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Impacts of aerosols on regional meteorology due to Siberian forest fires in May 2003

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ABSTRACT

We examine the impacts of aerosols on regional meteorology due to intense Siberian forest fires occurred in May 2003 using both reanalysis data and global model simulations. Our analysis of the NCEP-DOE reanalysis data shows 99% statistical significant changes in meteorological variables over East Asia in May 2003 relative to the 30 years climatology. In particular a significant surface cooling was observed up to −3.5 K over Siberia and extended to the North Pacific region with the surface pressure increases up to 5.6 hPa. Whereas, smoke aerosols affected the large-scale circulations and resulted in the increases in rainfall rates of 2.9 mm day^{-1} averaged over the NW Pacific (10–35°N, 130–170°E). We use the climate model simulations with and without biomass burning emissions over Siberia to examine the effects of smoke aerosols on the regional meteorology. The simulated results show consistent changes in meteorological variables including surface temperature, surface pressure and precipitation rates with the observations over East Asia and the NW Pacific, which support that the observed changes are likely due to smoke aerosols from the Siberian forest fires. The implication is that smoke aerosols from the forest fires should be properly considered to correctly simulate both regional climate and synoptic scale weather patterns.

1. Introduction

Aerosols affect climate by perturbing the Earth's energy and hydrological cycles (Ramanathan et al., 2001a,b; Menon et al., 2002; Lau et al., 2008). In particular, the radiative effects of aerosols have received considerable research attention over the past several years for their climate implications. Recent studies have mainly focused on the role of anthropogenic aerosols on climate (Ramanathan et al., 2001a, 2005; Lau et al., 2006; Collier and Zhang, 2009) by employing global climate models to examine resulting climate responses to idealized or indirectly observed changes in aerosol burden in the atmosphere. Direct observational evidences of aerosol effects on climate are difficult to detect since changes in aerosol concentrations occur over a climate time scale for which other natural or anthropogenic forcing also plays significant roles in a climate system (Lau and Kim, 2006).

Previous studies on biomass burning have focused largely on the measurements of optical properties of smoke aerosols in the context of radiative forcing estimates (e.g., Kaufman, 1998; Eck et al., 2003; Badarinath et al., 2007, 2009; Badarinath, 2008) or on the smoke aerosol mass concentrations for regional air quality degradations (e.g., Jaffe et al., 2004; Generoso et al., 2007). These studies have generally suggested that smoke aerosols from biomass burning acted as a cooling agent resulting in a negative radiative forcing at the surface (Duncan et al., 2003; Pfister et al., 2008). Smoke aerosols are comprised of organic and black carbon aerosols whose optical properties are vastly different. The first scatters solar radiation but the latter absorbs it and thus they result in highly complex climatic impacts (Chung and Seinfeld, 2002). The magnitude, chemical compositions, and morphology of smoke aerosols

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from biomass burning are highly dependent on humidity, burning materials, vegetation types and burning conditions (Eck et al., 2001, 2003) and thus are their radiative effects, which need to be carefully taken into account.

Intense forest fires occurred in Siberia in May 2003. It was one of the largest fires in Siberia in the past decade and affected air quality over East Asia and even in North America by enhancing aerosol concentrations (Jeong et al., 2008). Jeong et al. (2008) previously applied a 3-D global chemical transport model (GEOS-Chem) with the GFED biomass burning emission inventory constrained by the MODIS satellite fire counts observations to simulate smoke aerosol concentrations from the Siberian forest fires in May 2003. The simulated smoke aerosols and their AODs were shown to be in the good agreements with the observed aerosol mass concentrations in surface air and with the MODIS AOD observations (Jeong et al., 2008). In addition, they computed radiative forcing of smoke aerosols from those Siberian fires in May 2003 and showed a large cooling at the surface but a substantial warming in the upper troposphere due to fires. The change in vertical heat balance could significantly alter atmospheric stability and thus regional meteorological patterns (Menon et al., 2002).

We here examine the effects of Siberian fire aerosols on regional meteorology in East Asia during May 2003 using the National Centers for Environmental Prediction-Department of the Energy (NCEP-DOE) reanalysis II (NCEP R-2) data and the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM3) with a 3-D global chemistry-transport model (GEOS-Chem). Our analyses of the NCEP R-2 data and the GCM experiments show a consistent evidence that the observed changes in meteorological variables including surface temperature, surface pressure, and precipitation over the NW Pacific were likely due to Siberian fire aerosols indicating a direct and significant impact of aerosols on regional meteorology.

