AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2015JD023659

Key Points:
- The El Niño Modoki has considerable influences on aerosol concentrations over southern China
- The influences of El Niño Modoki on aerosol concentrations are different during its life span
- Aerosol concentrations anomalies are due to circulation changes associated with El Niño Modoki

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Citation:
Feng, J., J. Li, J. Zhu, and H. Liao (2016), Influences of El Niño Modoki event 1994/1995 on aerosol concentrations over southern China, *J. Geophys. Res. Atmos.*, *121*, 1637–1651, doi:10.1002/2015JD023659.

Received 13 MAY 2015
Accepted 29 JAN 2016
Accepted article online 5 FEB 2016
Published online 27 FEB 2016

Influences of El Niño Modoki event 1994/1995 on aerosol concentrations over southern China

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Abstract The potential influence of El Niño Modoki event 1994/1995 on tropospheric aerosol concentrations was investigated for southern China using the GEOS-Chem model with meteorological data collected from 1986 to 2006. The results suggest that aerosol concentrations increase during mature phases of El Niño Modoki event 1994/1995 (boreal winter) and decrease during decay phases (boreal spring, summer, and autumn). Aerosol concentrations anomalies were found to be due to circulation changes associated with El Niño Modoki, whereby both the horizontal and vertical transport of aerosol mass fluxes determined the pattern of aerosol concentrations associated with the event. In contrast, the role of wet deposition appeared to be limited. Furthermore, these results suggest that the amplitude of anomalous aerosol concentrations associated with El Niño Modoki event 1994/1995 have the potential to reach approximately 30% of the climatological mean, indicating that El Niño Modoki plays an important role in influencing aerosol concentrations over southern China.

1. Introduction

Aerosols are major air pollutants in the atmosphere and have an important influence on atmospheric visibility [*Watson*, 2002], global climate change, and human health [e.g., *Dockery et al.*, 1993; *Pope et al.*, 1995; *Tie et al.*, 2009]. A better understanding of the atmospheric impact of aerosols is therefore important in order to study both air quality and the climate and is beneficial to both scientific and social endeavors. The climate effects of aerosols have received a great deal of attention over the past few decades, including studies investigating both the direct and indirect effects of aerosols. The direct effect of aerosol particles involves absorption and scattering of incoming solar radiation and the Earth's long-wave radiation, thus influencing the radiation balance of the atmospheric system and directly affecting the climate [e.g., *McCormick and Ludwig*, 1967; *Thompson*, 1995]. Aerosols indirectly affect the climate through their role as cloud condensation nuclei and so can change the physical and microphysical characteristics of clouds, leading to changes in the optical properties of clouds and in precipitation rates [e.g., *Hansen et al.*, 1997; *Ramanathan et al.*, 2001; *Zhang et al.*, 2007].

Aerosols are both directly emitted into the atmosphere and created in situ through the chemical production of secondary aerosols. These processes are strongly affected by meteorological variation. Changes in the climate could impact aerosol concentrations through precipitation scavenging, the perturbation of ventilation rates, variation in natural emissions, dry deposition, changes in loss rates, etc. Therefore, understanding the impacts of climate variation on regional air quality is central to future air quality planning. The influence of variation in atmospheric circulation on the transport of aerosols has become a key topic. For instance, *Tan et al.* [1998] found a strong seasonal variation for aerosol concentrations in Hong Kong, with low values during summer in accordance with the onset of the monsoon season. A similar situation was seen in Taiwan [*Chen and Yang*, 2008], and it has been reported that variations in the Asian summer monsoon could impact the vertical transport of aerosols via deep convection and upper tropospheric anticyclones [e.g., *Gettelman et al.*, 2004; *Zhan et al.*, 2006; *Randel et al.*, 2010; *Zhang et al.*, 2010]. And *Zhu et al.* [2012] recently found that the decadal-scale weakening of the East Asian summer monsoon (EASM) has led to increased aerosol concentrations in eastern China, concluding that aerosol concentrations in weaker EASM years are larger than those in stronger EASM years by approximately 20%. The result above suggests that background circulation may have considerable influence on the distribution and amount of aerosol observed in the boundary layer.

The El Niño–Southern Oscillation (ENSO) has a significant impact on the seasonal climate around the world. This pattern corresponds to the leading mode of an empirical orthogonal function analysis performed using tropical Pacific Ocean sea surface temperature (SST), with peak SST anomalies (SSTAs) in the eastern Pacific [e.g., *Rasmusson and Carpenter*, 1982; *Trenberth*, 1997]. This phenomenon, which develops in the Pacific, generates significant anomalous patterns within the regional and global climate [e.g., *Harrison and Larkin*, 1998; *Trenberth and Caron*, 2000]. Recently, a new variant of the El Niño phenomenon has been revealed pertaining to warm SST anomalies located in the central Pacific, referred to as the date line El Niño [*Larkin and Harrison*, 2005], El Niño Modoki [*Ashok et al*., 2007], central Pacific El Niño [*Yu and Kao*, 2007; *Kao and Yu*, 2009], or warm pool El Niño [*Kug et al*., 2009]. The spatial patterns, dynamics, and evolution of this new type of ENSO (herein referred to as El Niño Modoki) have been extensively discussed [e.g., *Ashok et al*., 2007; *Kug et al*., 2009; *Yu et al*., 2010; *Li et al*., 2013]. Several studies have found that this new type of El Niño has important teleconnections and regional climatic effects, which are different from those associated with the canonical ENSO [e.g., *Weng et al*., 2007, 2009; *Feng and Li*, 2011; *Zhang et al*., 2011; *Karori et al*., 2013; *Xie et al*., 2012, 2014; J. Feng et al., Contrasting impacts of developing phases of two types of El Niño on southern China rainfall, submitted to *Journal of the Meteorological Society of Japan*, under review, 2016]. For example, El Niño Modoki has been found to profoundly impact circulation around China. Due to different Rossby wave response, the western Pacific subtropical high (WPSH) would shift more northwestward with El Niño Modoki events, connecting with northeasterlies and decreased rainfall anomalies over south China in the boreal spring and autumn [*Feng and Li*, 2011; *Zhang et al*., 2011], and the WPSH would be northward in the boreal summer [*Weng et al*., 2007; *Karori et al*., 2013], resulting in anomalous cyclone over southern China, connecting with above-normal rainfall there (J. Feng et al., under review, 2016). For the boreal winter, the East Asian winter monsoon-related anticyclone moves northwestward during El Niño Modoki events, causing reduced rainfall anomalies in southern China [*Weng et al*., 2009]. These impacts are distinct from that of the canonical ENSO.

Previous researches indicate that the climate in China is influenced by El Niño Modoki and, more specifically, that the El Niño Modoki appears to influence the climate in China in its developing (previous autumn), mature (winter), and decaying phases (i.e., the following spring and summer). Present-day China has relatively high concentrations of aerosols [*Donkelaar et al*., 2006; *Zhang et al*., 2007; *Tie and Cao*, 2009], commonly attributed to increase in emissions associated with its rapid economic development. As previously mentioned, background circulation plays a key role in determining the distribution of aerosol. Accordingly, a study of the potential influence of El Niño Modoki on aerosol concentrations over China is warranted. The tropical Pacific El Niño Modoki was recognized only recently, and its role in affecting aerosol concentrations remains unclear. If such a relationship exists, it will be important to consider how this impact changes through the seasons as an El Niño Modoki event develops. Therefore, one of the key goals of the present study is to explore the possible impacts of El Niño Modoki on seasonal aerosol concentrations in order to reveal any possible physical processes involved and to determine the relative roles of circulation and rainfall. The remainder of this manuscript is organized as follows. Section 2 describes the model, data sets, and methods used in this study; section 3 outlines the aerosol concentrations anomalies associated with El Niño Modoki events; section 4 discusses the possible physical processes and mechanisms that influence this phenomenon; and conclusions and discussions are provided in section 5.

