A Simulated Climatology of Asian Dust Aerosol and Its Trans-Pacific Transport. Part I: Mean Climate and Validation

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ABSTRACT

The Northern Aerosol Regional Climate Model (NARCM) was used to construct a 44-yr climatology of spring Asian dust aerosol emission, column loading, deposition, trans-Pacific transport routes, and budgets during 1960–2003. Comparisons with available ground dust observations and Total Ozone Mapping Spectrometer (TOMS) Aerosol Index (AI) measurements verified that NARCM captured most of the climatological characteristics of the spatial and temporal distributions, as well as the interannual and daily variations of Asian dust aerosol during those 44 yr. Results demonstrated again that the deserts in Mongolia and in western and northern China (mainly the Taklimakan and Badain Juran, respectively) were the major sources of Asian dust aerosol in East Asia. The dust storms in spring occurred most frequently from early April to early May with a daily averaged dust emission (diameter $d < 41$ μm) of 1.58 Mt in April and 1.36 Mt in May. Asian dust aerosol contributed most of the dust aerosol loading in the troposphere over the midlatitude regions from East Asia to western North America during springtime. Climatologically, dry deposition was a dominant dust removal process near the source areas, while the removal of dust particles by precipitation was the major process over the trans-Pacific transport pathway (where wet deposition exceeded dry deposition up to a factor of 20). The regional transport of Asian dust aerosol over the Asian subcontinent was entrained to an elevation of <3 km. The frontal cyclone in Mongolia and northern China uplifted dust aerosol in the free troposphere for trans-Pacific transport. Trans-Pacific dust transport peaked between 3 and 10 km in the troposphere along a zonal transport axis around 40°N. Based on the 44-yr-averaged dust budgets for the modeling domain from East Asia to western North America, it was estimated that of the average spring dust aerosol (diameter $d < 41$ μm) emission of ~120 Mt from Asian source regions, about 51% was redeposited onto the source regions, 21% was deposited onto nondesert regions within the Asian subcontinent, and 26% was exported from the Asian subcontinent to the Pacific Ocean. In total, 16% of Asian dust aerosol emission was deposited into the North Pacific, while ~3% of Asian dust aerosol was carried to the North American continent via trans-Pacific transport.

1. Introduction

Asian dust aerosol mainly originating from the high-elevation arid and semiarid regions in China and Mongolia, mostly during spring (Chen et al. 1999; Merrill et al. 1989; Sun et al. 2001; Xuan and Sokolik 2002; Zhang et al. 1997, 1998, 1996a, 2003a; Zhou 2001), is transported by surface level northwesterly winds associated with the Asian winter monsoon over the Asian continent and by westerly winds in the free troposphere from the eastern Asian continent to the Pacific Ocean, and occasionally to North America (Duce et al. 1980; Holzer et al. 2003; Husar et al. 1997, 2001; Uematsu et al. 1983; Uno et al. 2003). Asian soil dust is regarded as a major component of the tropospheric aerosols in the

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global atmosphere. Soil dust aerosols are considered to have a considerable direct impact on climate by altering the global radiative balance between incoming solar and outgoing planetary radiation in the atmosphere (Sokolik and Toon 1996; Sokolik et al. 2001; Takmura et al. 2002; Tegen and Fung 1994). In addition, they may modify cloud properties and precipitation development (Levin et al. 1996) as well as cycles of atmospheric species through heterogeneous reactions and photolysis rates (Dentener et al. 1996). The trans-Pacific transport of Asian dust aerosol not only causes significant changes in radiative forcing and atmospheric chemistry over large areas but also links the biogeochemical cycle of land, atmosphere, and ocean when dust aerosols are deposited to the ground and ocean (Bergametti 1998; Zhang et al. 1993). Atmospheric dust aerosols are also potentially highly sensitive to changes in climate, carbon dioxide, and human land use (Mahowald and Luo 2003) and therefore have substantial climatic variability (Liu 1985; Mahowald et al. 2003; Sun et al. 2001; Zender et al. 2003).

