Dust Storm Reduction due to Precipitation and Temperature Enhancement in Northwestern China: Possible Climatic Impact of Absorbing Aerosols

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Abstract

Dust storms originating in the Gobi desert and northwestern China have a significant influence on neighboring Pacific Rim countries, including the United States. Due to their impact on weather, climate, and public health, dust storms have emerged as one of the most critical concerns facing modern society. In the decades between 1954 and 2007, reports of annual dust storm occurrences and the corresponding amount of total precipitation at 753 Chinese meteorological sites show a reduction in the occurrence and intensity of dust storms and clearly demonstrate an inverse relationship between the two. The correlation between dust storm occurrence and temperature in northwestern China also displays a negative trend but is less significant. Using a global climate model, we demonstrate that increased loading of light-absorbing aerosols in China, such as black carbon, is the primary reason for precipitation and temperature increases over northwestern China, and the consequence of reductions in dust storm frequency and intensity.

Key word: black carbon, dust, dust storm, regional climate

1.Introduction

Recurrent dust storms have emerged as one of the most critical concerns arising from the man-made ecological imbalance in China. While dust is one of the major causes of environmental and public health concerns in China, it also has a significant impact on neighboring Pacific Rim countries, including Japan and Korea, as well as the United States. Observations indicate that the total days of dust storm occurrence per year have been decreasing since the late 1970s, and currently reside at a relatively low level (Zeng et al., 2006). Data analysis for the Gobi Desert area also shows a decreasing trend in dust storm intensity in the past 20 years (Fu et al., 2008). The decreasing trend of dust storms has been studied mostly by means of observations and attributed to global warming (e.g., Wang, 2005; Fu et al., 2008; Zhu et al., 2008).

The frequent occurrence of dust storms has been attributed to both deforestation and the changing environment (Menon et al., 2002). While China has achieved great progress in economic development since the 1980s, one of the major costs is severe atmospheric pollution due to the emission of large volumes of smoke, which can be transformed into sulfate and black (elemental) carbon aerosols in air (Lefohn, 1999; Xu, 2001). Through diffusion and turbulence processes, these aerosol particles can have substantial impact on regional and global climate. While reduction in the occurrence and intensity of dust storms originating in northwestern China could be caused by a number of coupled dynamic and thermodynamic factors, we note that the loadings of absorbing BC aerosols have increased in China concurrent with this reduction. BC is released from the incomplete combustion of carbonaceous fuels, including fossil fuel and biomass burning. China is the largest developing country in the world and has been obtaining 80% of its energy from coal combustion; it is generally recognized as a major global anthropogenic source for BC aerosols (Cooke et al., 1999; Bond et al., 2004) with its coal production during the 1990s being about 5 times larger than that during the 1960s (Sun et al., 1997).

Atmospheric aerosols affect climate through the scattering and absorption of solar radiation, referred to as the aerosol direct effect or direct climate forcing. Radiative forcing of aerosols has been studied by a number of scientists (e.g., Boucher and Anderson 1995; Pan et al. 1997), and the aerosol environmental and climatic effects have become an important scientific issue (e.g., Mitchell et al. 1995). Menon et al. (2002) used a global climate model to investigate the effect of enhanced atmospheric aerosols on regional climate in China and India, and suggested that absorbing black carbon aerosols may influence the large-scale circulation and hydrologic cycle with significant effects on regional climate. Gu et al. (2006) showed that increased aerosol optical depths in China leads to a noticeable increase in precipitation in the southern part of China in July due to the cooling in the mid-latitudes that results in the strengthening of the Hadley circulation.

In this paper, we present the trend of dust storm occurrences and its relation to the regional precipitation and temperature patterns based on the observations collected from weather stations in China between 1954 and 2007, as illustrated in Section 2. In Section 3, we describe the experiment design and discuss results from a global climate model to investigate the effect of increased loadings of black carbon in China on regional climate and the consequent impact on dust storms. Concluding remarks are given in Section 4.

2. **Data Analysis**

Dust storm formation is determined by a number of factors, including dryness, wind field, soil type, and precipitation, with precipitation being the most essential factor. Dust storms normally originate in northwestern China where annual precipitation is less than 400 mm, particularly in extremely dry areas (less than 200 mm), including the Taklamakan Desert, Tarim basin area, and Gobi Desert, where the most severe dust storms have been reported (Zeng et al., 2006). While observations indicate a decreasing trend in dust storm occurrence and intensity since the late 1970s (Wang 2005; Wang et al. 2005; Zeng et al., 2006; Fu et al., 2008; Zhu et al., 2008), the corresponding annual precipitation and temperature anomalies analyzed from data collected from weather stations in the same region show increasing trends since the 1980s.