2. Model, Data, and Methods

2.1. Model Description

The GEOS-Chem model [*Bey et al*., 2001], a three-dimensional model of tropospheric chemistry, was used to simulate aerosol distributions. The model is driven by assimilated meteorological observations from the Goddard Earth Observing System (GEOS) of the NASA Global Modeling and Assimilation Office. The GEOS-Chem model version 8.02.01 was used in the present study (http://acmg.seas.harvard.edu/geos/index.html). All simulations were driven by NASA/GEOS-4 assimilated meteorological fields including winds, convective mass fluxes, mixed layer depths, temperature, clouds, precipitation, and surface properties with a resolution of $2° \times 2.5°$ (latitude by longitude). Especially specific elucidation, the meteorological factors analyzed below are from the NASA/GEOS-4 assimilated meteorological data sets. To save memory, a reduced vertical resolution of 30 levels was applied to our experiment, based on the premise that aerosols are most concentrated in the middle and lower troposphere. Approximately 16 levels in the model were located in the troposphere, with 5 levels below 2 km.

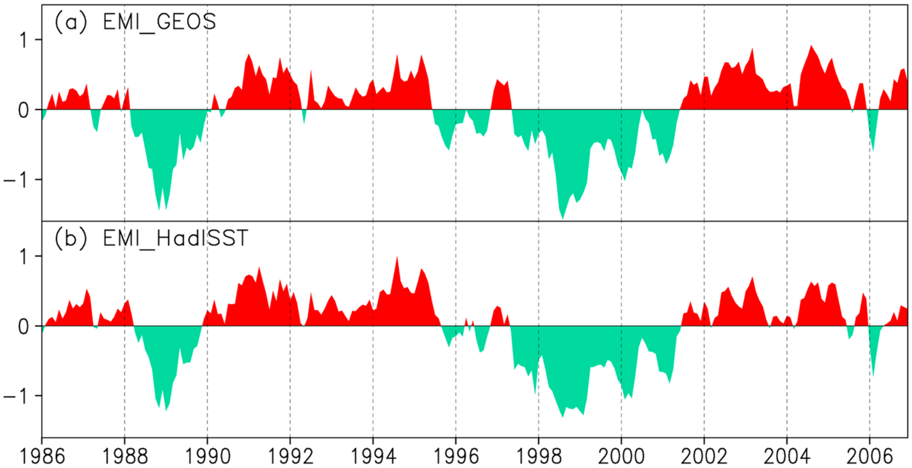

Figure 1. The time series of El Niño Modoki index based on the (a) GEOS-4 input skin temperature data and (b) HadISST for years of 1986–2006 (°C).

The GEOS-Chem model includes a detailed coupled treatment of tropospheric ozone-NO_x-hydrocarbon chemistry as well as aerosols and their precursors, including sulfate, nitrate, ammonium, organic carbon, black carbon, mineral dust, sea salt, and dust aerosols [*Bey et al*., 2001; *Park et al*., 2003, 2004; *Liao et al*., 2007] with all tracers listed by *Liao et al*. [2007]. Aerosol wet deposition within the GEOS-Chem model follows the scheme of *Liu et al*. [2001]. Dry deposition of aerosols and gases follows a standard resistance-in-series model [*Wesely*, 1989], which was implemented as described in *Wang et al*. [1998]. To discuss any possible influences that El Niño Modoki events may have on aerosol levels; concentrations were expressed as $PM_{2.5}$, according to *Malm et al*. [1994] and *Liao et al*. [2007] defined as

$$[PM_{2.5}] = 1.37\times\left[SO_4^{2-}\right] + 1.29\times\left[NO_3^{-}\right] + [BC] + [POA] + [SOA],$$

where 1.37 and 1.29 are factors used for converting the Interagency Monitoring of Protected Visual Environments (IMPROVE) measured sulfate $\left(SO_4^{2-}\right)$ and nitrate $\left(NO_3^{-}\right)$ ions to concentrations of ammonium sulfate and ammonium nitrate, respectively. Sea salt and mineral dust aerosol is not considered, so there is an inherent underestimation of $PM_{2.5}$.

2.2. Emissions

Global emissions of ozone precursors, aerosol precursors, and aerosols in the GEOS-Chem model generally follow *Park et al*. [2003, 2004, 2006], with the exception of anthropogenic emissions in the Southeast Asian domain, which were updated based on the emission scenario described in *Streets et al*. [2003, 2006] and *Zhang et al*. [2007].

The time frame simulated in this study was 1986–2006, corresponding to the period that the GEOS-4 data sets are available. Note that anthropogenic emissions and biomass burning emissions are fixed in the simulation, so that any variation of aerosol concentrations observed in this study was caused by variation in meteorological conditions, thus reflecting the impact of climatic events on aerosol concentrations.

2.3. El Niño Modoki Events

Following *Ashok et al*. [2007], the ENSO Modoki index (EMI) is defined as

$$EMI = [SSTA]_c - 0.5[SSTA]_E - 0.5[SSTA]_W,$$

where square brackets with a subscript represent the area-mean SSTA over the central Pacific region (C: 165°E–140°W, 10°S–10°N), eastern Pacific region (E: 110°–70°W, 15°S–5°N), and western Pacific region (W: 125°–145°E, 10°S–20°N). Here the UK Meteorological Office Hadley Centre's sea ice and SST data sets (HadISST) [*Rayner et al*., 2003] were employed to further test the reliability of the input of underlying forces in GEOS-Chem. Since there is no direct SST data in the GEOS-Chem meteorological fields, we used the skin temperature (i.e., it is surface temperature on land and SST over ocean) to replace. Three well-defined El Niño Modoki events as 1994/1995, 2002/2003, and 2004/2005 are observed from Figure 1. Generally, the EMI calculated with GEOS-4 assimilated meteorological data agreed well with that calculated using the