Despite its climatic and geochemical importance, the climatology of Asian dust aerosol and its trans-Pacific transport is not well known because of a short and sparse record of dust observations. Previous observations, including meteorological observations of visibility and lidar and satellite remote sensing data, lack either the spatial coverage or length of record necessary to establish a comprehensive climatology. To date, the most commonly used approach to analyze the spatial and temporal distributions of dust storm frequencies is to use the visibility data from surface observation networks because of its long time of records (Chung 1992; Natsagdorj et al. 2003; Sun et al. 2001, 2003; Zhou 2001; Zhou and Zhang 2003). However, this approach is only a semiquantitative indicator for dust aerosol loading, as it focuses on the frequency rather than the strength of dust storms. That is, beyond the threshold criteria for reporting an event, the quantities of dust aerosol vary from storm to storm, and a region with less frequent but more severe dust storms may be a stronger source than areas with more frequent but weaker events. Observer bias is also an intrinsic limitation of the visibility approach. Furthermore, there is not necessarily a direct correspondence between dust storm frequency and dust source strength because dust transported into a region also can reduce visibility. Satellite data have been used to analyze dust aerosol loading and in reconstructing the transport patterns of dust aerosols (Chung et al. 2003; Moulin et al. 1998; Prospero et al. 2002). This approach has limitations due to the interference from cloud cover and uncertainties in assumptions concerning particle size/shape and refractive index.

Numerical modeling provides an alternative and systematic approach for examining the properties, climatology, and interannual variability of dust aerosols. Previous modeling efforts have included the use of microphysical, radiative transfer, chemical transport, weather forecasting, and global and regional climate models (Liu et al. 2003; Luo et al. 2003; Ginoux et al. 2001; Tegen and Miller 1998; Uno et al. 2003; Zender et al. 2003). In our own research, a regional climate model with a size-distributed active aerosol algorithm, Northern Aerosol Regional Climate Model (NARCM), was used to simulate the production and transport of soil dust in East Asia and over the northern Pacific Ocean during the Aerosol Characterization Experiment-Asia (ACE-Asia) in spring 2001 (Gong et al. 2003a). This model is driven by National Centers for Environmental Prediction (NCEP) reanalyzed meteorological fields as initial and nudged boundary conditions and considers all atmospheric aerosol processes. A detailed soil texture dataset and up-to-date desert distribution in China were introduced to drive the size-distributed dust emission module. Surface observations of the size distribution of dust aerosol during local dust storm conditions at nine Chinese desert regions (Zhang et al. 2003b) were used to constrain the size distribution of vertical dust flux and to simulate the production of Asian dust aerosol. Comparisons of NARCM simulations with ground-based and aircraft measurements in East Asia and North America together with satellite observations showed that the model captured most of the dust mobilization episodes during ACE-Asia in spring 2001. It also produced reasonable estimates of the dust concentrations in source regions and downwind areas from eastern China to western North America (Gong et al. 2003a; Zhao et al. 2003).

On the strength of NARCM's successful characterization of Asian dust aerosol and its trans-Pacific transport during ACE-Asia in spring 2001 (Gong et al. 2003a; Zhao et al. 2003), the modeling is extended in this study in order to investigate the climatology of Asian dust aerosol for the period from 1960 to 2003. A full 44-yr mean climatology of Asian dust aerosol and its long-range transport is here characterized with NARCM simulations including (a) the spatial and temporal distribution of surface dust aerosol in East Asia; (b) the typical daily variation of Asian dust emission from the source regions; (c) the distribution of Asian dust aerosol loading and dry and wet deposition over East Asia, the North Pacific, and western North America; (d) the pattern of Asian dust regional transport and the trans-Pacific transport routes from East Asia to North America; and (e) the budgets of Asian soil dust aerosol for the model domain during its trans-

Pacific transport. In a companion paper (Gong et al. 2006), interannual variability and linkages to climate indices such as the circulation teleconnection pattern, East Asian monsoon and ENSO are examined. The first 43-yr simulations of Asian dust emissions were analyzed and compared with available meteorological observations (Zhang et al. 2003a).