2. Data and models

We use the NCEP R-2 data from 1979 to 2008 to diagnose changes in regional meteorology over East Asia in May 2003. Data include monthly-mean surface air temperature, pressure, and total precipitation rates. We also compute anomalies of those variables for May 2003 by subtracting the 30 year May climatology from the monthly-mean values for May 2003 to examine the observed changes. For the data analysis a statistical significance test (t-statistic) at 99% confidence level (two-sided $t \geq 2.756$) was conducted. In addition, we also use the monthly land precipitation data from Climatic Research Unit (CRU), University of Anglia, UK, during 1958–2008 (Mitchell and Jones, 2005) and the precipitation data derived by the Global Precipitation Climatology Project (GPCP) from 1979 to 2008 (Huffman et al., 1997; Adler et al., 2003).

To understand observed meteorological changes and their triggering mechanisms we carried out the model simulations using the NCAR CAM3 model (Collins et al., 2006) coupled to the Community Land Surface Model version 3 (CLM3) (Dickinson et al., 2006). The CAM3 model is based on the finite volume (FV) dynamical core at a $2^\circ \times 2.5^\circ$ horizontal resolution and with 26 levels (Collins et al., 2006). For this study, the ocean and the ice are not fully coupled but communicated to the atmosphere via an oceanic surface boundary condition, given as mid-month values of sea surface temperature (SST) as well as sea ice fractions over the polar region. The SST input data including sea ice fraction are a time series of multi-year SST forcing data constructed by concatenating and interpolating global HadISST data from the Met Office Hadley center (Rayner et al., 2003) to FV core grids of CAM3. The observed multi-year SST forcing may also serve for the purpose of eliminating the uncertainty related to interactions between the atmosphere and the ocean although the ocean is not likely to be involved in such a short time scale change shown below.

We conducted a baseline simulation using the daily-varying global climatological aerosol concentrations and a sensitivity simulation using the daily-varying global climatological aerosol concentrations plus smoke aerosol concentrations from the Siberian fires. The smoke aerosol concentrations are determined as differences between the GEOS-Chem simulations with and without the GFED biomass burning emissions from the Siberian forest fires (40°N–80°N, 90°E-160°E) (Jeong et al., 2008). Except for the smoke aerosol concentrations, both simulations are forced by other identical forcing of historical ozone, solar cycles, volcanoes, greenhouse gases, sulfur dioxide/trioxide, and carbon dioxide. Therefore, the simulated changes are solely due to the presence of Siberian fire aerosols and are determined by differences between the baseline and the sensitivity simulations. The set of simulations begin on January 1st 2003 with initial meteorological fields, which are obtained from the 33 years CAM3 spin-up integration from 1970 with daily climatological aerosols from the GEOS-Chem simulations, driven by GEOS-4 assimilated meteorology from the GMAO (Park et al., 2004). Prescribed data include aerosol optical depths of sea salt, sulfate, soil dust, and black and organic carbons for the period of 1988–2006. The daily aerosol data are interpolated onto CAM3 grids during the model integration. Therefore, the simulations here are very similar to those by Lau et al. (2006) in that the evolution of aerosol optical thickness (AOT) is prescribed.

3. Results

Fig. 1 shows the enhancement of the monthly-mean AOD due to the Siberian forest fires and the NCEP R-2 anomalies for surface temperatures, surface pressures, and precipitation rates for May 2003, respectively. The AOD values are obtained as differences between two CAM3 simulations with and without Siberian fire aerosols. Carbonaceous aerosols are major contributors to the simulated AOD values as high as 0.35, which are in good agreements with the MODIS satellite observations (Jeong et al., 2008). In Fig. 1, anomalies of meteorological variables are displayed with contours and color shadings and the latter indicates statistically significant changes above the 99% confidence level.

A large temperature drop in surface air occurred up to −3.5 K over Chita and Amur regions in Russia and extended to the North Pacific region. The pattern in surface cooling is consistent with that in the AOD enhancement (Fig. 1a). The surface cooling in Siberia and downwind regions (Fig. 1b) is attributed to decreases in solar radiation at the surface due to aerosol extinctions (direct effect), consistent with recent studies by Badarinath et al. (2007) and Badarinath (2008). However, there are regions in Northeast China (Manchuria) showing significant surface warming, which is related to decreases in total cloud cover and thus increases in incoming solar radiation as well as enhanced downward motion over the region (not shown).