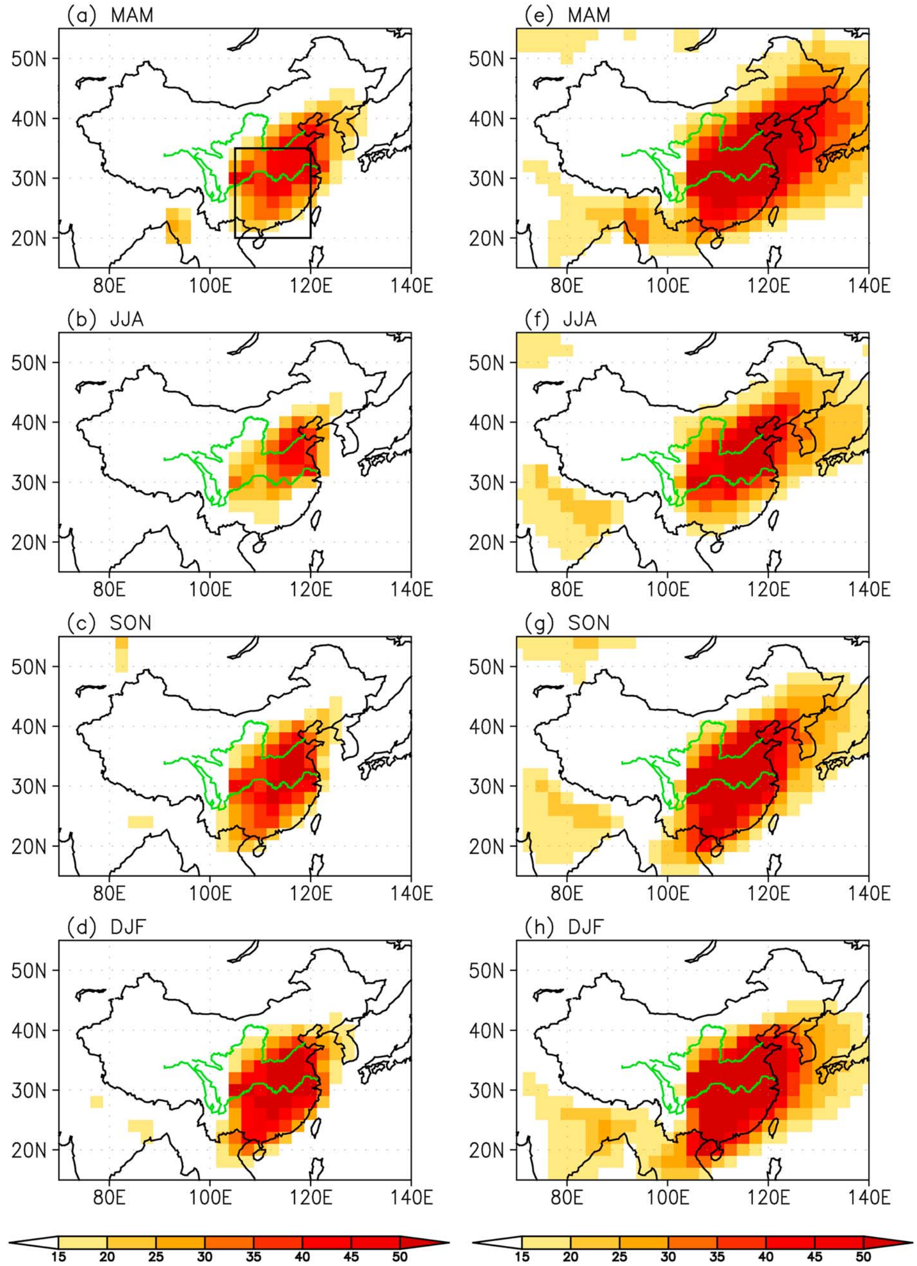

Figure 2. The spatial distribution of the simulated (a–d) surface layer $PM_{2.5}$ concentrations ($\mu g\, m^{-3}$) and (e–h) column burdens of $PM_{2.5}$ ($mg\, m^{-2}$) during the seasonal cycle averaged from 1986 to 2006.

HadISST data sets, with a correlation coefficient of 0.94, significant at the 0.01 level, indicating that the GEOS-4 data are able to provide a good representation of El Niño Modoki events. Note that the mature values (mean of December-January-February) based on HadISST and GEOS in EMI show the extent of differences in the event 2004/2005 (0.64°C versus 0.51°C); thus, this event is not considered since the El Niño Modoki event itself and its impacts are involving strong air-sea interactions. In addition, the climate in eastern China is largely influenced by the EASM, which therefore has a significant impact on aerosol concentrations over eastern China in the summertime [*Zhu et al.*, 2012]. To clearly distinguish the roles of El Niño Modoki and EASM on aerosol concentrations, and to avoid the results of this study being contaminated by the monsoon circulation, only the El Niño Modoki event in 1994/1995 is considered, as the event in 2002/2003 coincides with a strong EASM (Figure 1; as shown in *Zhu et al.* [2012]).

2.4. Transport of Aerosol Mass Flux

The transport of aerosol mass flux is defined as

$$Q = \int_{P_S}^{P_T} f_{EW} \mathrm{d}p\bar{i} + \int_{P_S}^{P_T} f_{NS} \mathrm{d}p\bar{j} = Q_\lambda \bar{i} + Q_\phi \bar{j},$$

where Q is the aerosol transport flux and Q_λ and Q_ϕ are the vertical integrations of the aerosol mass transport fluxes in the zonal and meridional directions, respectively. f_{EW} and f_{NS} are the horizontal aerosol transport fluxes in the zonal and meridional directions for each single level, respectively. P_S and P_T are the pressure values at the surface and top levels, respectively. For southern China, aerosol mass fluxes for the four boundaries are

$$Q_W = \sum_{i=1}^{m} Q_\lambda(i) L_W$$

$$Q_E = \sum_{i=1}^{m} Q_\lambda(i) L_E$$

$$Q_N = \sum_{i=1}^{n} Q_\phi(i) L_N$$

$$Q_S = \sum_{i=1}^{n} Q_\phi(i) L_S,$$

where Q_W, Q_E, Q_N, and Q_S are the aerosol mass fluxes at the western, eastern, northern, and southern boundaries, respectively; L_W, L_E, L_S, and L_N are the lengths of the four boundaries; and m and n are the grid numbers in the zonal and meridional directions, respectively. The net aerosol mass flux in a given region is therefore calculated as

$$Q_{\mathrm{net}} = Q_W - Q_E + Q_S - Q_N.$$

A value of $Q_{\mathrm{net}} > 0$ indicates an increase in aerosol concentrations, and $Q_{\mathrm{net}} < 0$ indicates a decrease in aerosol concentrations. Since the region chosen for this study (105°–120°E, 20°–35°N) locates in the tropics where the latitude effect is small, and the actual length for four boundaries are $0.08\pi a$, $0.08\pi a$, $0.07\pi a$, and $0.08\pi a$ (a is the radius of the Earth), respectively. Considering the differences among the four boundaries are eligible, here we ignore the latitude effect of the Earth; thus, the values presented in Figure indicate the magnitude of the aerosol mass flux per unit.

3. Anomalies in Aerosol Concentrations Associated With the El Niño Modoki Event 1994/1995

Before investigating the possible influences of El Niño Modoki event 1994/1995 on aerosol concentrations, we first accessed the reliability of the meteorological fields and simulations of GEOS-Chem. The input meteorological fields of GEOS-Chem, such as winds, temperature, and humidity, have been evaluated in *Zhu et al*. [2012], and their results suggest that the input meteorological fields of model are highly consistent with the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis [*Kalnay et al*., 1996]. Besides, the spatial distribution of wind anomalies at 850 hPa during 1994/1995 event based on the GEOS-Chem input meteorological fields and those from NCEP/NCAR show similar spatial structures (figures not shown), implying high consistencies between the model meteorological fields and reanalysis. As to the reliability of the model simulations, the simulated aerosols in the GEOS-Chem model have been evaluated in a number of studies by using ground-based measurements in East Asia [*Jeong and Park*, 2013; *Jiang et al*., 2013; *Mu and Liao*, 2014; *Lou et al*., 2014; *Yang et al*., 2015]. And previous studies have reported that the GEOS-Chem could well capture the seasonal and interannual variations of aerosol concentrations and O_3 over eastern China (including southern China) [e.g., *Zhang et al*., 2010, Table 1 and Figure 1; *Wang et al*., 2011, Figure 2 ; *Lou et al*., 2014, Table 4; *Yang et al*., 2014, Figure 2]. In this study, we focus on the relative influences of climatic event on the aerosol concentrations rather than the absolute values of aerosol concentrations, and the impacts of El Niño Modoki on aerosol concentrations during the seasonal cycle are focused. These aspects are well simulated in GEOS-Chem as reported. The above discussions provide confidence for employing the GEOS-Chem to explore the influences of climatic events on aerosol concentrations.

