonally evolving dominant interannual variability modes of East Asian climate, *J. Clim.*, *22*, 2992–3005, doi:10.1175/2008JCLI2710.1.

Xia, X. A., H. B. Chen, P. C. Wang, W. X. Zhang, P. Goloub, B. Chatenet, T. F. Eck, and B. N. Holben (2006), Variation of column-integrated aerosol properties in a Chinese urban region, *J. Geophys. Res.*, *111*, D05204, doi:10.1029/2005JD006203.

Xu, J. J., Q. G. Zhu, and T. H. Zhou (1999), Sudden and periodic changes of East Asia winter monsoon in the past century, *Q. J. Appl. Meteorol.*, *10*, 1–8.

Xu, M., C.-P. Chang, C. Fu, Y. Qi, A. Robock, D. Robinson, and H. Zhang (2006), Steady decline of east Asian monsoon winds, 1969–2000: Evidence from direct ground measurements of wind speed, *J. Geophys. Res.*, *111*, D24111, doi:10.1029/2006JD007337.

Yu, R., and T. Zhou (2007), Seasonality and three dimensional structure of the interdecadal change in East Asian monsoon, *J. Clim.*, *20*, 5344–5355, doi:10.1175/2007JCLI1559.1.

Yu, R., B. Wang, and T. Zhou (2004), Tropospheric cooling and summer monsoon weakening trend over East Asia, *Geophys. Res. Lett.*, *31*, L22212, doi:10.1029/2004GL021270.

Zhang, G. Z., L. G. Bian, J. Z. Wang, Y. Q. Yang, W. Q. Yao, and X. D. Xu (2005), The boundary layer characteristics in the heavy fog formation process over Beijing and its adjacent areas, *Sci. China Ser. D*, *48*, 88–101.

Zhang, Y., K. R. Sperber, and J. S. Boyle (1997), Climatology and interannual variation of the East Asia winter monsoon: Results from the 1979–95 NCEP/NCAR reanalysis, *Mon. Weather Rev.*, *125*, 2605–2619, doi:10.1175/1520-0493(1997)125<2605:CAIVOT>2.0.CO;2.

Zhao, F., and Z. Li (2007), Estimation of aerosol single scattering albedo from solar direct spectral radiance and total broadband irradiances measured in China, *J. Geophys. Res.*, *112*, D22S03, doi:10.1029/2006JD007384.

Zhou, T., D. Gong, J. Li, and B. Li (2009), Detecting and understanding the multi-decadal variability of the East Asian Summer Monsoon—Recent progress and state of affairs, *Meteorol. Z.*, *18*(4), 455–467, doi:10.1127/0941-2948/2009/0396.

Zhu, J., and S. Wang (2002), 80 yr oscillation of summer rainfall over north China and East Asian Summer Monsoon, *Geophys. Res. Lett.*, *29*(14), 1672, doi:10.1029/2001GL013997.

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