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Steady decline of east Asian monsoon winds, 1969–2000: Evidence from direct ground measurements of wind speed

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[1] It is commonly believed that greenhouse-gas-induced global warming can weaken the east Asian winter monsoon but strengthen the summer monsoon, because of stronger warming over high-latitude land as compared to low-latitude oceans. In this study, we show that the surface wind speed associated with the east Asian monsoon has significantly weakened in both winter and summer in the recent three decades. From 1969 to 2000, the annual mean wind speed over China has decreased steadily by 28%, and the prevalence of windy days (daily mean wind speed > 5 m/s) has decreased by 58%. The temperature trends during this period have not been uniform. Significant winter warming in northern China may explain the decline of the winter monsoon, while the summer cooling in central south China and warming over the South China Sea and the western North Pacific Ocean may be responsible for weakening the summer monsoon. In addition, we found that the monsoon wind speed is also highly correlated with incoming solar radiation at the surface. The present results, when interpreted together with those of recent climate model simulations, suggest two mechanisms that govern the decline of the east Asian winter and summer monsoons, both of which may be related to human activity. The winter decline is associated with global-scale warming that may be attributed to increased greenhouse gas emission, while the summer decline is associated with local cooling over south-central China that may result from air pollution.

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1. Introduction

[2] The monsoon is one of the most important climatic phenomena on Earth. Driven by differential heating between the land and ocean, it features strong seasonal reversal in atmospheric circulation and rainfall anomalies, and occurs most conspicuously in Asia, Australia, and Africa. The east Asian (EA) monsoon alone covers a major portion of the largest continent on Earth and provides rainfall for 1,500,000,000 people and other life in the region [*Fu*, 2003]. Thus the stability and variability of the EA monsoon are of wide concern, especially because of the potential for the monsoon to change with global warming. In this study we analyzed the declining trend of the EA monsoon and discussed its possible causes related to global and regional events. Here we distinguish the EA monsoon from the south Asian monsoon, which affects India and neighboring regions. The EA monsoon is characterized by strong northerly (including NE and NW) winds from the cold-core Siberia-Mongolia High in winter and southerly (including SE and SW) winds with warm and moist air masses from the South China Sea and the Bay of Bengal in summer [*Lu and Chan*, 1999; *Ding*, 1994; *Boyle and Chen*, 1987]. Taking advantage of a recently available historical climate data set for China, the current study focuses on examining the temporal dynamics of the surface wind speed in China in the recent three decades. We recognize that the EA monsoon covers the Korean Peninsula, Japan, and Taiwan, but we exclude these regions in the current study to keep the uniform standard of the data set. We do not expect this will significantly change our conclusions on the EA monsoon wind because of the relatively small area of

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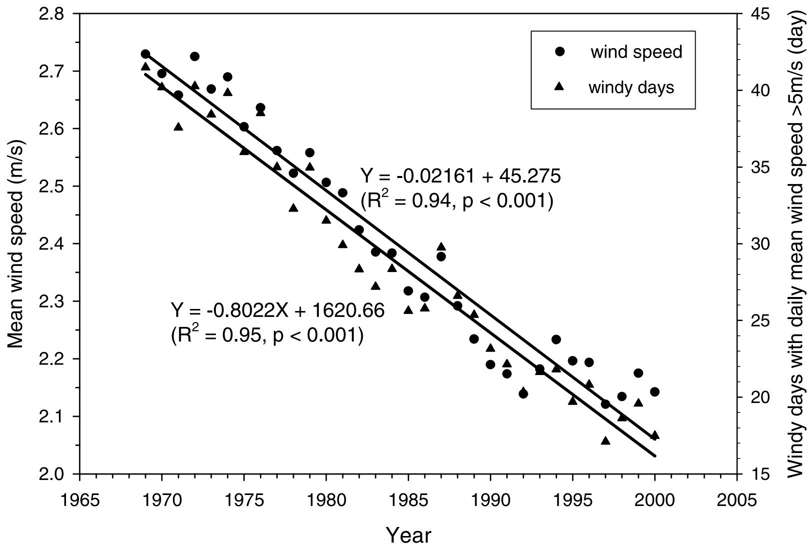

Figure 1. Declining trend of mean surface wind speed (m/s) and the prevalence of windy days (daily mean wind speed > 5 m/s) over China from 1969 to 2000 indicate the weakening of the east Asian monsoon. The mean wind speed was spatially averaged using area weighting of the 305 weather stations. The top regression line and formula are for wind speed, and the bottom regression line and formula are for windy days.

these regions in comparison with the area of continental China.

