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# Winter monsoon variability and its impact on aerosol concentrations in East Asia ☆

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We investigate the relationship between winter aerosol concentrations over East Asia and variability in the East Asian winter monsoon (EAWM) using GEOS-Chem 3-D global chemical transport model simulations and ground-based aerosol concentration data. We find that both observed and modeled surface aerosol concentrations have strong relationships with the intensity of the EAWM over northern (30–50°N, 100–140°E) and southern (20–30°N, 100–140°E) East Asia. In strong winter monsoon years, compared to weak winter monsoon years, lower and higher surface $PM_{2.5}$ concentrations by up to 25% are shown over northern and southern East Asia, respectively. Analysis of the simulated results indicates that the southward transport of aerosols is a key process controlling changes in aerosol concentrations over East Asia associated with the EAWM. Variability in the EAWM is found to play a major role in interannual variations in aerosol concentrations; consequently, changes in the EAWM will be important for understanding future changes in wintertime air quality over East Asia.



## 1. Introduction

Economic growth has unavoidably been accompanied by increased use of fossil fuels in East Asia (Kurokawa et al., 2013). Ohara et al. (2007) showed that the total energy consumption in Asia doubled between 1980 and 2003. Consequently, atmospheric aerosol concentrations over East Asia have increased dramatically in recent decades (Wang and Shi, 2010), and severe air pollution and visibility degradation have therefore occurred more frequently. Severe hazy days with high aerosol concentrations have occurred particularly frequently during winter (Ding and Liu, 2014). For example, China experienced severe regional pollution episodes with hourly $PM_{2.5}$ concentrations reaching 1000 $\mu g\ m^{-3}$ in January 2013 (Wang et al., 2014; Jiang et al., 2015).

Severe haze events typically occur in association with high anthropogenic emissions under weather conditions that favor inefficient ventilation (Xu et al., 2011; Wang et al., 2015; Ye et al., 2016; Zhang et al., 2015). Local and uncontrolled anthropogenic emissions are also closely related to winter weather because cold weather leads to increased coal and wood burning for heat. Weather conditions thus affect the frequency and longevity of severe pollution events, although long-term changes in air pollutant concentrations principally reflect changes in anthropogenic emissions (Yang et al., 2015).

Synoptic weather conditions in East Asia, including atmospheric stability, geopotential height, sea level pressure, temperature, relative humidity, and wind speed, are often subject to large-scale meteorological variability associated with monsoons (Webster et al., 1998; Wang et al., 2008), Arctic Oscillation (Gong et al., 2001; Sun et al., 2012), and El Niño–Southern Oscillation (ENSO) (Wang et al., 2000). Many studies have therefore been conducted to quantify the impacts of large-scale meteorological variability, especially monsoon circulation, on aerosol concentrations over East Asia, although most have focused on summertime conditions (Zhang et al., 2010; Liu et al., 2011; Zhu et al., 2012). Several studies have examined the impact of the Indian winter monsoon on aerosol loading over the Indian Ocean (Nair et al., 2003; Niranjan et al., 2006; Kaskaoutis et al., 2011), but the mechanism of the Indian winter monsoon differs considerably from that of the East Asian winter monsoon (EAWM).

A previous study by Li et al. (2016) revealed long-term variations of the EAWM and their impact on observed haze and fog days in eastern and central China in winter. They found that the observed wintertime haze and fog days correlate negatively with the intensity of the EAWM. A previous modeling study of the relationship

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between the EAWM and winter aerosol concentrations identified anomaly patterns of northern high- and southern low-aerosol concentrations over China in weak winter monsoon periods (Cheng et al., 2016). However, a period of only 10 years (1995–2004) was modeled in this study, which is too short to evaluate the impact of the EAWM on aerosol concentration variability.

In this study, we examine long-term (1980–2013) variations of wintertime aerosol concentrations associated with the EAWM using the GEOS-Chem 3-D global chemical transport model. Anthropogenic emissions in East Asia were fixed at 2006 levels for the full simulation period to focus on the effects of monsoon variability on wintertime aerosol concentrations. We thus obtain better quantitative information regarding the relationships between the EAWM and aerosol concentrations. In conjunction with EAWM forecasting, this quantitative analysis will enable better prediction of interannual variations in wintertime aerosol concentrations over East Asia.

## 2. Methods and data

### 2.1. Model description

We use GEOS-Chem model (v9-01-02) to conduct long-term simulations of aerosols over East Asia (Bey et al., 2001; Park et al., 2006). This model uses assimilated meteorological data from the Modern-Era Retrospective analysis for Research and Applications (MERRA). The native horizontal resolution of the MERRA data is 0.5° × 0.667°, which we regrid to cells of 2° × 2.5° for computational expediency. The MERRA data set has a temporal resolution of 1 h for surface variables and 3 h for atmospheric variables.