2. NARCM

NARCM is a modeling system in which the Canadian Regional Climate Model (RCM) is coupled with the Canadian Aerosol Module (CAM; Gong et al. 2003b). RCM includes the physics package from the Canadian Global Climate Model (McFarlane et al. 1992), Canadian Land Surface Scheme (CLASS; Verseghy 1991), and a semi-Lagrangian and semi-implicit transport scheme for dynamics and passive tracers (Robert et al. 1985). NARCM possesses all the atmospheric aerosol processes: production, transport, growth, coagulation, dry and wet deposition, and an explicit microphysical cloud module to treat aerosol–cloud interactions. A size-segregated multicomponent aerosol mass conservation equation in CAM is expressed as follows (Gong et al. 2003b):

$$\frac{\partial \chi_{ip}}{\partial t} = \left.\frac{\partial \chi_{ip}}{\partial t}\right|_{\text{TRANSPORT}} + \left.\frac{\partial \chi_{ip}}{\partial t}\right|_{\text{SOURCES}} + \left.\frac{\partial \chi_{ip}}{\partial t}\right|_{\text{CLEAR AIR}} + \left.\frac{\partial \chi_{ip}}{\partial t}\right|_{\text{DRY}} + \left.\frac{\partial \chi_{ip}}{\partial t}\right|_{\text{IN-CLOUD}} + \left.\frac{\partial \chi_{ip}}{\partial t}\right|_{\text{BELOW-CLOUDS}}, \quad (1)$$

where the rate of change of mixing ratio of dry particle mass constituting p in a size range i has been divided into factor terms (or tendencies) for transport, sources, clear air, dry deposition, and in-cloud and below-cloud processes. The transport includes resolved motion as well as subgrid turbulent diffusion and convection. The sources include 1) surface emission rate of both natural and anthropogenic aerosols and 2) production of secondary aerosols (i.e., airborne aerosol mass-produced by chemical transformation of their precursors). The latter together with particle nucleation, condensation, and coagulation contribute to the clear-air processes. Dry deposition of gases and particles affects the "dry" tendency. Scavenging in in-cloud and below-cloud processes is regarded as wet deposition of gases and particles.

NARCM simulations were conducted to produce the climatological spatial/temporal distributions and trans-Pacific transport of Asian dust aerosol for 44 consecutive springs from 1960 to 2003. The meteorological boundary and initial conditions used in RCM for wind, temperature, air pressure, geopotential height, and vapor mixing ratio are driven with the 6-hourly NCEP reanalyzed meteorological data for the period. NARCM runs on a stereographic projection with a horizontal resolution of 100 km at 60°N and 22 vertical levels on a Gal–Chen terrain-following coordinate system from the ground to about 30 km. This model domain covered the Northern Hemispheric region encompassing East Asia, the North Pacific, and western North America (Gong et al. 2003a; Zhao et al. 2003). The integration time step was 20 min. Twelve diameter classes from 0.01 to 40.96 μm were used to represent the size distribution of all aerosols (Zhao et al. 2003). All atmospheric aerosol quantities including dust emission fluxes, concentrations, and deposition were calculated for each size bin. A size-distributed soil dust scheme (Alfaro and Gomes 2001; Marticorena and Bergametti 1995; Marticorena et al. 1997) in NARCM was modified and driven with a Chinese soil texture that infers the size distribution with 12 categories and an up-to-date desert distribution in China corresponding to three periods representing the 1960s–70s, 1980s–90s, and twenty-first century (Gong et al. 2003a; Zhang et al. 2003a). Combined datasets for the desert distribution/texture, satellite-derived land use/roughness length, and observed soil moisture provide a coherent input parameter set for the soil dust emission scheme for deserts in East Asia. The simulations with four mixed aerosols of soil dust, sulfate, sea salt, and black carbon were conducted for 4 months from 1 February to 31 May of each year from 1960 to 2003. This generated comprehensive spring "climatology" of Asian dust aerosol emission, concentration, deposition, loading, and transport between 1 March and 31 May.