2. Data Analysis

[3] Data for this study were obtained from the National Centers for Environmental Prediction (NCEP) and the China Meteorological Administration (CMA) through a bilateral agreement of joint research between CMA and the U.S. Department of Energy (DOE) on global and regional climate change [*Riches et al.*, 2000]. The China climate data were derived on the basis of a daily database, meeting the World Meteorological Organization's (WMO) standards, operated by the CMA. Most of the weather stations were established in the 1950s and we excluded wind speed data before 1969 in this study because the data from the early years contain more gaps due to instrument malfunctions [*Liu et al.*, 2004a]. As a result, 305 stations were selected for this study. The wind speed was measured with anemometers 10 m above the ground following the WMO's Guide on the Global Observing System and CMA's Technical Regulations on Weather Observations.

[4] The 305 weather stations are not evenly distributed across the country, with more stations located in central and eastern China and fewer stations in western China, especially on the Tibetan Plateau [*Liu et al.*, 2004a]. To estimate the mean over the whole country, each climate variable, such as temperature and wind speed, was spatially averaged according to an area-based weighting factor for each station. The area that each station controls was determined by a Thiessen polygon which was created using GIS software (Arc/Info 8.2). The temporal trend of the climate variables was determined on the basis of annual mean values using regression analysis. Solar radiation was measured at 85 out of the 305 stations. *Liu et al.* [2004b] give details on the measurements and data processing.

[5] To confirm our results and to examine the temperature contrast between the land and ocean, the driving force of the EA monsoon, we used the surface wind speed and air temperature data from the NCEP reanalysis data set, which has continuous global coverage since 1948 [*Kistler et al.*, 2001]. The NCEP reanalysis data, coupling ground-based observations with climate models, are on a 2.5° × 2.5° latitude-longitude grid. The annual mean surface wind speed and sea surface air temperatures over the South China Sea and western North Pacific Ocean region were calculated on the basis of the monthly mean values from the NCEP data set.

3. Results and Discussion

[6] By analyzing the data from the 305 weather stations across China, we found that the annual mean wind speed at 10 m height has decreased about 28% from 1969 to 2000 (Figure 1). The EA monsoon has changed not only in mean intensity (wind speed), but also in frequency of extremes. During the same period, the number of yearly windy days with daily mean wind speed > 5 m/s has declined nearly 60%, from 42 days in 1969 to 17 days in 2000 (Figure 1). Generally, the wind speed has declined more at higher latitudes, correlated with the latitudinal trend of temperature increase. Annual mean wind speed changed by −0.08 m/s per decade in south China (<25°N), −0.14 m/s per decade in central China (25–35°N), and −0.29 m/s per decade in north China (≥35°N). Most of the decline of the monsoon wind speed was found in 1970s and 1980s and the wind speed trend was flat in 1990s (Figure 1).

[7] To ensure data quality, we chose the 305 first-order weather observing stations meeting the WMO standards. From the metadata we found no evidence that the trends are caused by changing observing conditions and practices, such as overgrowing trees around the stations and instru-

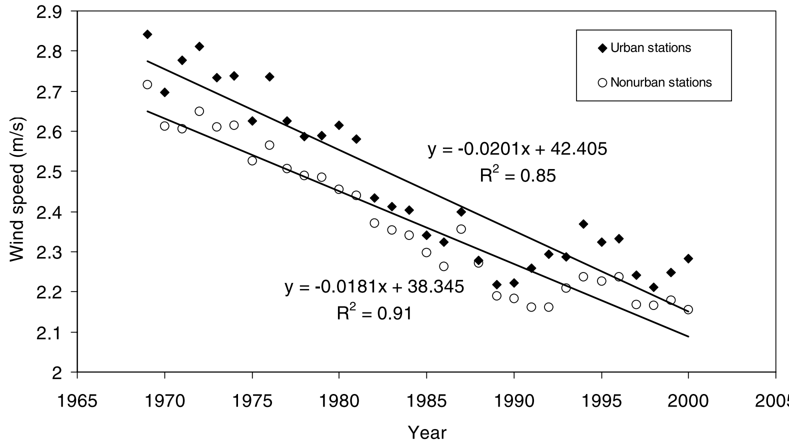

Figure 2. Urban stations including the top 30 largest cities in China and the ‘‘nonurban’’ stations totaling 275 first-class weather stations.