Fig. 1c shows significant positive anomalies in monthly-mean surface pressure from Siberia to the NW Pacific. Regions with significant surface pressure increases are generally consistent with regions with temperature decreases. The pronounced rise in the surface pressure may result from a decrease in mean-column atmospheric temperature as ensured by the hydrostatic balance. The regions of positive surface pressure anomaly are thus consistent with those of downward motion (Fig. 3) and regions with decreases in precipitation rates (Fig. 1d). The cooling in surface air over Siberia and downwind regions (Fig. 1b) reduces the atmospheric instability, thus suppressing precipitation (Fig. 1d) in the vicinity. In contrast, precipitation rates over the NW Pacific increased and this is likely due to large-scale changes in secondary circulations as confirmed

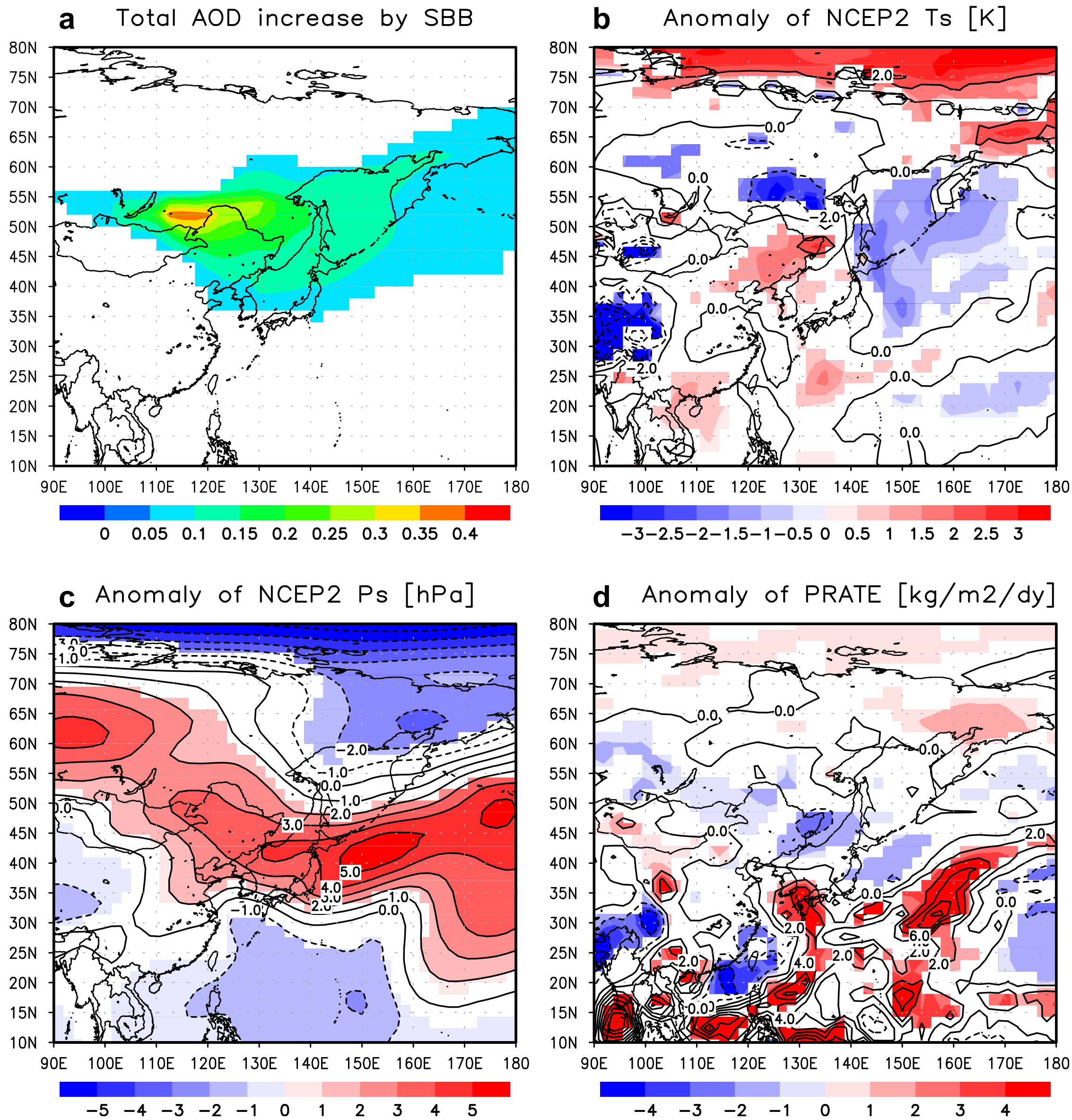

Fig. 1. Horizontal distributions of (a) simulated increases in aerosol optical depths (AODs) due to the Siberian forest fires and anomalies in the NCEP R-2 data for (b) surface air temperature, (c) surface pressure, and (d) total precipitation rate in May 2003. AOD values shown here are obtained using a global 3-D chemical transport model (GEOS-Chem) with GEOS-4 assimilated meteorology. Anomalies are computed by subtracting 30-yrs May climatology from May 2003 data. Color shadings indicate statistically significant anomalies above 99% confidence level.

by model simulations shown in Figs. 2 and 3 below. These spatial patterns of precipitation changes are also consistently found in the Global Precipitation Climatology Project Version 2 monthly precipitation data (Adler et al., 2003) (not shown). It is noteworthy that the regions of positive south–north surface pressure gradient are well matched with those of precipitation increases over South Korea to the NW Pacific.

Fig. 2 shows differences in monthly-mean surface variables between the CAM3 simulations with and without the Siberian forest fire aerosols. The inclusion of the fire aerosols into the CAM3 simulation results in a cooling in surface air over Siberia and downwind region (Fig. 2a). A decrease in surface temperature is up to −4 K, comparable with statistically significant anomaly shown in the NCEP R2 data (Fig. 1b). However, the simulated cooling center is located north to the intense fire occurrences and is wider than the observations. We note that the cooling over Siberia is caused not only by the direct effect of aerosols but also by the induced cold advection due to the large-scale circulation changes (Fig. 2a) (Lau et al., 2006). The model also successfully reproduces the observed increases in surface air pressure from Siberia to the NW Pacific (Fig. 2b).

On the other hand, the resulting changes in precipitation rates due to smoke aerosols in the model (Fig. 2c) show some similarities and discrepancies in comparison with the observations. The most noticeable feature is the increase in rainfall rate over the ocean, generally south of 40°N, which corresponds to the region with upward motion (Fig. 3). The top panel in Fig. 3 shows the simulated cross sections of zonal mean temperatures and vertical velocities due to the Siberian fire aerosols compared with the NCEP anomalies in the bottom. It is found that the atmospheric warming in the south and the cooling in the north occur due to smoke aerosols in the model and are in good agreements with the statistically significant changes of the NCEP anomalies above the 99% confidence level. The resulting upward and downward motions are also