3. Validation

Prior comparisons between NARCM model output and surface network, satellite, and aircraft observations in East Asia and North America during the ACE-Asia 2001 have shown that the model reproduces with reasonable accuracy the dust emission strength and hence the soil dust concentrations in China and areas downwind the source regions (Gong et al. 2003a). The comparison with the synoptic records on annual dust storm frequencies from the meteorological network in China confirmed the reliability of NARCM results, which reproduced the typical distribution of Asian dust sources in spring and the interannual change of Asian soil dust emission over the period from 1960 to 2002 (Zhang et al. 2003a). The focus of this section is to verify the 44-yr

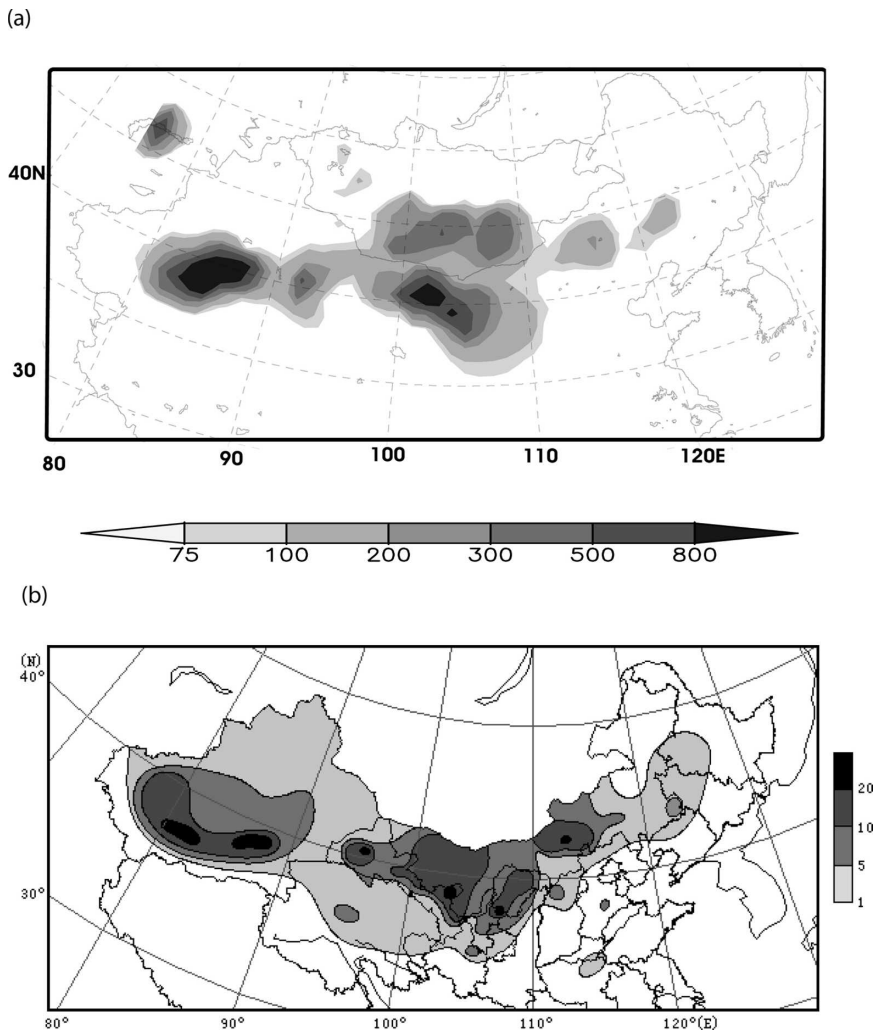

FIG. 1. (a) Distribution of 44-yr-averaged surface dust concentrations (μg m^{-3}) in spring (March, April, and May) from 1960 to 2003 in the arid and semiarid regions of China and its surrounding area from NARCM simulations and (b) spatial distribution of dust storms expressed as the number of observed dust storm events per year in northern China from 1954 to 2002.