ment changes. The distance between each weather station and any obstacles should be at least 10 times of the height of the obstacle. Most of the urban stations in China are located in the cities, not at the airports. Tall buildings associated with urbanization may cause wind speed reduction as well. Careful examination of this urbanization effect by comparing the trend of the stations in the 30 largest cities to that of the rest (‘‘nonurban’’ stations), revealed that the urbanization effects are minor, although the urban stations showed a slightly greater declining trend than the nonurban stations (Figure 2). The minor influence of urbanization on this wind data set is also confirmed by the temporal trend of the wind speed because China’s construction boom began in the late 1980s and early 1990s, and the wind weakening was not enhanced but has stabilized since then (Figures 1 and 2). In addition, systematic errors from individual instrument replacements and observation method changes tend to be step functions at the specific locations and times, and cannot explain the consistent decline over the 32 years and averaged over all of China. Of the 305 stations, wind speed declined at 257 stations and only slightly increased at 48 stations. Spatially, we did not find any consistent patterns of the wind speed decline though fewer stations seem to show declining trends in the Sichuan Basin (Figure 3).

[8] The reduction of the EA monsoon wind speed can be caused by many factors, such as global warming, regional

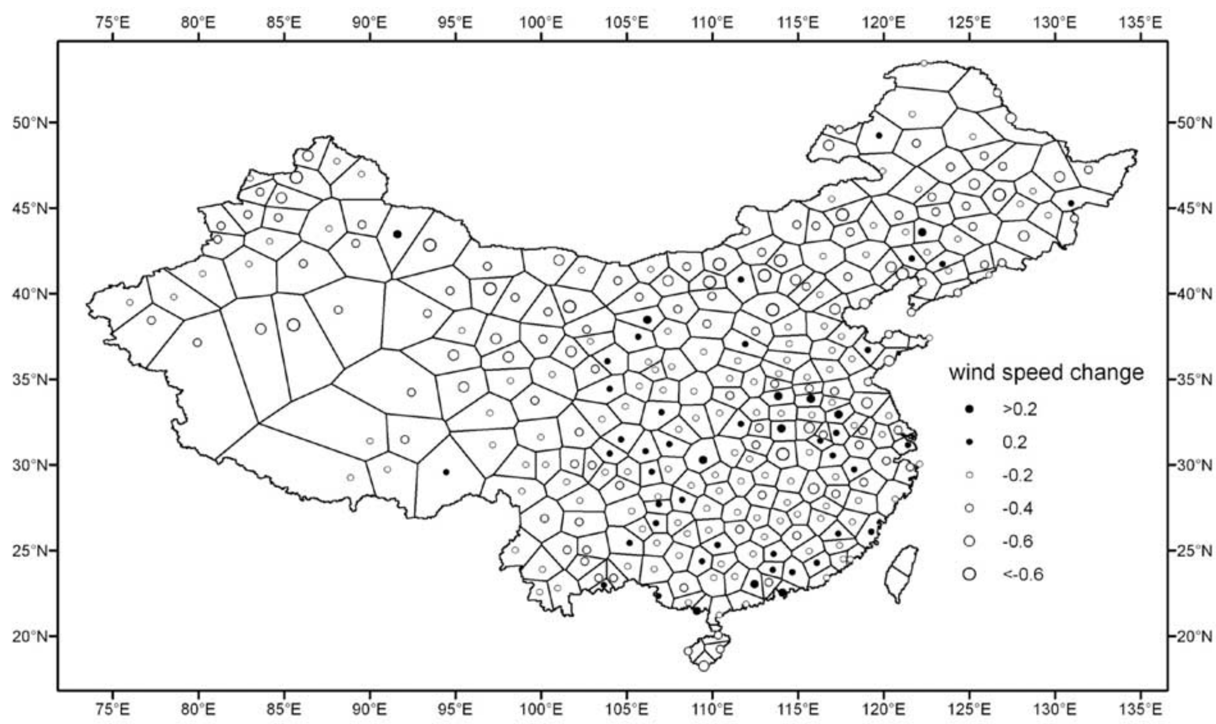

Figure 3. Change of wind speed (m/s per decade) from 1969 to 2000, decreasing at 257 stations and increasing at 48 stations. Each station is surrounded by a Thiessen polygon.

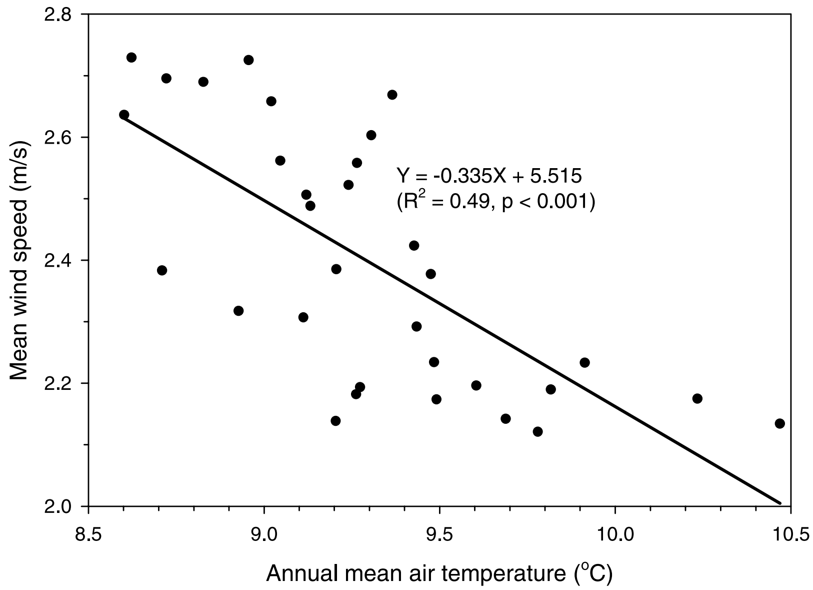