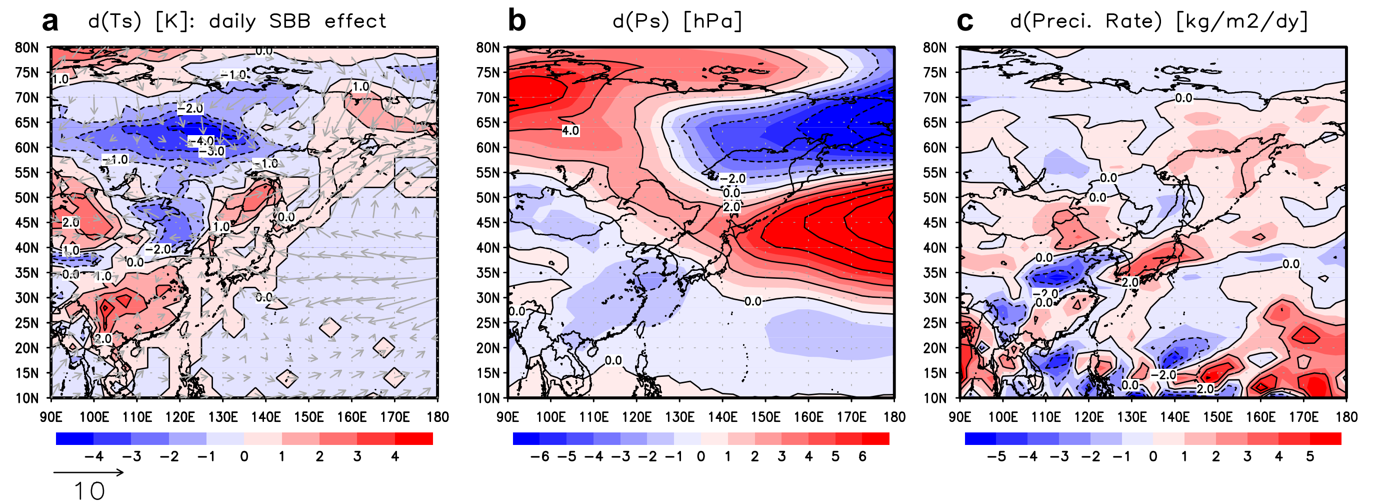

Fig. 2. Simulated changes of (a) surface temperature and wind vector (m s^{-1}), (b) surface pressures, and (c) precipitation rates due to the Siberian forest fires aerosols in May 2003. Values are obtained from the differences between the CAM3 simulations with and without fire aerosols.

clearly shown in both the model and the NCEP data. The upward motion in the south appears to trigger the precipitation increase in the ocean.

However, the changes in precipitation over the continent are more complex. For example, the decreases in precipitation rates over Siberia are generally consistent with the observed NCEP anomaly but the model overestimates the decrease in precipitation rates over northern China. In addition, the simulated precipitation generally decreases in further north (over the latitudes higher than 70°N) and differs from the observations. These discrepancies reflect