NARCM simulations of Asian dust aerosol with the available observational data and the previously published results on Asian dust storms in East Asia for the period from 1960 to 2003.

Chemical methods have been used in studies of dust provenance, and the application of an elemental tracer system led to the conclusion that the major source regions for Asian dust were the western Chinese deserts with Taklimakan as its center and the northern high- and low-dust deserts with Badain Juran Desert as its main body (Zhang et al. 1996b). The elemental tracer studies were based on samples simultaneously collected at nine Chinese desert sites, and they provided a means for identifying the sources of modern-day dust. Studies of dust storm frequencies with visibility data (Sun et al. 2001; Zhou 2001; Zhou and Zhang 2003) have supported the importance of the main sources mentioned above. The dust source strength and its interannual variability in Asia have been further reported (Zhang et al. 2003a) for 10 dust source regions with three major areas in the deserts in Mongolia and in western and northern China (mainly the Taklimakan and Badain Juran, respectively). In the meteorological records of China, dust storms are generally defined, for observation locations in the deserts and adjacent areas, by horizontal visibility reduced to less than 1 km. The low visibility is caused by the high dust concentration in the air. In most cases, there is a direct proportion between dust storm frequency and the surface dust concentration, although the visibility-based data for dust storms

are semiquantitative without the quantities of dust concentration. The surface dust concentrations from the 44-yr NARCM simulations produced the similar spatial distribution of averaged spring surface dust concentrations (Fig. 1), coinciding reasonably well with the climatological spatial distribution of dust storms that the arid and semiarid regions in East Asia were major areas of Asian dust storm occurrences with three dominant dust centers in Mongolia and in western and northern China. The spatial distribution of surface dust concentrations over the desert regions somewhat reflects the relative larger source regions of Asian dust aerosol emission. However, the three centers of surface dust concentrations correspond also with the three dominant source regions of Asian dust aerosol (Zhang et al. 2003a).

Climatologically, dust storms in East Asia are reported mainly in spring with the most frequency in April when approximately one-third to one-half of yearly dust storms occur (Liu 1985; Natsagdorj et al. 2003). Daily distribution data of dust storms from 1960 to 1999 show that the period from 2 April to 1 May is most favorable for Asian dust storms (Sun et al. 2001). In Fig. 2, the modeled daily variation of 44-yr-averaged surface dust concentrations between 1 March (Julian day 60) and 31 May (Julian day 151) over the arid and semiarid regions in East Asia are compared with the daily distribution of observed dust storm frequency there. This confirms that the NARCM modeling system is able to simulate the daily evolution of spring dust storm episodes.

Atmospheric dust aerosols are highly sensitive to changes in climate, carbon dioxide, and human land use

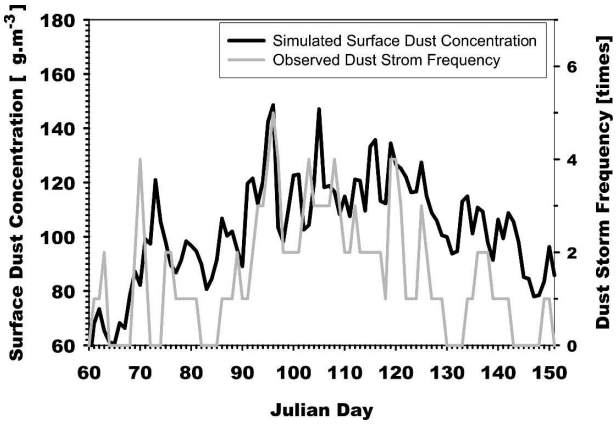

FIG. 2. Comparisons of 44-yr-averaged daily distribution of the modeled surface dust concentrations with the observed dust storm frequency over the arid and semiarid regions of China and its surrounding area from March to May.