Figure 4. Relationship between annual mean wind speed and air temperature over China, 1969–2000.

and global atmospheric circulation change, and even human factors (e.g., land use change and air pollution). Here we examined possible relationships between the wind speed decline and other climate variables. The weakening of the monsoon wind may be associated with global warming because the monsoon is mainly driven by the temperature gradient between land and ocean. Indeed, we found that the wind speed is negatively correlated with near-surface air temperature during the past three decades (Figure 4). Significant warming in the second half of the 20th century in China, especially in northern China and in the winter, has been reported in a number of studies [*Karl et al.*, 1991; *Shen and Varis*, 2001; *Wang and Gaffen*, 2001; *Liu et al.*, 2004a] and is correlated with global warming. Thus the negative correlation between the monsoon wind speed and temperature suggests a possible relationship between wind speed reduction and regional and global warming. However, this cannot explain the flat trend of wind speed in the 1990s (Figure 1) because air temperature increased dramatically in the 1990s in both China and the world [*Liu et al.*, 2004a; *Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. Our further analysis shows that the annual mean wind speed and surface incoming solar radiation are positively correlated (Figure 5) and these two variables share similar decadal trends, significantly decreasing in 1970s and 1980s and slightly increasing or being stable in 1990s [*Liu et al.*, 2004b; *Wild et al.*, 2005]. This suggests that the decrease of solar radiation may also contribute to the weakening of the monsoon wind speed.