According to the guidelines set by Chinese Meteorological Observations for more than 50 years, a dust storm is defined as a situation in which the horizontal visibility at the ground is less than 1 km with a wind speed greater than 10 m/s (Zhou and Zhang, 2003; Zeng et al., 2006). Dust storm data recorded at a meteorological station in China has included starting and ending times of a dust event, atmospheric visibility, and maximum wind speed and direction. If more than one dust storm event occurs at a particular site in the same day, two dust storms are registered separately only if the interval between these two dust events is longer than three hours. We have analyzed the annual total dust storm occurrences reported from 753 Chinese meteorological stations out of which 479 stations have at least one dust storm recorded during 1954-2007. These records can be considered an index for both dust storm frequency and intensity, since a stronger dust storm normally transports dust particles further, affects a larger area, and will be recorded at more weather stations. The annual mean total precipitation and surface temperature in northwestern China, including the Taklamakan Desert (30° - 48°N, 75° - 95°E) and Gobi Desert (~ 40° N, 95° - 110°E) during 1954-2007 have also been examined. To illustrate the correlation between dust storm and precipitation, Figure 1a shows the anomalies (calculated using the 54-year mean from 1954 to 2007) of total dust storm occurrences and the corresponding anomalies of total annual mean precipitation in northwestern China, along with their 5-year means. The observed precipitation trend revealed an increase beginning around 1975 (with positive anomalies after 1985), whereas dust storm clearly displays a decreasing trend from late 1970s (with negative anomalies occur after 1985) during a 54-year time period. Temperature patterns also show a negative correlation with the dust storm occurrence after 1985 (Fig. 1b). During the 1960s, precipitation displays a decrease, but dust storm occurrence fluctuates without a clear increasing trend, probably because northwestern China experienced a warming during that time period, which partially offset the effect of decreased precipitation. During the late 1970s to 1985, temperature shows a slight decrease, but dust storm occurrence decreases are found to be associated with precipitation increase. Note that there is a small increase in dust storm occurrence from 1998 to 2000 as shown in Fig. 1, but decrease is found again since 2000. Wang et al. (2005) also reported that the frequency of spring dust storms in northern China generally decreased from 1954 to 2000, with a small increase since 1998. They did not show the decrease from 2000 since they analyzed the data only up to 2000. The slight increase from 1998 to 2000 could be due to the inter-annual variation of dust storms, which has a 3-4 year cycle (Wang et al. 2005).

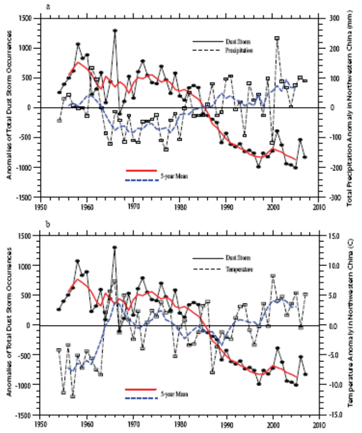

Fig. 1 Anomalies of the observed annual total dust storm cases during the period from 1954 to 2007 (solid) and the corresponding anomalies of the observed annual mean (a) total precipitation (mm) and (b) surface temperature (C°) (dashed), along with their 5-year mean values (dust storm in red; precipitation/temperature in blue) in northwestern China.

The correlation coefficient between the 5-year mean total dust storm occurrence and total precipitation in the northwestern China is about -0.85, illustrating a rather strong inverse correlation between the two. The coefficient of determination (the square of the correlation coefficient) is about 0.73, indicating that about 70% of the total variation in dust storm occurrence can be explained by the linear relation between precipitation and dust storm. The correlation between dust storm occurrence and temperature is less significant, with a coefficient of determination of about 0.31. Additionally, increased temperature tends to suppress the intensity of cold fronts from Northwest Mongolia, a primary triggering weather process for dust storm in the Gobi desert (Fu et al., 2008). Finally, multiple regression analysis also shows a negative relationship between the combined precipitation and temperature data and dust storm occurrence.