The GEOS-Chem model includes primary black carbon (BC), organic carbon (OC), secondary organic aerosol, and $H_2SO_4$–$HNO_3$–$NH_3$ aerosol thermodynamics (Park et al., 2003, 2004; Heald et al., 2005). The model also includes soil dust and sea salt aerosols, but only anthropogenic aerosols were considered in this work because those natural aerosols do not contribute significantly to total winter aerosol concentrations. A thermodynamic equilibrium model (ISORROPIA II) was applied to calculate gas/particle partitioning of $SO_4^{2-}$, $NO_3^-$, and $NH_4^+$ aerosols (Fountoukis and Nenes, 2007). The model simulation of OC and BC follows that of a previous study by Park et al. (2003). Dry and wet deposition have been described by Zhang et al. (2001) and Liu et al. (2001), respectively. We use fixed anthropogenic emissions over East Asia for the base year of 2006 (Zhang et al., 2009) to eliminate the influence of changes in anthropogenic emissions and isolate the effects of the EAWM variability on changes in aerosol concentrations over East Asia.

### 2.2. East Asian winter monsoon index

The EAWM is a major weather and climate system in the northern hemisphere during the boreal winter season (Webster et al., 1998; Jhun and Lee, 2004; Gong et al., 2014). It is characterized by a warm Aleutian low and a cold Siberian high at the surface and northerly winds in the low troposphere (Chen et al., 2000; Wang et al., 2009a; Gong et al., 2014). A simple and representative index is useful in EAWM studies to help explain the mechanisms and variability of the EAWM (Wang and Chen, 2014b). A previous study by Wang and Chen (2010) categorized four types of EAWM based on atmospheric variables used to define the intensity of the winter monsoon, such as upper-level zonal wind shear, low-level wind, sea level pressure (SLP) gradient, and East Asian trough. However, most EAWM indices have focused on the subtropics and tropics (10–30°N) of East Asia (Pak et al., 2014). In contrast, the east–west SLP gradient-based index used in this study is focused mainly on the mid-latitudes (20–60°N) of East Asia (Wang and Chen, 2010; Pak et al., 2014), where rapid economic growth in recent years has resulted in significantly increased anthropogenic emissions.

In this study, the EAWM index proposed by Wang and Chen (2014b) is used, which reflects monsoonal variations in meteorological variables such as surface air temperature, precipitation, and circulation (Wang and Chen, 2014a, b). The definition of the EAWM index is as follows:

$$I_{EAWM} = \frac{\left(2 \times SLP_1^* - SLP_2^* - SLP_3^*\right)}{2},$$

where $SLP_1^*$, $SLP_2^*$, and $SLP_3^*$ indicate the area-averaged, normalized SLP values over Siberia, the North Pacific, and the Maritime continent, respectively. Normalized SLP is used because variation in the SLP is small on the Maritime continent compared to in the mid-latitudes (Wang and Chen, 2014b). Typically, when the EAWM is abnormally strong, above-normal SLP is observed in the mid-latitudes on the Asian continent because of amplification of the Siberian high. In contrast, below-normal SLP is observed in the region around the North Pacific (Zhang et al., 1997; Takaya and Nakamura, 2005; Wang and Chen, 2014b). The difference in SLP between the Siberian high and the Aleutian low enhances the east–west pressure gradient, which is an important feature associated with variations in the EAWM (Wang and Chen, 2010, 2014b). More detailed information on the EAWM index is provided by Wang and Chen (2014b).

## 3. Model evaluation

We first evaluate simulated aerosol concentrations using surface observations of aerosol mass concentrations from the Acid Deposition Monitoring Network in East Asia (EANET, http://www.eanet.asia), the China Atmosphere Watch Network (CAWNET, http://www.cma.gov.cn), the Chinese Ministry of Environmental Protection (MEP, http://datacenter.mep.gov.cn), and the Korea Ministry of Environment (MOE, http://www.airkorea.or.kr). Because gridded anthropogenic emissions from 2006 have been selected to conduct simulations of wintertime aerosols over East Asia, we focus our evaluation on modeled surface aerosol concentrations in winter 2006.

Data from EANET sites are used to evaluate the simulated results for $SO_4^{2-}$–$NO_3^-$–$NH_4^+$ concentrations. To avoid the direct effects of local pollution, EANET sites are mostly located in remote and rural regions. Among a total of 47 EANET sites, data from 17 are used in this study. Although nine sites have been established in China, observations of $SO_4^{2-}$, $NO_3^-$, and $NH_4^+$ aerosols are unavailable for winter 2006. For China, observed carbonaceous aerosol concentrations, including BC and OC, and $PM_{2.5}$ concentrations from CAWNET sites are available for evaluation of the model. The CAWNET network was initiated in 2006 to measure ambient aerosol concentrations in China (Guo et al., 2009). To validate the model, we use the observed daily aerosol concentrations of 15 CAWNET sites.

We use surface observations of $PM_{10}$ mass concentrations from the Air Pollution Index (API) data from the MEP in China (Gong et al., 2007), the MOE in Korea and the EANET in Japan. Daily API data, which are semi-quantitative measurements, from 86 sites in China are used. The $SO_2$, $NO_2$, and $PM_{10}$ concentrations are automatically obtained at each monitoring station. In particular, the $PM_{10}$ data are automatically collected via the tapered element oscillating microbalance (TEOM) or β-ray absorption methods (Choi