[9] Model simulations and ground-based measurements have demonstrated that global warming is more pronounced over land than over ocean and preferentially at high

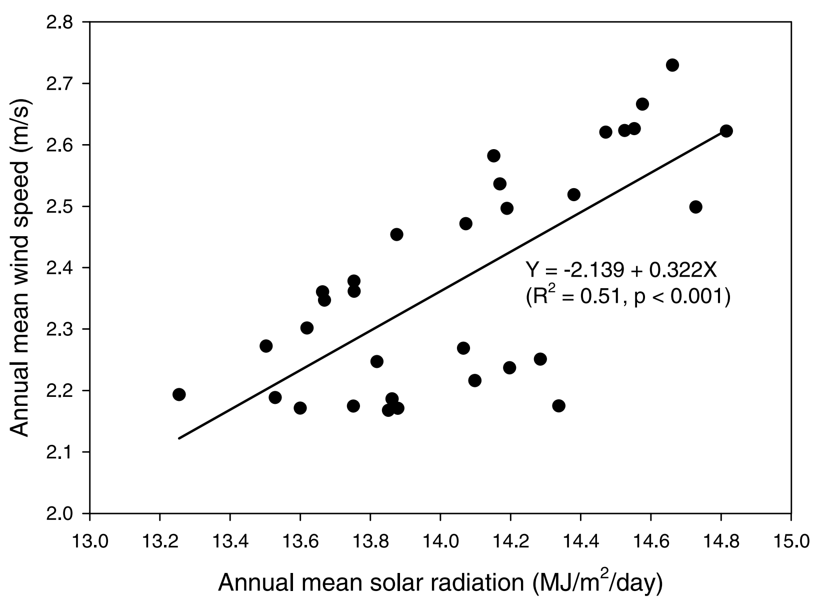

Figure 5. Positive correlation between annual mean wind speed and solar radiation.

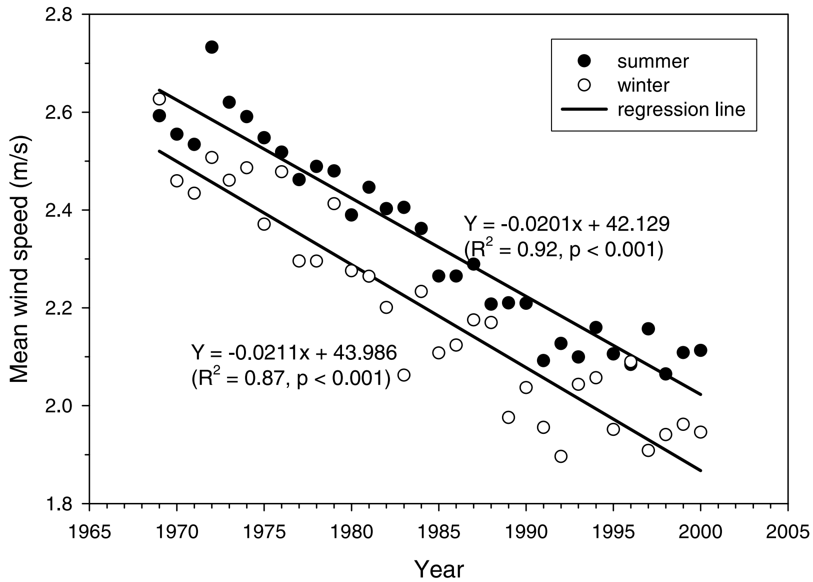

Figure 6. Declining trend of approximately 0.2 m/s per decade, which is quite similar in winter (NDJF) and summer (JJA).

latitudes rather than low latitudes [*IPCC*, 2001; *Min et al.*, 2004]. Given this asymmetric warming, the thermal contrast between land and ocean should increase in summer and decrease in winter. Therefore one would expect a strengthening summer monsoon and a weakening winter monsoon in east Asia. However, our study revealed that the surface wind speed has significantly declined in both winter (November-February) and summer (June-August) (Figure 6). Indeed, the wind speed decline in winter over China is highly correlated with the rise of air temperature in north China, especially in the daily minimum temperature (Figure 7), suggesting the suppression of the EA winter monsoon may be linked to the warming at high latitudes. That global warming weakens EA winter monsoon is also confirmed by a recent study by comparing nine coupled atmosphere-ocean general circulation models (AOGCMs) [*Hori and Ueda*, 2006]. Then how can one explain the weakening of the EA summer monsoon?