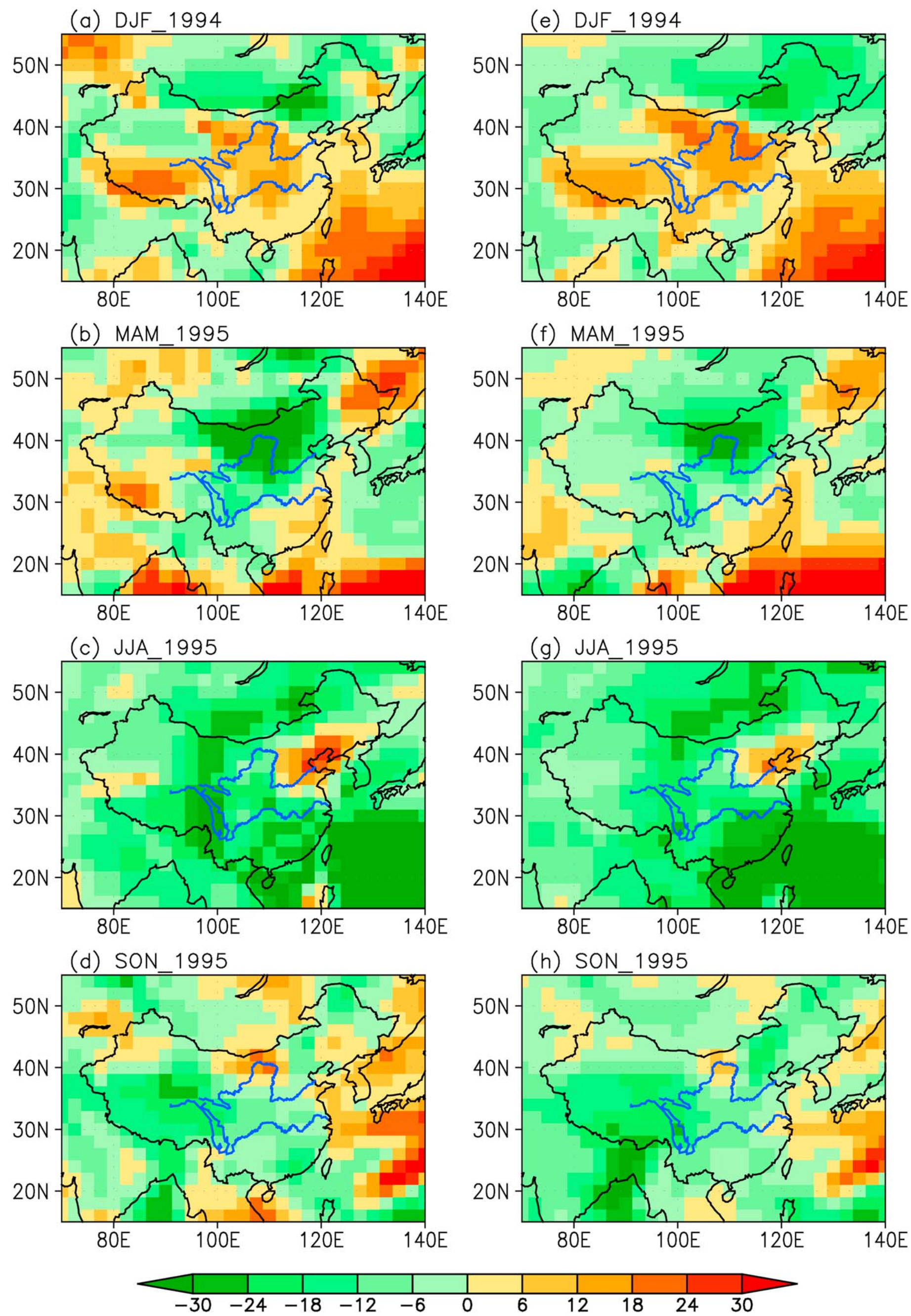

Figure 3. As in Figure 2 but for the spatial distribution of percentage of $PM_{2.5}$ concentration anomalies during El Niño Modoki event 1994/1995 related to the climatological mean (%).

The climatological mean (i.e., averaged from 1986 to 2006) spatial distribution of aerosol is displayed in Figure 2 for each season as a reference to provide the non–El Niño Modoki background. Southern China (105°–120°E, 20°–35°N; as shown in Figure 2a) is located in an area with high levels of aerosol throughout the seasonal cycle, in both surface layer and column concentrations. The maximum aerosol concentrations are reached during the winter, and the minimum occurs in the summertime, consistent with the previous observations [*Ye et al.*, 2003; *Cao et al.*, 2007].

To quantify any influences that El Niño Modoki may have on aerosol concentrations, the relative percentage of an anomaly's departure from the climatological mean during the El Niño Modoki event of 1994/1995 was

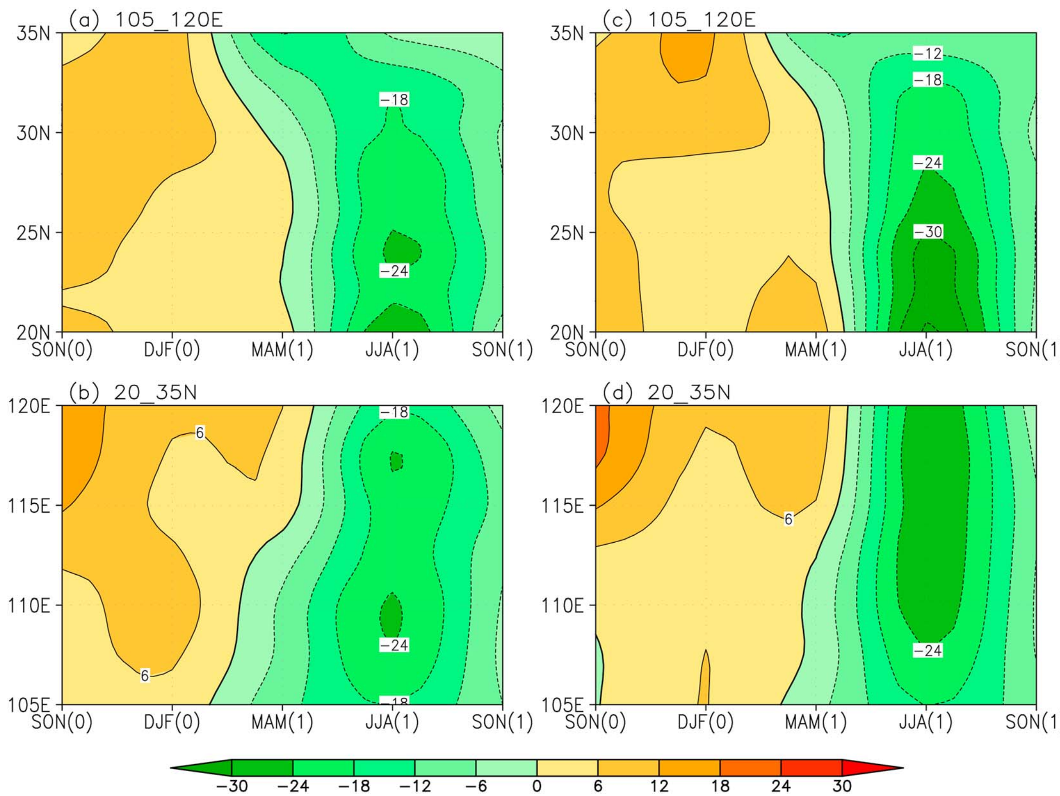

Figure 4. As in Figure 3 but for the (a, c) latitude-time across section averaged over longitude range of 105°–120°E and (b, d) longitude-time across section averaged over latitude range of 20°–35°N during El Niño Modoki event 1994/1995. The SON(0) and DJF(0) refer to the SON and DJF in 1994, and March-April-May (MAM)(1), June-July-August(JJA)(1), and SON (1) refer to the MAM, JJA, and SON in 1995, respectively (%).