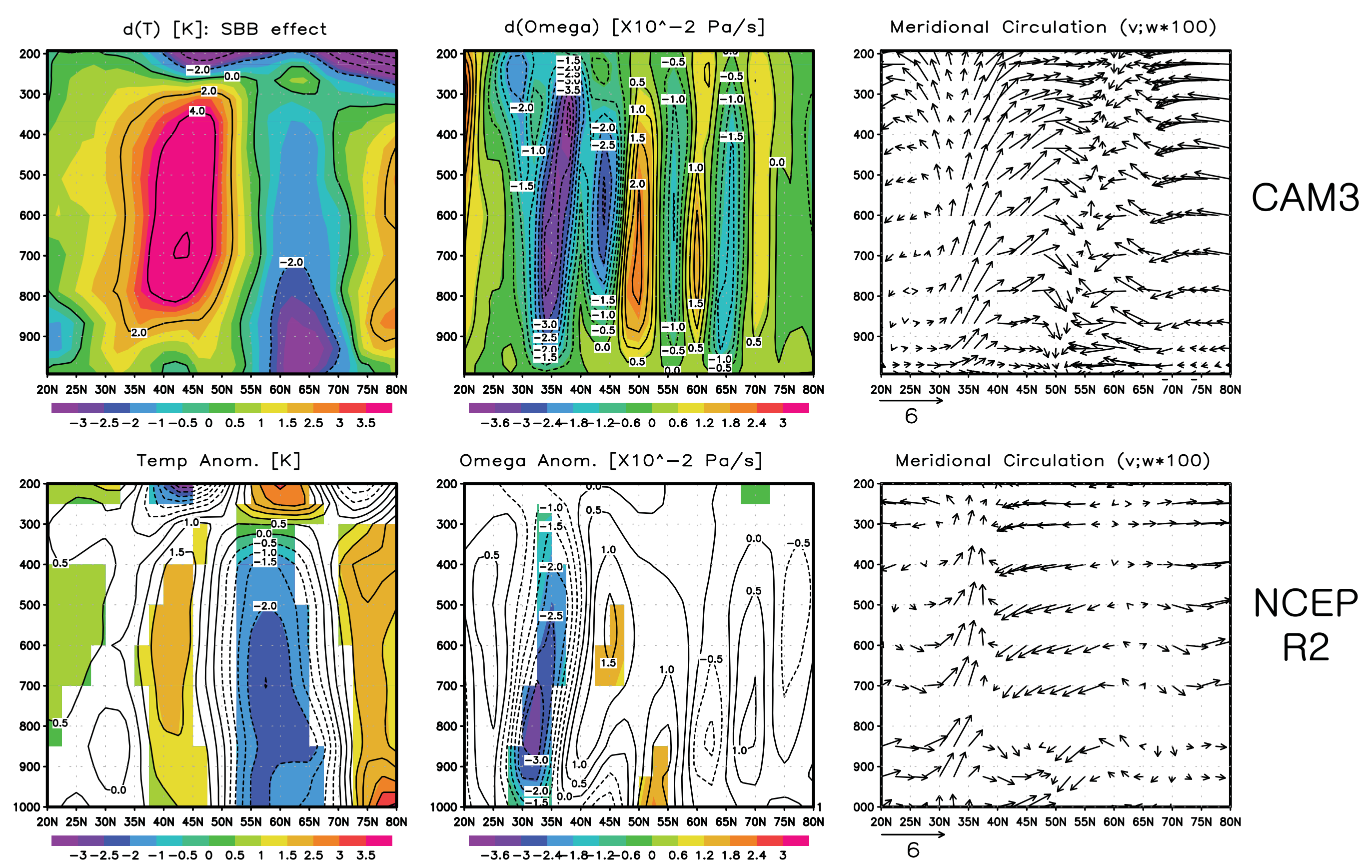

Fig. 3. Simulated changes of zonal mean temperature (top left), omega values (ω) (top middle), and scaled wind vectors top right) at 120–140°E as functions of latitude and pressures due to smoke aerosols from the Siberian forest fires. Positive and negative omega values indicate downward and upward vertical motions, respectively. Simulated values are obtained from the differences between the CAM3 simulations with and without smoke aerosols. The bottom panel shows the anomalies in the NCEP R-2 data for zonal mean temperature (bottom left), omega values (ω) (bottom middle), and scaled wind vectors (bottom right) as functions of latitude and pressures in May 2003. The anomalies are computed by subtracting the 30-yrs May climatology from the May 2003 data. Color shadings in the bottom panel indicate statistically significant anomalies above the 99% confidence level.

the difficulty of precipitation simulations by climate models. We also have to acknowledge that the aerosol indirect effect was not taken into account in the model simulations and needs to be considered in the future. Despite these issues, it is found that the overall spatial patterns of the simulated changes due to the Siberian forest fires are generally consistent with the observed NCEP anomaly data for May 2003, supporting that the observed changes of regional meteorology over East Asia in May 2003 are likely due to the effect of smoke aerosols from the Siberian forest fires.

4. Summary and discussions

The anomalies of the NCEP R-2 data for May 2003 show statistically significant large-scale changes over East Asia above the 99% confidence level. The anomalous features of temperature, pressure, and precipitation rate in surface air were coincident with large increases of atmospheric aerosols from the intense Siberian forest fires occurred in May 2003. Here, we present both data analysis and climate model simulations to examine the effects of Siberian fire aerosols on those observed changes in regional meteorology. Using the CAM3 simulations with the simulated aerosol fields from the GEOS-Chem model driven by the assimilated meteorology, we were able to largely reproduce the observed large-scale meteorological features and concluded that the observed changes in regional meteorology were likely due to the Siberian fires, which need to be considered importantly not only for better regional climate simulations but also for synoptic scale weather prediction.