[10] The EA summer monsoon is mainly driven by the pressure differences between the High over the South China Sea and the western North Pacific and the Low over the EA continent [*Ding*, 1994]. The near surface air moves northward or northeastward from the ocean to land, reaching the southern coast of China around middle or late May. The summer monsoon holds sway across most of China from June to August, reaching northern China in July [*Tao and Chen*, 1987; *Samel et al.*, 1999; *Zeng and Lu*, 2004]. The pace and the strength of the summer monsoon are mainly

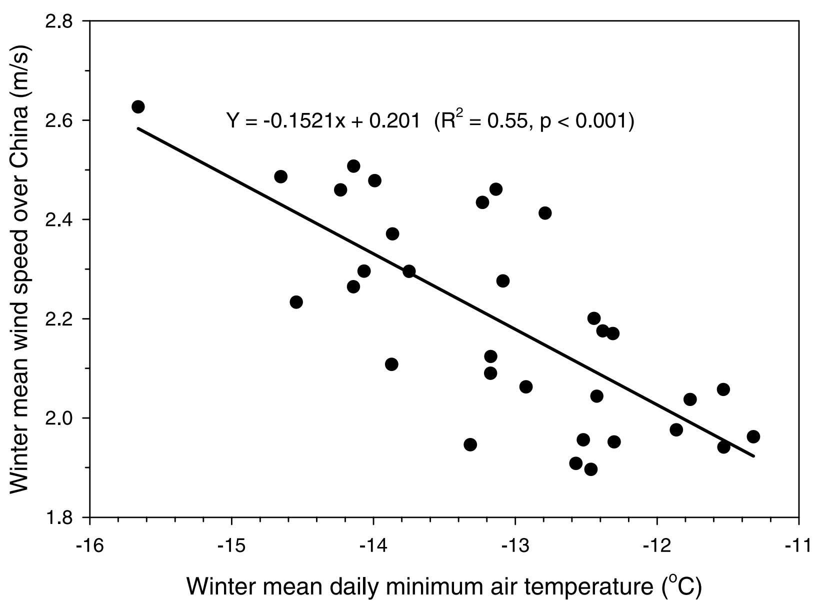

Figure 7. Relationship between the winter mean wind speed over China and the winter mean daily minimum air temperature over north China (>35°N) from 1969 to 2000.

driven by the land-ocean temperature gradient [*Li and Yanai*, 1996; *Chen and Yoon*, 2000]. During the summer the land is warmer than the ocean, so either a warmer land or a colder ocean or a combination of both will enhance the land-ocean temperature gradient. Conversely, a colder land or a warmer ocean or a combination of both will reduce the temperature gradient and weaken the summer monsoon circulation [*IPCC*, 2001; *Li and Yanai*, 1996; *Zhu and Houghton*, 1996].

[11] Using the NCEP reanalysis data, we examined the sea surface air temperature over the South China Sea and the western North Pacific (7.5–20°N and 105–120°E), where the maximum summer southerly flow of the EA monsoon is located [*IPCC*, 2001; *Wang et al.*, 2001]. We found that the summer sea surface air temperature over the South China Sea and the western North Pacific increased much more than the land surface air temperature across terrestrial China [*Chang et al.*, 2000]. The summer air temperature over the ocean increased 0.23°C per decade from 1969 to 2000, while the summer air temperature in south-central China (from the mid Yellow River Basin to the mid-lower Yangtze River basin) has actually significantly decreased, particularly in terms of daily maximum temperature (Figure 8a). This means that the summer temperature gradient between the land and ocean actually decreased rather than increased during the recent decades. The combination of the strong warming over the ocean and the cooling in south-central China has contributed to the suppression of the EA summer monsoon, as seen in the reduction of wind speed. A recent study also confirmed that the Indian summer monsoon rainfall is highly associated with land and sea surface temperature difference [*Robock et al.*, 2003]. It should be noted that other factors, such as precipitation and pressure changes, may also contribute to the cooling in south-central China. Our recent study found that the summer rainfall has significantly increased in south-central China in recent decades, which may cool the surface [*Liu et al.*, 2005]. Recent studies also found that the enhanced summer rainfall and surface cooling in south-central China is associated with a large-scale circulation change in EA, which prevents the northward advance of the summer monsoon [*Weng et al.*, 2004; *Wang and Zhou*, 2005].