3.Model Experiments

Aerosols are transported through large-scale circulation and interact closely with cloud and radiative processes. A comprehensive study of aerosol direct climate forcing requires a climate model that incorporates various interactive atmospheric processes. In the following, we report on the direct climatic effect in the China region of absorbing BC and its impact on regional climatic perturbations, using the AGCM developed at the University of California, Los Angeles (UCLA). The UCLA AGCM is a state-of-the-art grid point model of the global atmosphere extending from the Earth's surface to a height of 50 km, which has been successfully applied to a number of climate studies, including El Niño/Southern Oscillation and the Asian Monsoon (e.g., Arakawa, 1999; Mechoso et al., 1999), as well as aerosol direct radiative forcing (Gu et al., 2006) using a physically-based spectral radiation scheme recently incorporated in the UCLA AGCM (Gu et al., 2003). The radiation calculation is performed using the Fu-Liou-Gu scheme (Gu et al. 2003; Gu et al, 2006), which was a modified and improved version based on the original Fu-Liou scheme (Fu and Liou 1992, 1993; Fu et al. 1996) with the inclusion of 18 aerosol types by employing the Optical Properties of Aerosols and Clouds (OPAC) database (d'Almeida et al., 1991; Tegen and Lacis, 1996; Hess et al., 1998). The overall radiative forcing produced by aerosols is dependent on their single-scattering properties, which are associated with composition, size, and shape. Estimation of the single-scattering albedo at 24 stations across China for the year 2005 yields a value of 0.89 ± 0.04 (Lee et al., 2007), obtained by combining the clear-sky measurements from ground-based spectral transmittances determined from the Chinese Sun Hazemeter Network with the reflected spectral radiances measured by the NASA Moderate Resolution Imaging Spectroradiometer (MODIS).

For this study, we performed two primary numerical experiments (Experiments A and B) and one supplementary experiment which examines the global warming effect of CO_2 (Experiment C). In experiment A (the control run), the aerosol effect is accounted for by globally incorporating a background aerosol optical depth of 0.2, consisting of 90% non-absorbing aerosols and 10% BC resulting in a single-scattering albedo of about 0.92 to represent the condition in China in the 1970s. The selection of 0.2 for aerosol optical depth is in part based on the averaged aerosol optical depth derived from the TOMS observations for regions (e.g., Southern Hemisphere) relatively free of the effect of anthropogenic aerosols (Torres et al., 1998). In experiment B, we included the observed aerosol optical depths in China (Luo et al., 2001) along with a background value of 0.2 for areas outside China (Gu et al., 2006). The yearly and monthly mean aerosol optical depths at the wavelength of 0.75 μm over China have been determined from the data involving the daily direct solar radiation, sunshine duration, surface pressure, and vapor pressure from 1961 to 1990 (Luo et al. 2001). The larger aerosol optical depths are found in the southern China with a maximum value of about 0.7. More details of this data can be found in Gu et al. (2006). The aerosols were assumed to consist of 15% BC aerosols (assuming external mixing) and 85% non-absorbing aerosols, corresponding to an overall single-scattering albedo of about 0.88, in order to represent the current aerosol conditions in China (Lee et al., 2007). The input aerosol optical depth represents the vertically integrated column value, which have been distributed vertically according to a certain weighting profile based on the layer pressure and scale height, a height at which the aerosol loading is reduced to e^{-1} of the surface value, which is set to be 3 km in this study. The aerosol loading decreases exponentially and the highest aerosol layer in the model is placed at 15 km (Charlock et al. 2004). Consequently, the spectral single-scattering properties are dependent on height according to aerosol type and relative humidity. To exclude other warming mechanisms that could affect precipitation in China, we have also examined the effects of CO_2 increases on temperature and precipitation patterns in China from the 1970s (330 ppmv, control run) to the 2000s (370 ppmv, perturbation run, Experiment C) in which aerosols are not included. The sea surface temperature, greenhouse gases, and other forcings are fixed in experiments A and B so that aerosols are the only forcing in these two 5-year long simulations.

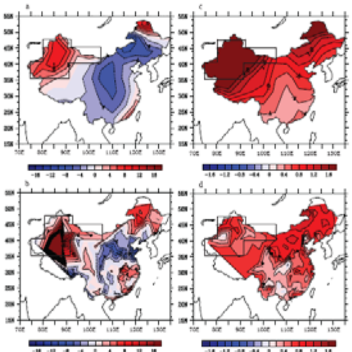

Fig. 2 Simulated annual mean differences in (a) precipitation (%) and (c) the surface air temperature (K) between Experiments B and A, along with the observed (b) precipitation (%) and (d) the surface air temperature anomalies over China in the 1990s.