calculated as shown in Figure 3. It can be seen that during the mature phase, there are positive aerosol concentration anomalies over most of eastern China. The anomalies are also seen in the southeastern region around the ocean (Figure 3a). However, the positive anomalies are largely reduced in the following spring, particularly in the regions north of 30°N, which correspond to negative anomalies. The aerosol concentrations over eastern China are continuously reduced through the El Niño Modoki summer and autumn, reflecting totally negative anomalies. Similar features are observed in the column concentrations. This result indicates that alongside a developing El Niño Modoki event, aerosol levels in eastern China are governed by a nonuniform process that acts to increase and gradually decrease observed concentrations. This anomalous increase during the winter mature phase could act to worsen the poor air quality associated with the climatological mean. In contrast, negative anomalies during the summer and autumn decay phase

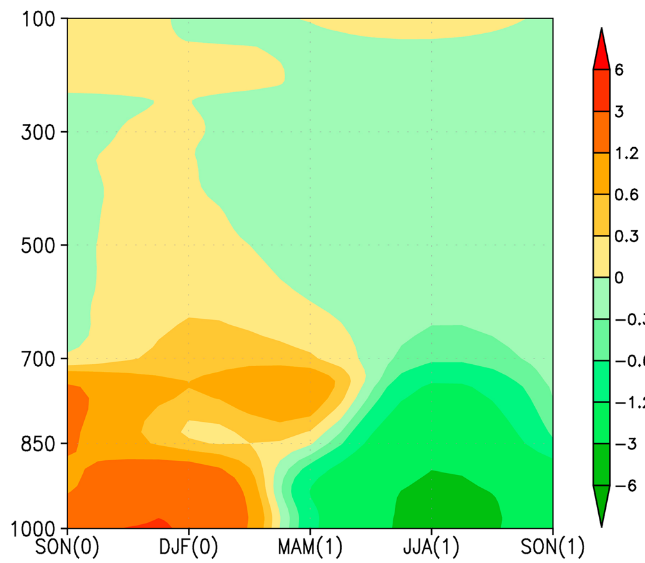

Figure 5. As in Figure 4 but for the pressure-time distribution of areal-averaged $PM_{2.5}$ concentration anomalies over southern China within 105°–120°E, 20°–35°N during El Niño Modoki event 1994/1995 ($\mu g\ m^{-3}$).

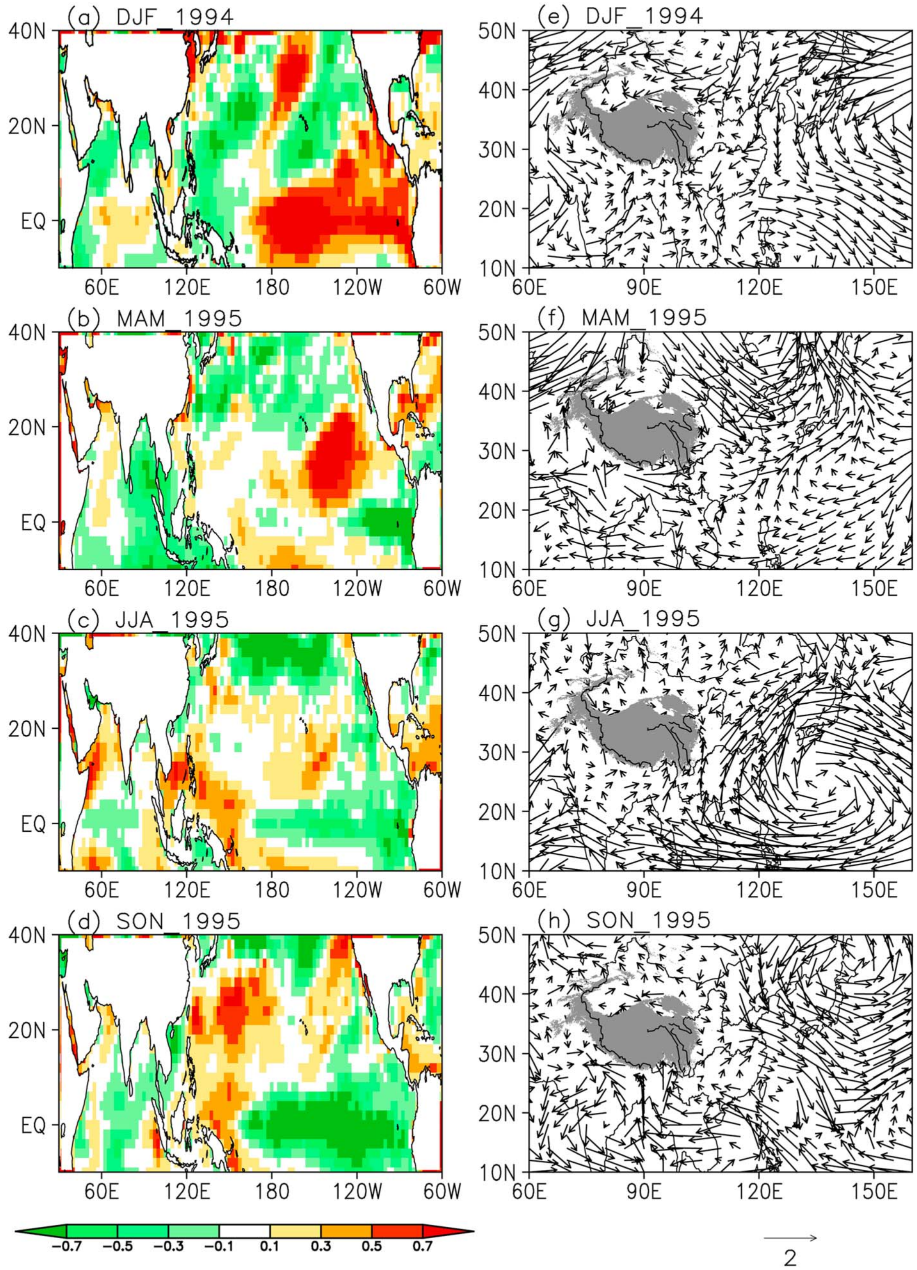

Figure 6. The horizontal distribution of (a–d) skin temperature anomalies (°C) and (e–h) wind anomalies at 850 hPa based on the assimilated meteorological data (m s^{-1}) during El Niño Modoki event 1994/1995.

would result in a relative cleaning of the air, as concentrations are lower during the summer (Figure 3c); i.e., an improvement in air quality would be expected during the decay of an El Niño Modoki event.

These features, which relate variation in aerosol concentrations to the processing of an El Niño Modoki event, can be further seen in Figure 4. Here the region 105°–120°E, 20°–35°N is chosen to display the temporal evolution of aerosol concentrations anomalies, selected as anomaly distribution appears to be approximately uniform across this region, and as the climatological mean aerosol concentrations are relatively large in this area. Variation in aerosol concentrations during the El Niño Modoki event can clearly be seen in the temporal-spatial distribution displayed in Figure 4. Here during the developing phase of the El Niño Modoki event, i.e., September-October-November (SON)(0) to December-January-February (DJF)(0), aerosol concentrations increase while there is an evident reduction during the decay of phase, most prominent in the decaying