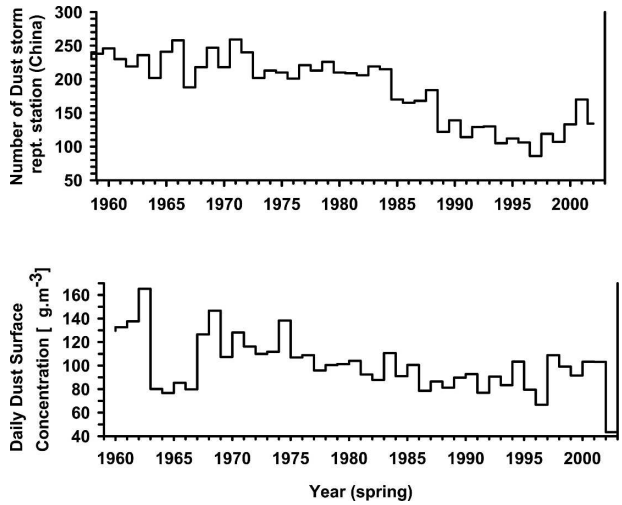

FIG. 3. (top) Annual series of the averaged surface dust concentrations in spring over the arid and semiarid regions of China and its surrounding area and (bottom) the station number of dust storm report in China from 1960 to 2003.

(Mahowald and Luo 2003), each of which exhibits substantial climatic variability (Mahowald et al. 2003; Sun et al. 2001). Observational analyses of dust storms suggested that they display obvious interannual variation (Natsagdorj et al. 2003; Sun et al. 2001; Zhao et al. 2004; Zhou 2001). In Fig. 3 modeled interannual variations of averaged surface dust concentrations over the arid and semiarid regions in East Asia for springtime are compared with annual series of the station number with dust storm reports in China from 1960 to 2002. The overall trends of both NARCM simulations and dust storm observations are similar, although there are some inconsistencies. These may be due to differences between the quantitative NARCM simulations over the whole arid and semiarid regions in East Asia and semiquantitative synoptic record data from Chinese stations. Figure 3 indicates an averaged annual trend of decreasing surface dust concentration or Asian dust storms over the arid and semiarid regions in East Asia from 1960 to 1999. The observational data also show different annual trends of dust storms at some stations in northern China from the averaged annual trend over the arid and semiarid regions (Natsagdorj et al. 2003; Sun et al. 2001; Zhou 2001). The number of observed dusty days has tripled from the 1960s to 1990s but has decreased in Mongolia since 1990 (Natsagdorj et al. 2003). In Figs. 4 and 5a the model results show reasonably good agreement with the number of days with dust storms and blowing dust from six Chinese stations around the deserts and in Mongolia. There are some exceptions, especially from the 1960s to mid-1970s in