Figures 2 (a) and (b) shows the aerosol effect on the simulated annual mean precipitation and the observed precipitation anomalies in 1990s over China (both are shown in percentage). Increased precipitation generated from the AGCM is seen over the Taklamakan and Gobi Deserts, in agreement with the observed precipitation changes in northwestern China. Simulated changes in precipitation patterns in other areas of China also match the observations, including increases in southern and northeastern China and a decrease in central China, although the decreased precipitation areas simulated from the model are larger. Zhao et al. (2006) also showed that the increased loadings of absorbing aerosols correlates well with the decrease in precipitation over eastern central China, which is in close agreement with the simulation results presented in this study.

Absorbing aerosols can play a key role in climate change because of their absorption of sunlight and the subsequent heating of the air column, affecting vertical temperature profile, atmospheric stability, and the strength of convection (Menon et al., 2002). The perturbed temperature profile (Fig. 3) shows that warming is found in the mid- to high latitudes, which weakens the Hadley circulation and reduces the tropical convection and precipitation. As a result, precipitation moves to higher latitudes towards the Himalayas, Tibet, and northwestern China, as shown in Fig. 2 (a). Similar results are also found in the simulations associated with the effect of dust particles, which increases the heating of the air column over the Himalayas and subsequently moves the monsoon circulation further landward (Miller and Tegen, 1998). Also note that the warming in the mid- to high latitudes causes a reduction in the longitudinal temperature gradient and induces weakening of the westerly jet stream in northwestern China and Mongolian regions. Consequently, the frequency of occurrence and the intensity of Mongolian cyclones have been suppressed, resulting in the decreasing dust storm in northwestern China, as also reported by Zhu et al. (2008) based on their Empirical Orthogonal Function (EOF) analysis of the dust storm frequency in northern China and the correlation analysis between dust storm frequency index and surface air temperature. Wang (2005) analyzed the dust layers in the Malan ice core from the northern Tibetan Plateau and reported that dust events became less frequent during the past 200 years associated with increasing precipitation and weakening westerly related to the decrease in longitudinal temperature gradient produced by global warming. These discussions are in line with the findings presented in this study.

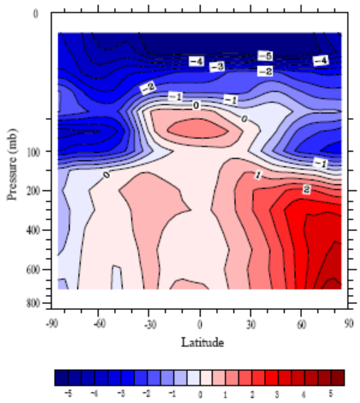

Fig. 3 Simulated annual mean differences in the zonal mean temperature (K) between Experiments B and A

In past decades, increased temperature in northwestern China has resulted in snowmelt water depth enhancement from glaciers in the Tibetan Plateau (Shi et al., 2003). An increase of about 10-20% was found in the river flow from the Plateau through the Hexi Corridor to the deserts. This is coupled with the enlargement of inner lakes, causing soil moisture to increase in the arid regions and/or deserts, and suppressing the production of dust storms. The dominant circulation pattern for dust storm occurrence was related to a low pressure system that was coupled with a cold front (Qian et al., 2006). When the cold-dry air originating in northern Mongolia moves to the south and encounters the warm and humid air, cold fronts and low pressure systems are established in the midlatitude, usually with a ridge over the east part of the Ural Mountains, strengthening surface wind and kicking up dust particles on the surface. As temperature increases in northwestern China, however, the intensity of the low-pressure system and the strength of the cold front both decrease, leading to the reduction of dust storm occurrence and/or intensity. Figures 2 (c) and (d) display simulated differences in the annual mean surface air temperature and observed anomalies over China in the 1990s, respectively. Due to tropospheric heating produced by absorbing BC, warming is found in most areas (e.g. northwestern and eastern China) similar to the observed temperature anomalies. It is noted that a weather station in the Gobi desert reported an increase in the average temperature by about 1.6 °C in the past 20 years (Fu et al., 2008).

Now we examine the effects of CO_2 increases on temperature and precipitation patterns in China from the simulation results of Experiment C. Global greenhouse effects during this 30-year period led to increases in temperatures in most areas in China (Fig. 4a), but a substantial reduction in precipitation in northwestern China, contrary to the observed pattern (Fig. 4b). The decreasing precipitation in that area appears to be related to the fact that while the tropospheric warming produced by increases in CO_2 is rather uniform in the tropics and midlatitude (Fig. 4c), significant warming occurs in high latitudes, resulting in a strengthening of the downward motion in midlatitude areas and consequent suppression of precipitation in that region.