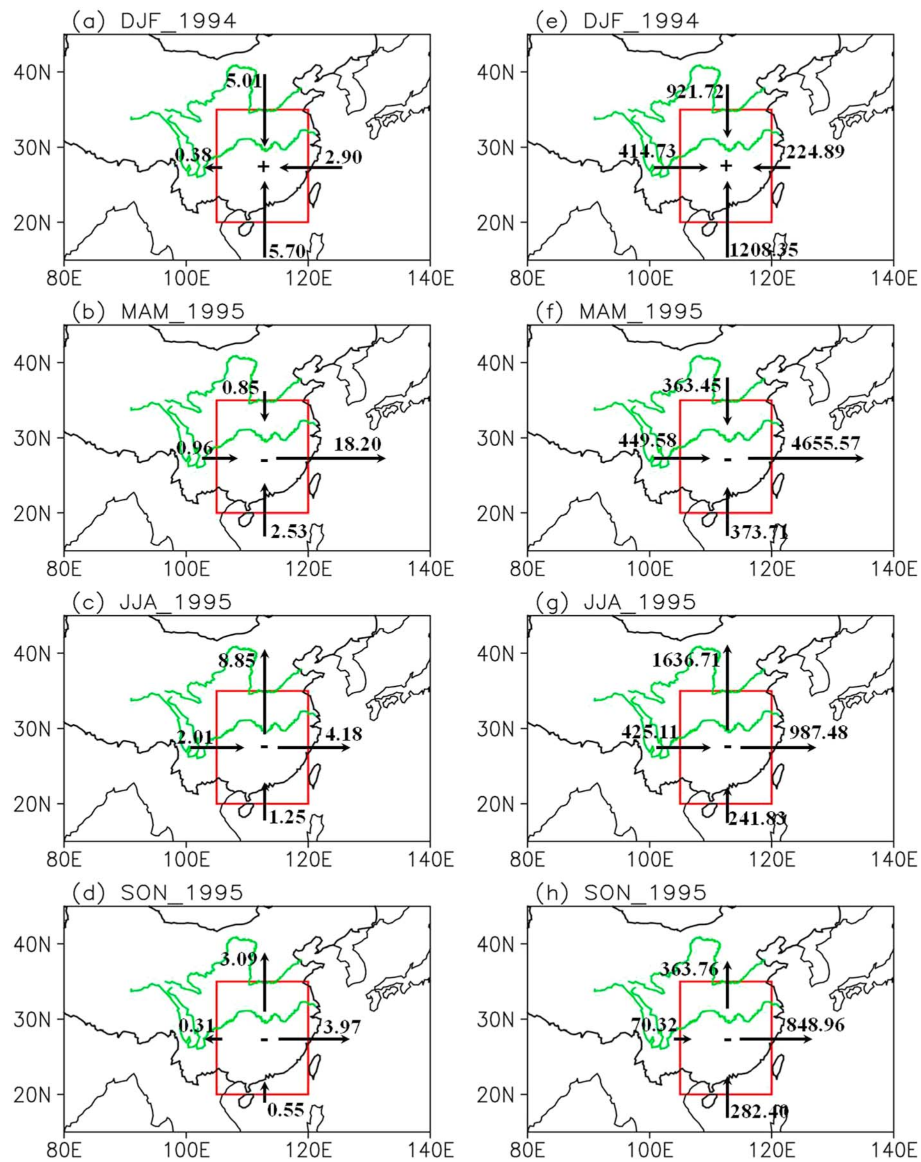

Figure 7. The simulated horizontal budget anomalies of $PM_{2.5}$ concentration mass fluxes (a–d) at 700 hPa and (e–h) integration within the lower troposphere from 1000 to 700 hPa during El Niño Modoki event 1994/1995 ($\mu g\ m^{-3}$).

summer. This study suggests that the amplitude in concentration anomaly could reach approximately 30% of its climatological mean during the summertime decay phase, implying that this process may significantly reduce total aerosol concentrations and therefore plays an important role in cleaning the atmosphere.

The vertical distribution of the aerosol concentrations anomalies averaged over southern China is shown in Figure 5. From the developing to the mature phase of the El Niño Modoki event (from SON(0) to DJF(0)), increased aerosol concentrations are seen from the lower to the upper troposphere; however, opposite case is observed from the mature to the decay phase. The most negative aerosol concentration anomalies occur during the summertime decay phase, consistent with surface layer and column concentrations. Furthermore, Figure 5 shows that the anomalies are strongest in the lower troposphere; thus, in the following section the possible impacts of circulation in the lower troposphere on aerosol concentrations are discussed.

4. Mechanisms of El Niño Modoki on the Aerosol Concentrations

The results described in section 3 indicate that aerosol concentrations exhibit considerable variation during an El Niño Modoki event and that the amplitude of this variation could reach up to 30% in the wintertime

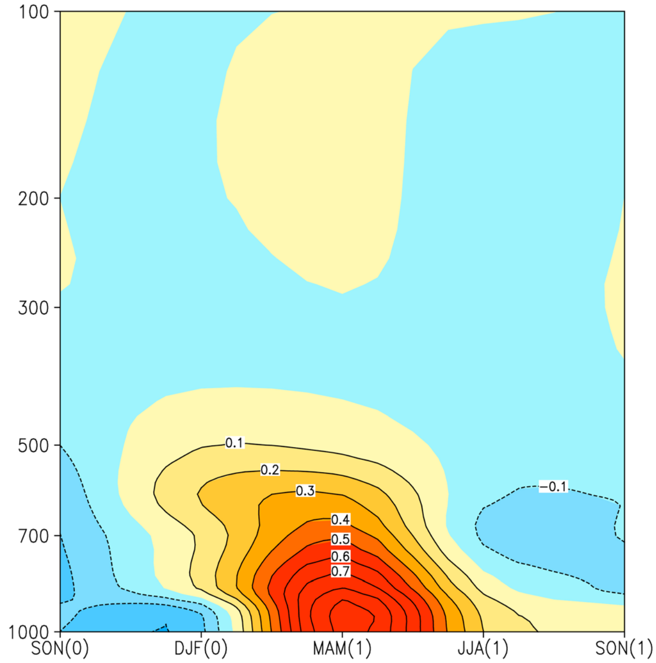

Figure 8. As in Figure 5 but for the pressure-time distribution of simulated $PM_{2.5}$ concentration upward mass flux anomalies averaged over southern China within 105°–120°E, 20°–35°N during El Niño Modoki event 1994/1995 (kg s^{-1}).

mature phase of the event and may possibly exceed this in the summertime decay phase. In this section, the possible processes involved in this phenomenon are discussed.

Circulation anomalies of lower tropospheric winds at 850 hPa and skin temperature over ocean associated with El Niño Modoki events are shown in Figure 6. In response to the warming over the central Pacific (Figure 6a), anomalous convergence occurs during the mature phase of the El Niño Modoki event, with anomalous north westerlies/northerlies over the western Pacific (west of 120°E) to the north of the equator (Figure 6e), implying that the prevailing wind is strengthened in this region, associated with a negative SSTA (Figure 6a). The negative SSTAs act to induce anticyclonic rotational flow over the southern China coastal regions such that southern China is controlled by anomalous southerlies