[12] Several climate model simulations suggest that air pollution, especially sulfate aerosols, caused cooling in south-central China during the past decades [*IPCC*, 2001; *Xu*, 2001; *Menon et al.*, 2002]. Thus anthropogenic air pollution, such as that due to coal burning, may have contributed to the decline of the EA summer monsoon. It is possible that the reduction in wind speed may form a positive feedback to local and regional air pollution because the suppressed wind will slow down the dispersal of the pollutants in the air, especially in south-central China where the economy has grown rapidly during the recent decades. In addition, the air quality in the region may also deteriorate with the reduced wind speed.

[13] The decline of the summer monsoon circulation may have changed the rainfall pattern in China. The main source of this rainfall is the southerly transport of moisture from the warm ocean surface. The weakening of the summer monsoon wind tends to produce more precipitation in southern China and less moisture transport to regions further north. Furthermore, the warmer western Pacific and South China Sea tend to enhance the subtropical high that will hold the summer rain belt, the Meiyu front, longer in southern China [*Chang et al.*, 2000; *Wang and Li*, 2004]. This is consistent with a recent study reporting that the enhancement of the global hydrological cycle is more likely due to increased moisture advection from the oceans than from local evapotranspiration [*Wild et al.*, 2004]. Thus the decline of the EA summer monsoon may have contributed to severe rainfall anomalies over the past decades, including floods in southern China, especially in the Yangtze River basin, and droughts in northern China [*Fu*, 1994; *Gong and Ho*, 2002; *Menon et al.*, 2002]. This is further confirmed by our recent study that summer precipitation has barely changed across the whole country, but significantly increased in the mid-lower Yangtze River basin, excluding the Sichuan Basin, and decreased in north-central and northeast China (Figure 8b) [*Liu et al.*, 2005; *Wu et al.*, 2006]. The largest increase of summer precipitation in south-central China happened approximately in the area where significant summer cooling has been observed (Figures 8a and 8b). The increased rainfall undoubtedly is associated with cooling. A positive feedback is likely to further weaken the summer monsoon and thus bring more summer rainfall in south-central China.

[14] The observed decline of the EA monsoon winds is further supported by the NCEP reanalysis data, which also showed significant declines in the mean surface wind speed over China during the past three decades. The decline is further corroborated by similar declines in various EA monsoon indices represented by wind anomaly at 850 hPa averaged over east China and the coastal ocean [*Xue*, 2001], land and ocean pressure difference [*Guo et al.*, 2003, 2004], meridional wind averaged between 850 and 500 hPa over central-east China [*Yu et al.*, 2004], and weighted average of 500 hPa height anomaly over China [*Huang and Yan*, 1999]. The geopotential heights at 850 and 500 hPa over the Eurasian continent and western Pacific showed a similar trend during 1961–2001 [*Weng et al.*, 2004; *Wang and Zhou*, 2005]. This similarity suggests that the decline of EA monsoon may also be related to other broader-scale climate changes that are known to affect the Asia-Pacific region. In addition to global warming, such changes include the increased frequency of positive index of the northern annular mode [*Wallace and Thompson*, 2001] and the decadal-scale climate regime shift around 1976 in the North Pacific [*Wang and Li*, 2004].

4. Conclusions

[15] The surface EA monsoon wind speed has significantly declined in both winter and summer since the late 1960s. The decline of the winter monsoon is highly correlated with the stronger warming over north China than over the southern oceans, while the decline of the summer monsoon is linked to the summer cooling in central south China and warming over the South China Sea and the western North Pacific Ocean. In addition, the surface incoming solar radiation is also highly correlated with the monsoon wind speed. Our results, when interpreted together with those of recent climate model simulations, suggest that the decline of the EA winter monsoon may be related to

