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Increases in aerosol concentrations over eastern China due to the decadal-scale weakening of the East Asian summer monsoon

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[1] China has been experiencing increased concentrations of aerosols, commonly attributed to the large increases in emissions associated with the rapid economic development. We show by using a chemical transport model driven by the assimilated meteorological fields that the observed decadal-scale weakening of the East Asian summer monsoon also contributed to the increases in aerosols in China. We find that the simulated aerosol concentrations have strong negative correlations with the strength of the East Asian Summer monsoon. Accounting for sulfate, nitrate, ammonium, black carbon, and organic carbon aerosols, the summer surface-layer $PM_{2.5}$ concentration averaged over eastern China (110°–125°E, 20°–45°N) can be 17.7% higher in the weakest monsoon years than in the strongest monsoon years. The weakening of the East Asian Summer monsoon increases aerosol concentrations mainly by the changes in atmospheric circulation (the convergence of air pollutants) in eastern China. **Citation:** Zhu, J., H. Liao, and J. Li (2012), Increases in aerosol concentrations over eastern China due to the decadal-scale weakening of the East Asian summer monsoon, *Geophys. Res. Lett.*, *39*, L09809, doi:10.1029/2012GL051428.

1. Introduction

[2] Aerosols are major air pollutants that affect human health (U.N. Environment Programme and World Meteorological Organization, Integrated assessment of black carbon and tropospheric ozone: Summary for decision makers, 2011, http://www.unep.org/dewa/Portals/67/pdf/Black_Carbon.pdf), atmospheric visibility [*Wang et al.*, 2009], and global climate change [*Intergovernmental Panel for Climate Change* (*IPCC*), 2007]. Concentrations of aerosols are relatively high in China, which have been attributed to the increases in emissions along with the rapid economic development. A number of studies have reported that the abundances of aerosols can also be influenced by climate change based on the simulated climate change in general circulation models (GCMs) [*Liao et al.*, 2006; *Unger et al.*, 2006; *Bauer et al.*, 2007; *Dawson et al.*, 2007; *Jacob and Winner*, 2009; *Pye et al.*, 2009]. Given the uncertainties in the simulated regional climate change in GCMs, especially in the simulated changes in precipitation [*IPCC*, 2007], it has been difficult to have a robust understanding of the sign and magnitude of the changes in aerosol concentrations by regional climate change.

[3] Climate change in China is associated with the observed weakening of the East Asian summer monsoon (EASM) since 1950s [*Chang et al.*, 2000; *Ding et al.*, 2008]. A strong EASM has strong southerlies extending from southern China to northern China, a deficit of rainfall in the middle and lower reaches of the Yangtze River, and large rainfall in northern China, because the movement of the rain belts is associated with the strength of the southerlies. In contrast, in a weak EASM year, weak southerlies and a deficit of rainfall are found over northern China, and large rainfall occurs in southern China.

[4] The changes in aerosol concentrations in China are coupled with the changes in EASM. While studies in the past decades were generally focused on the impacts of aerosol direct and indirect forcing on the weakening of the Asian monsoon [*Ramanathan et al.*, 2005; *Menon et al.*, 2002; *Bollasina et al.*, 2011], few studies have quantified the impacts of the EASM on aerosol concentrations in China. Observations and modeling studies have shown that the summer monsoon influences seasonal to interannual variations of aerosol concentrations in East Asia. Ground measurements over eastern China [*Duan et al.*, 2006; *Cao et al.*, 2007; *Qu et al.*, 2010; *Ho et al.*, 2011] showed that aerosol concentrations are generally the lowest in summer because of the summer monsoon rainfall. Modeling studies also reported that the strength of the Asian summer monsoon can influence aerosol mass concentrations and optical depths over eastern Asia [*Zhang et al.*, 2010; *Yan et al.*, 2011]. However, none of the previous studies has examined the impact of the decadal-scale weakening of the EASM on aerosol concentrations over eastern China, which is essential for long-term planning of air quality and for understanding the climatic effects of aerosols.

2. Methods

2.1. Model Description and Numerical Experiments

[5] We simulate aerosols using the global chemical transport model GEOS-Chem (version 8.02.01, http://acmg.seas.harvard.edu/geos) driven by the assimilated meteorological fields from the Goddard Earth Observing System (GEOS) of the NASA Global Modeling and Assimilation Office (GMAO). The version of the model used here has a