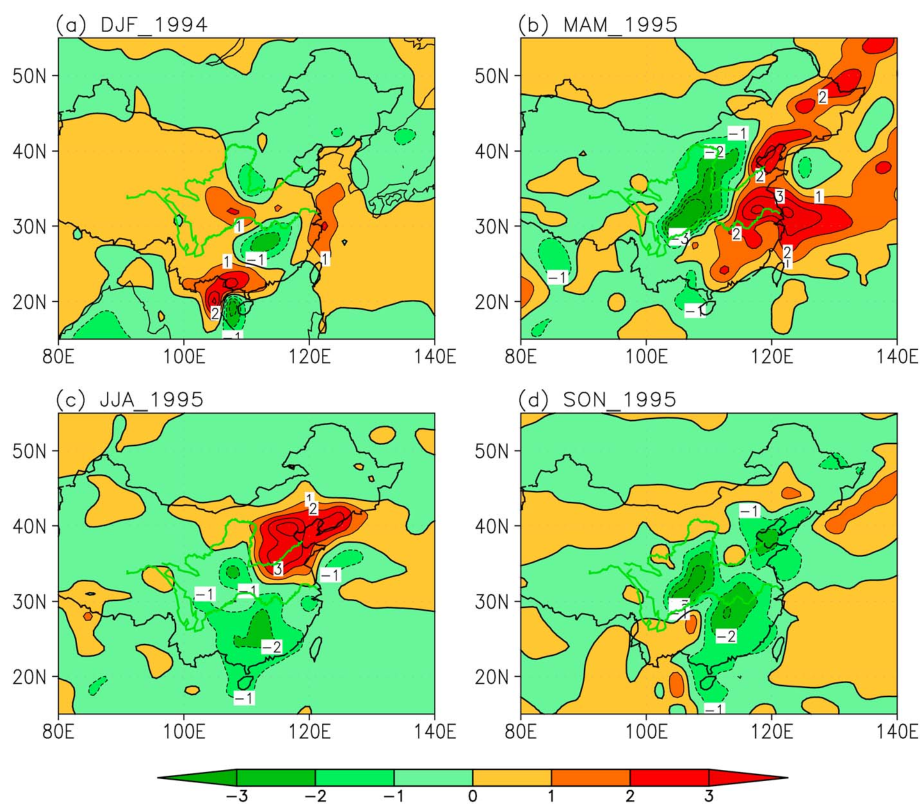

Figure 9. The simulated vertical integral wet deposit flux anomalies during El Niño Modoki event 1994/1995 for (a) mature winter and decaying (b) spring, (c) summer, and (d) autumn (kg s^{-1}).

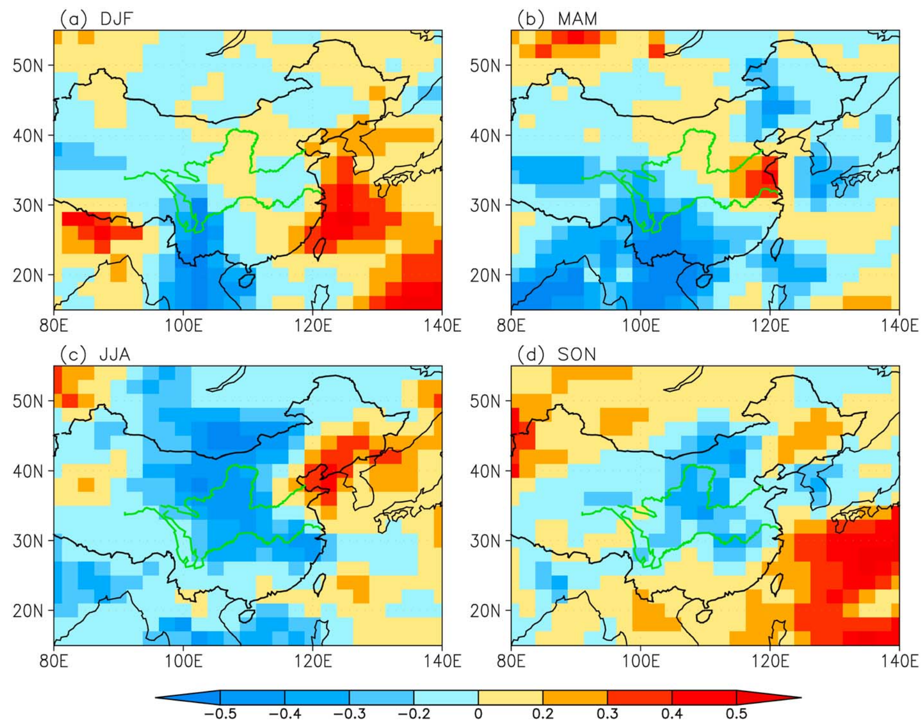

Figure 10. The spatial distribution of the correlation coefficients between the winter El Niño Modoki index and (a) simultaneous, following (b) spring, (c) summer, and (d) autumn surface layer $PM_{2.5}$ concentrations, respectively.

resulting in a weakened prevailing wind (the prevailing wind is northerlies or northeasterlies) over the region (Figure 6e). These conditions are not favorable for air quality and induce positive concentration anomalies in the region. Conversely, positive SSTAs occur in the North Pacific during the occurrence of the El Niño Modoki event [*Weng et al*., 2009] (see Figure 3b). The positive SSTAs intensify convergence in the region, associated with anomalous northerlies. In this case, strengthened northerlies over northern China converge with southerlies from southern China at around 30°N. This anomalous convergence results in enhanced concentrations around 30°–40°N in eastern China. This point is further exemplified by the net aerosol mass flux in the lower troposphere within southern China, whereby a positive aerosol mass flux input in both the zonal and meridional directions (Figures 7a and 7e) contributes to enhanced aerosol concentrations in the region.

In the springtime decay phase, due to a westward shift and weakening of the SSTA located in the central Pacific (Figure 6b), the anomalous anticyclone present in the western Pacific also moves westward. In this situation, anomalous southwesterlies and divergence occur over most of southern China (Figure 6f), corresponding to reduced aerosol concentrations over the region. This result is also seen in the horizontal net mass aerosol flux (Figures 7b and 7f). Although there is a net aerosol input in the western and northern boundaries, the amount is less than the output from the eastern and southern boundaries. Thus, negative aerosol mass input in both the zonal and meridional directions results in a total reduction in aerosol concentrations. Transport in the meridional direction is much weaker than in the zonal direction, indicating that the reduction of aerosol concentrations during the springtime decay phase is mainly associated with zonal wind anomalies.

During the summertime decay phase, the anomalous anticyclone in the western Pacific moves farther northwestward due to a northward shift in the warming SSTA present in the central Pacific (Figure 6c). Anomalous divergent circulation and southeasterlies occur over southern China, paralleling the situation in the strong EASM (Figure 6g). This circulation pattern is favorable for the diffusion of the aerosols, corresponding to negative anomalies in aerosol concentrations. Additionally, there are negative aerosol mass inputs from both the zonal and meridional directions; however, in contrast to the spring, the meridional transport is a significant contributor in this case (Figures 7c and 7g).

During the midautumn decay phase, as the warm SSTA weaken in the central Pacific (Figure 6d), the anomalous anticyclone influencing southern China moves farther northwestwardly to the southeast coastal regions of China (Figure 6h) and the meteorology over southern China is dominated by anomalous southeasterlies. The circulation pattern in this case is opposite to that of the climatological mean. The anomalous southeasterlies emanate from the ocean area and so provide cleaner air than the northerlies from the land, implying that southern China would experience a drop in aerosol levels, a result also reflected by the horizontal mass flux of aerosol (see Figures 7d and 7h).

This analysis shows that with the development of an El Niño Modoki event, the distribution of aerosol concentrations over southern China would exhibit strong seasonality. During the mature phase, aerosol concentrations in southern China would increase significantly and would decrease during the succeeding decay phase accordingly. These variations in aerosol concentrations are closely linked to the circulation anomalies associated with El Niño Modoki. It is important to consider why the aerosol concentrations are different during the spring and summertime decay phases when similar divergent circulation with anomalous southerly winds is observed during both spring and summer decay. To examine this issue, the vertical transport of aerosol mass flux over southern China must be examined further (Figure 8). It is clear that positive anomalies occur for aerosol concentrations in southern China during the springtime decay phase, implying a net downward income of aerosol, corresponding to increased aerosol concentrations in the vertical profile. This would partially offset horizontal aerosol divergence. The strong downward flow is induced by the northwestward shift of western Pacific subtropical high (WPSH), in this case, southern China is influenced by anomalous anticyclonic circulation; inducing anomalous downward flows [*Feng and Li*, 2011, Figure 11a]. Conversely, downward positive transport during the summertime decay phase is much smaller than in spring, since the WPSH would shift northward, and southern coastal region of China is influenced by anomalous cyclonic circulation [*Karori et al*., 2013, Figure 8a]. Therefore, based on both the horizontal and vertical transport of aerosol mass, the peak in aerosol concentrations reduction would occur in the summer.