Limitations in our study, however, still remain due to a number of factors, including the use of prescribed aerosol forcing and the lack of aerosol indirect effects, etc. In particular, the prescribed aerosols may have caused dynamical inconsistency in climate simulations since aerosol spatial distributions were determined by the assimilated meteorology in CTM. This issue will be explored later in our companion paper. In addition, the interactions between aerosol changes and meteorology through aerosol indirect effect were not taken into account in the model experiments. In spite of these limitations, the simulated results indicate that aerosols direct effects can be significant enough to cause considerable changes in regional meteorology.

In addition, the use of daily-varying aerosols is crucial for the proper inclusion of fire aerosol effects on synoptic meteorology, which is different from traditional climate simulations. On the other hand, model experiments are sensitive to initial state of the atmosphere, but our model experiments after enough spin-up runs with consistent aerosol climatology show the significance of Siberian fire aerosols effect on regional meteorology. The robustness of our simulated results is assured by consistent model results as above from 1) five CAM3 ensemble simulations for each experiment with and without Siberian fire aerosols, wherein each member of ensembles begins on different dates such as the 1st to 5th of January 2003 and 2) additional simulations using monthly climatological SST.

According to recent studies, the climatic impact of forest fires will be of increasing importance since the number of forest fires is expected to increase with increasing temperature in the warming climate (Stocks et al., 1998; Westerling et al., 2006; Soja et al., 2007; Malevsky-Malevich et al., 2008). Our result suggests that an accurate quantification of fires effects is needed to correctly simulate regional weather and climate in particular under the future global warming conditions.

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