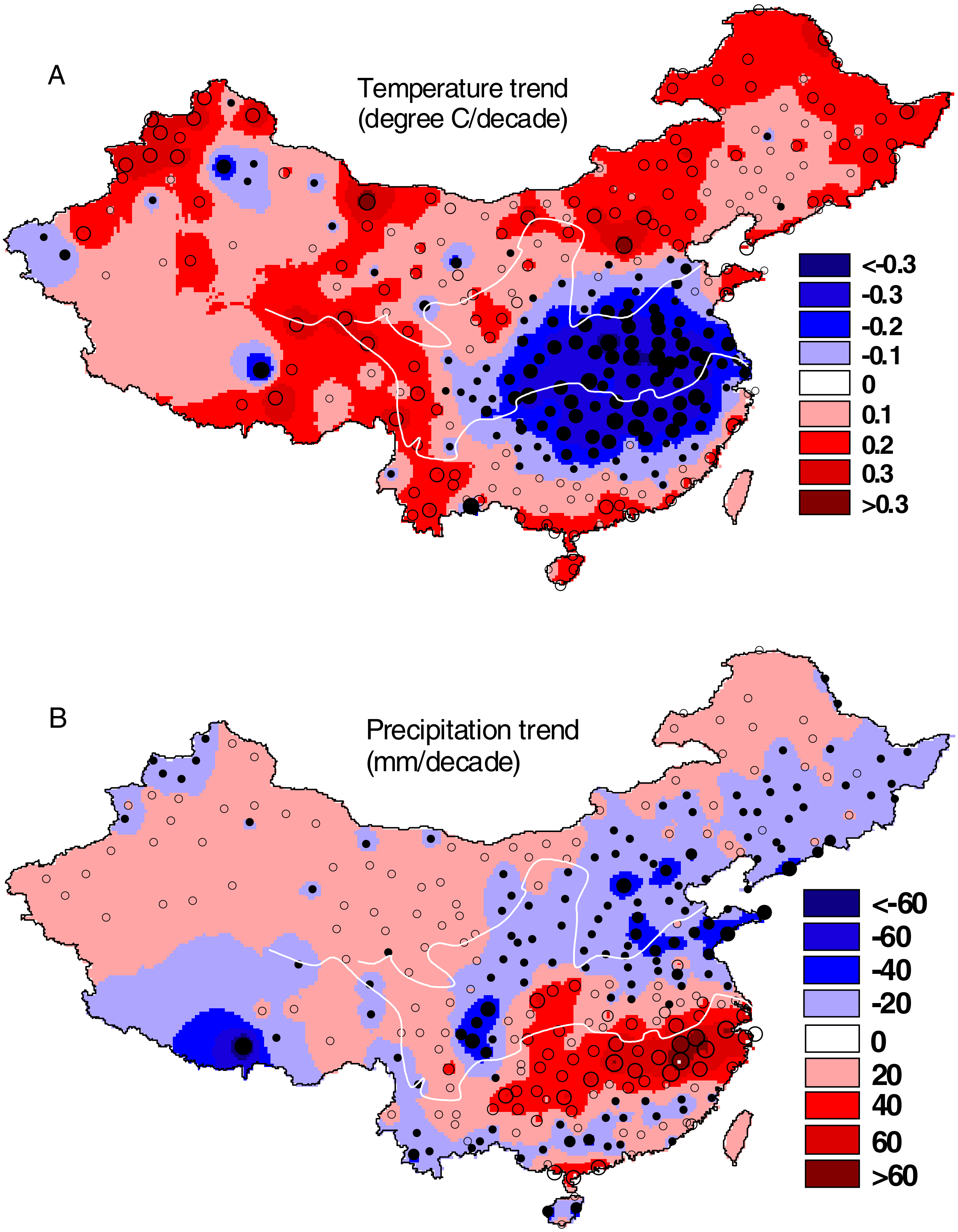

Figure 8. (a) Trend (°C/decade) of summer (JJA) daily maximum air temperature indicating the cooling in south-central China (mid Yellow River Basin to the mid-lower Yangtze River Basin) from 1969 to 2000 and (b) trend of summer precipitation (mm/decade) showing the increasing rainfall in the same area. The main branches of Yellow River (north) and Yangtze River (south) are sketched on both panels.

global-scale warming, while the decline of the EA summer monsoon may be related to the regional cooling over south-central China. This means that human activity could contribute to the decline of both monsoons: green house gas production for the winter decline and air pollution for the summer decline. These changes may also feedback to enhance the impact of human activity in the region, since a less windy climate has also consequences for air quality and dust entrainment.

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