Finally, we note that the model simulation similar to Experiment B which employed the aerosol optical depth observations in China but used less BC than Experiment B (10% BC), representing a single-scattering albedo of about 0.92, reproduced the enhanced precipitation in the southern China, but missed the increases in northwestern China (Gu et al., 2006). In view of these simulation results, it appears reasonable to conclude that the primary reason for precipitation increase over northwestern China must be associated with the increased loading of absorbing aerosols in China.

Other mechanisms that might also affect precipitation patterns in China include El Niño/La Niña. For example, the 1997/98 El Niño event was one of the strongest on record by most standards, and appeared to have an impact on the drying of climate in southern China during the 1990s. However, this strong El Niño was immediately followed by a La Niña event in 1998/99 which had a reverse effect (Gu et al. 2003). The El Niño-Southern Oscillation (ENSO) phenomenon is the primary component in global inter-annual climate variability. However, it appears to play a less crucial role in decadal climate change. The 1997/98 El Niño event did not significantly affect the precipitation pattern in northwestern China (Gu et al., 2003).

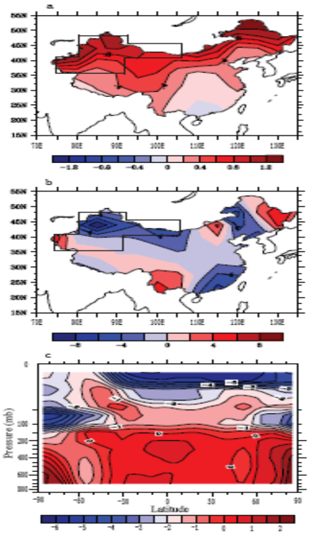

Fig. 4 Simulated annual mean differences in (a) the surface air temperature (K), (b) precipitation (%), and (c) the zonal mean temperature (K) between Experiments C and A

4.Concluding Remarks

Analysis of the observed data obtained from weather stations in China during 1954-2007 reveals that dust storm occurrences have been decreasing since late 1970s. Based on analysis of the corresponding precipitation and temperature observations in northwestern China, the decreasing trend in dust storm occurrence is shown to be well-correlated with an overall increase in precipitation and, to a lesser degree, temperature increase in northwestern China. The correlation coefficient between the 5-year mean total dust storm occurrence and total precipitation in the northwestern China is about -0.85, indicating a rather strong inverse correlation between the two. The coefficient of determination is about 0.73, inferring that about 70% of the total variation in dust storm occurrence can be linked to the change of precipitation pattern with a linear relationship. The correlation between dust storm occurrence and temperature is less significant, with a coefficient of determination of about 0.31.

Absorbing aerosols, such as BC, can significantly affect the regional climate due to their heating of the air column. This heating effect modifies the vertical thermal structure, atmospheric stability, and convection strength and affects regional precipitation patterns. AGCM simulations show that increased loadings of absorbing aerosols in China result in enhanced precipitation over the Taklamakan and Gobi Deserts, the most reliable sources of dust storms, in agreement with the observed precipitation changes in northwestern China. Simulated changes in precipitation patterns in other areas of China also match the observations, including increases in southern and northeastern China and a decrease in central China. Due to tropospheric heating produced by absorbing BC, warming is found in most areas (e.g. northwestern and eastern China) similar to the observed temperature anomalies. Increasing tropospheric absorbing aerosols in the mid-latitudes lead to the increase in surface air temperature in the mid- to high latitudes, which in turn causes a reduction in the north-south temperature gradient and induces weakening of the westerly jet stream in the northern China and Mongolian regions, resulting in the decreasing dust storm in northwestern China. Simulated cloud cover decreases in most areas in China except the northwest, including northern and central regions, which also agrees well with the observations.

We have also examined the warming mechanism produced by increased CO_2 using the same AGCM to understand its effect on precipitation pattern. Global greenhouse effects led to increases in temperature in most areas in China; however, a substantial reduction in precipitation in northwestern China is produced, contrary to the observed precipitation pattern. Based on GCM simulation results and physical interpretations, we conclude that the increased loading of black carbon, in China appears to be the primary reason for precipitation enhancement over northwestern China and the subsequent suppression of dust storm occurrences.

Acknowledgments. We would like to thank X. Yue and L. Zhou of the Institute of Atmospheric Physics, Chinese Academy of Science, for their assistance in providing the observed data for this study. Yu Gu and K. N. Liou have been supported by NSF Grants ATM-0437349, ATM-0924876, and ATM-0331550, DOE Grant DEF03-00ER62904, and NASA Grant NNX08AN69G.

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