While changes in rainfall associated with an El Niño Modoki event are expected to have some influences over aerosol concentrations, this is likely to be less important than the influence of circulation. Figure 9 shows the wet deposition anomalies associated with the El Niño Modoki event. Positive anomalies are clearly seen over southern China during the decaying spring (Figure 9b), and negative anomalies are found in the decaying summer and autumn over southern China (Figures 9c and 9d). This situation is opposite to the distribution of aerosol concentrations over southern China as shown in Figure 3. However, for the mature winter, inhomogeneous variations (southern positive and northern negative) are observed over southern China. The negative anomalies are favorable for increased aerosol concentrations, which is consistent with the distribution of aerosol concentrations. This point implies that wet deposit plays a certain role in influencing the aerosol concentrations; however, the influence depends on season and region. These changes in wet deposition are consistent with the general features of increased rainfall in the mature phase of El Niño Modoki [*Weng et al*., 2009], and reduced rainfall associated with the decay spring and autumn of El Niño Modoki [*Feng and Li*, 2011; *Zhang et al*., 2011]. However, anomalies in wet deposition oppose the $PM_{2.5}$ concentration anomalies connected with El Niño Modoki, implying wet deposition plays a limited role in impacting the $PM_{2.5}$ concentrations during the decaying phase of an El Niño Modoki event. Note that the result here agrees with *Wu* [2014] regarding the important role of circulation in determining the pollutants. In addition, *Wu* [2014] reported that the effect of rainfall on aerosol vary with the season, similar feature is seen as shown above, indicating the role of circulation plays a dominant role in impacting the aerosol concentrations in southern China during El Niño Modoki event 1994/1995. In addition, we have compared the GEOS-Chem input precipitation and the observed precipitation data during 1994/1995 and found that the two are consistent with each other (figures not shown). This result indicates that it is not due to the poor quality of precipitation inducing limited role of wet deposit on aerosol concentrations.

5. Summary and Discussion

By using the GEOS-Chem model and its simulations, the potential influence of the recently recognized El Niño Modoki on aerosol concentrations has been demonstrated. These results suggest that different aerosol concentration anomalies are associated with different phases of the El Niño Modoki event 1994/1995. During the mature phase of this event, increased aerosol concentrations are observed, while aerosol concentrations decrease during the decay phase over southern China. This behavior is mainly due to the different circulation anomalies that arise during the El Niño Modoki event. Both horizontal and vertical aerosol mass fluxes were found to contribute to the associated aerosol concentration anomalies, while the role of wet deposition in the decaying phases of El Niño Modoki event 1994/1995 was found to be limited.

It is worth noting that based on this work, the amplitude of anomalous aerosol concentrations associated with the El Niño Modoki event 1994/1995 could reach up to ~30% of its climatological mean value, comparable to the quantity influenced by the EASM (e.g., *Zhu et al*. [2012] found that the summer surface layer $PM_{2.5}$ concentration averaged over eastern China can be 17.7% higher in the weakest monsoon years than in the strongest monsoon years). The influence of El Niño Modoki on aerosol concentrations is therefore significant and must be taken into account in future studies. Furthermore, these findings underscore the importance of taking into account the influence of El Niño Modoki on aerosol concentrations when studying the influence of climate change on aerosol concentrations over China. As El Niño Modoki episodes could occur more frequently in the future [e.g., *Weng et al*., 2007], it would be interesting to fully estimate its impacts on aerosol concentrations to better understand the role of climate on aerosol levels.

This study concludes that El Niño Modoki exerts important influences on the aerosol concentrations over southern China during both their mature and decay phases and suggests that changes associated with circulation have a more dominant influence on seasonal anomalous aerosol concentrations than changes in precipitation. As these results are based on one El Niño Modoki event, and as each El Niño event may not be exactly the same [*Weng et al*., 2007], further insight can be gained by extending the study period to 1986–2006. In Figure 10, positive correlations are located in southern China during the mature phase of El Niño Modoki, and negative correlations are seen over southern China during the decaying phases in spring, summer, and autumn. This result supports the relevance of this study as applied to the investigation of the relationship between El Niño Modoki events and aerosol concentrations over southern China. However, as previously mentioned, the two types of El Niño have opposite influences on regional circulation (e.g., in southern China) and an examination into how the canonical El Niño affects aerosol concentrations in China would be of interest, particularly as the SSTA associated with the canonical El Niño is even larger than that of El Niño Modoki [*Feng and Li*, 2011]. However, this question is not addressed in the present study due to the limitation of the data. In this study period (1986–2006), there are two well-defined El Niño events, i.e., 1987/1988 and 1997/1998; however, both of these coincide with well-defined EASM events that have already been reported as playing a determining role in influencing aerosol concentrations in China. Besides, the autumn of 1995 is related to the developing phase of 1995 La Niña event; thus, whether La Niña events play any role in determining the aerosol concentrations over eastern China and what are the differences between the warm and cold events in the two types of ENSO all need further investigations. Therefore, long-term data sets are needed to explore the possible influence of canonical El Niño on aerosol concentrations over China. In addition, the result in this study is based on the model simulations; long-term available and high-quality aerosol observations are needed to further examine climatic impacts of El Niño Modoki events on aerosol concentrations and to fully access the performance of GEOS-Chem.

In addition, although we have indicated that El Niño Modoki plays a role in impacting the aerosol concentrations over southern China, it should be noted that southern China is also influenced by other large-scale circulations such as the EASM, WPSH, and annular modes; and the impacts of these circulations may interact with each other. How the individual and combined impacts of these circulations could be quantified during different seasons remains an open question and should be addressed in future work.

It has been reported that America is also largely influenced by the canonical El Niño and El Niño Modoki. Furthermore, aerosol concentrations in America peak during summer [*Zhang et al*., 2010], corresponding to the decay phase of an ENSO event. Therefore, it would be of interest to examine the possible influences of ENSO on aerosol concentrations during this phase as well as during its whole life span. A full comparison of the differences in ENSO-influenced aerosol concentrations between America and China would not only provide a better understanding of the aerosol concentrations in both countries but may also bridge the dynamics of the two types of ENSO.

Acknowledgments

We thank three anonymous referees, whose comments improved the paper. This work was jointly supported by "the Fundamental Research Funds for the Central Universities" (2015KJJCB07), 973 Program (2013CB430200), and the National Natural Science Foundation of China (41475076). All results reported in the study are from GEOS-Chem simulations. We thank Harvard Atmospheric Chemistry Modeling Group for providing the GEOS-Chem model (http://acmg.seas.harvard.edu/geos/geos_overview.html). The aerosol concentrations were the output of GEOS-Chem model driven by the NASA/GEOS-4 assimilated meteorological data. The simulations of aerosol concentrations used in this study may be obtained by contacting the authors (fengjuan@bnu.edu.cn and zhujl@mail.iap.ac.cn). The NASA/GEOS-4 assimilated meteorological data are available online at http://wiki.seas.harvard.edu/geos-chem/index.php/Downloading_GEOS-Chem_source_code_and_data#Alternative_download_site. The HadISST data set was obtained from the Met Office Hadley Centre and is available online at http://www.metoffice.gov.uk/hadobs/hadisst/data/download.html.

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