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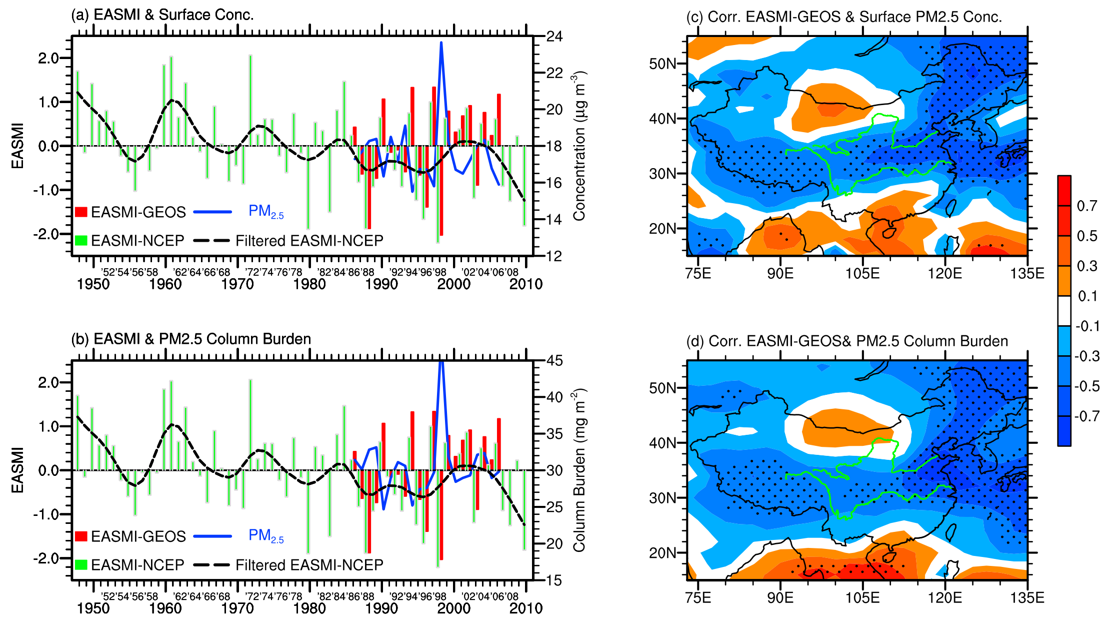

Figure 1. (a) The normalized time series of EASMI (bars, the left y-axis) and the simulated JJA surface-layer $PM_{2.5}$ concentrations (blue line, right y-axis, $\mu g\ m^{-3}$) averaged over eastern China (110°–125°E, 20°–45°N) for years of 1986–2006. The EASMI-GEOS for years 1986–2006 (red bars) are calculated with the GEOS-4 assimilated meteorological data, while the EASMI-NCEP for years 1948–2010 (green bars) are calculated using the NCEP/NCAR reanalysis data. The thick dash line is 9-year Gaussian-type filtered value of EASMI-NCEP, which represent the decadal variation of EASM. (b) The same as Figure 1a, but for the tropospheric column burdens of $PM_{2.5}$ (right y-axis, $mg\ m^{-2}$). (c) Spatial distribution of the correlation coefficients between the EASMI-GEOS and the JJA surface-layer $PM_{2.5}$ concentrations. (d) Spatial distribution of the correlation coefficients between the EASMI-GEOS and the JJA tropospheric column burdens of $PM_{2.5}$. The dotted areas areas indicate statistical significance with 95% confidence (p-value <0.05) from a two-tailed Student's t-test.

horizontal resolution of 2.5° × 2° (longitude by latitude) and 30 vertical layers from the surface to 0.01 hPa. The GEOS-Chem model includes a fully coupled treatment of tropospheric ozone-NOx-VOC chemistry and aerosols including sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), organic carbon (OC), black carbon (BC) [*Park et al.*, 2003; *Park*, 2004], mineral dust [*Fairlie et al.*, 2007], and sea salt [*Alexander et al.*, 2005].

[6] We simulate aerosol concentrations in China for years 1986–2006 driven by the GEOS-4 meteorological fields. The climate-sensitive mineral dust and sea salt aerosols are not considered in this study, because they are not major aerosol components in summer in China based on measurements [*Xuan et al.*, 2000; *Ye et al.*, 2003; *Duan et al.*, 2006]. The years of 1986–2006 are chosen for chemistry-aerosol simulation because these are the years that the GEOS-4 datasets are available. Among the GMAO meteorological products that can be used to drive the GEOS-Chem model with 2° × 2.5° resolution, the GEOS-4 datasets have the longest temporal coverage. In the simulations for 1986–2006, anthropogenic and biomass burning emissions of aerosols and aerosol precursors are fixed at the year 2005 levels. The anthropogenic emissions in Asia are taken from David Streets' emissions inventories [*Streets et al.*, 2003] and are scaled to 2005 levels (see auxiliary material, Table S1 in Text S1).[1] We fix the biomass burning emissions because no datasets are available for the whole period of 1986–2006.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL051428.

2.2. The Calculation of East Asian Summer Monsoon Index (EASMI)

[7] The change in the strength of EASM is commonly represented by the East Asian summer monsoon index (EASMI). The EASMI introduced by *Li and Zeng* [2002] is used in this study to quantify the decadal-scale changes in EASM (see auxiliary material). As shown by the 9-year Gaussian-type filtered values of the EASMI (the black dashed line in Figures 1a and 1b), this smoothed time series of the EASMI changes from mostly positive values (strong monsoon years) in the years of 1948–1979 to mostly negative values (weak monsoon years) in years of 1980–2010, indicating the general trend of weakening of the EASM that has been reported by many previous studies [*Chang et al.*, 2000; *Ding et al.*, 2008].

[8] The bars in Figures 1a and 1b are the time series of the normalized EASMI, which represent the interannual variation of the strength of the EASM. We show the EASMI for years of 1986–2006 calculated with the GEOS-4 assimilated meteorological data (referred to as EASMI-GEOS) and those for years 1948–2010 calculated using the reanalyzed NCEP/NCAR datasets [*Kalnay et al.*, 1996] (referred to as EASMI-NCEP). The EASMI-GEOS agrees well with the EASMI-NCEP over 1986–2006, indicating that the GEOS-4 data has a good representation of the strength of the EASM.

3. Results

[9] Figures 1a and 1b also show simulated summertime (June-July-August, JJA) surface-layer concentrations (Figure 1a) and tropospheric column burdens (Figure 1b) of