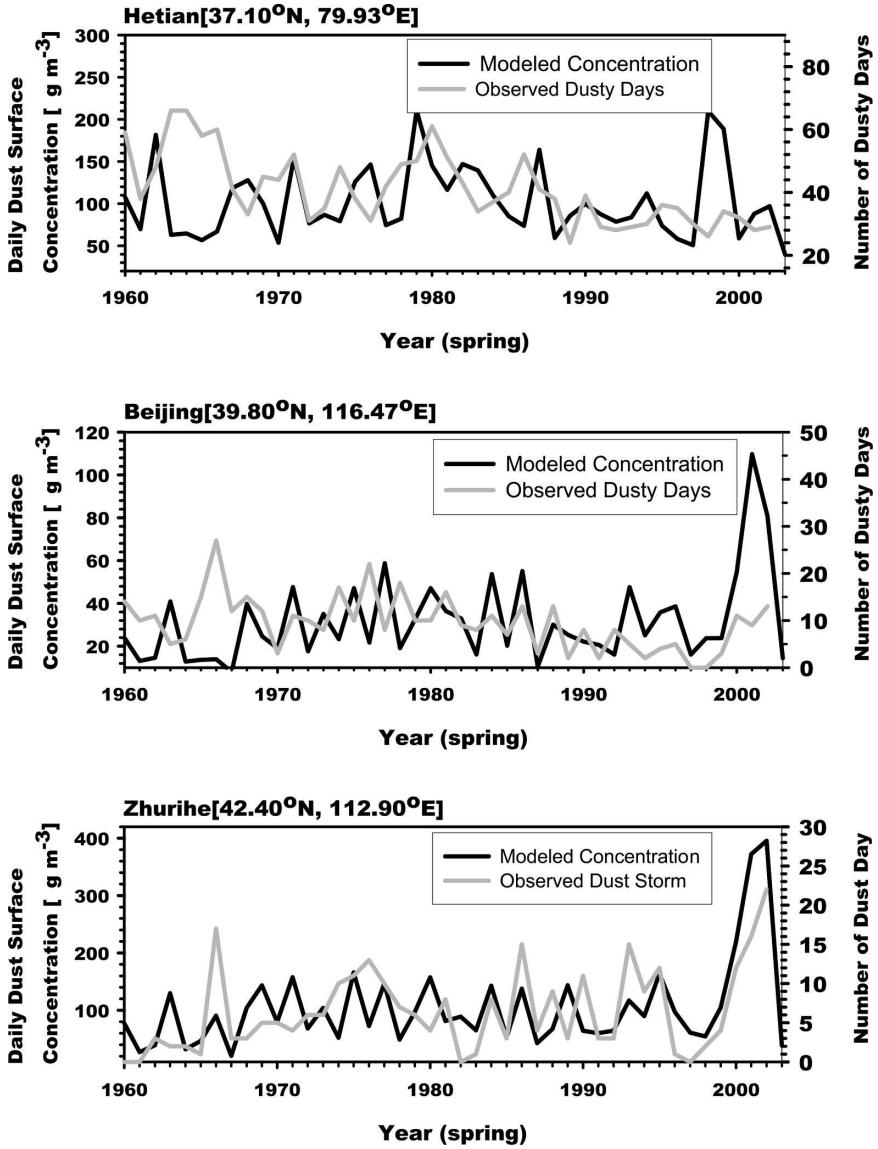

FIG. 4. Comparisons of the modeled surface dust concentrations with the observed dust weather frequency for six stations in northern China in spring from 1960 to 2003.

Mongolia, as the quantitative NARCM simulations over the whole Mongolian region including all deserts in spring are compared with the semiquantitative annual dust storm and drifting dust data obtained from 49 meteorological stations in Mongolia. With respect to the trans-Pacific transport of dust, Fig. 5b shows a comparison of the time series of 10-day-averaged surface dust aerosol concentrations by NARCM with the calcium concentrations from air filter measurements by the Canadian Air and Precipitation Monitoring Network (CAPMON) in spring during the available period of 1994–2001 at Saturna Island (48.78°N, 123.13°W) in Canada. Again NARCM is able to satisfactorily capture the interannual variability in the surface time series.

Available observations from the Total Ozone Mapping Spectrometer (TOMS) Aerosol Index (AI) on *Nimbus-7* from 1979 to 1992 and the *Earth Probe* satellites from 1996 to 2003 were used to validate the simulated column loading distribution of Asian dust aerosol with the goal of verifying the Asian dust loadings and long-range transport of Asian dust. Figure 6 compares the monthly averaged spatial distributions of dust loading from NARCM simulations and the corresponding TOMS AI in March, April, and May for the periods of 1979–92 and 1996–2003. The modeled spatial distribu-

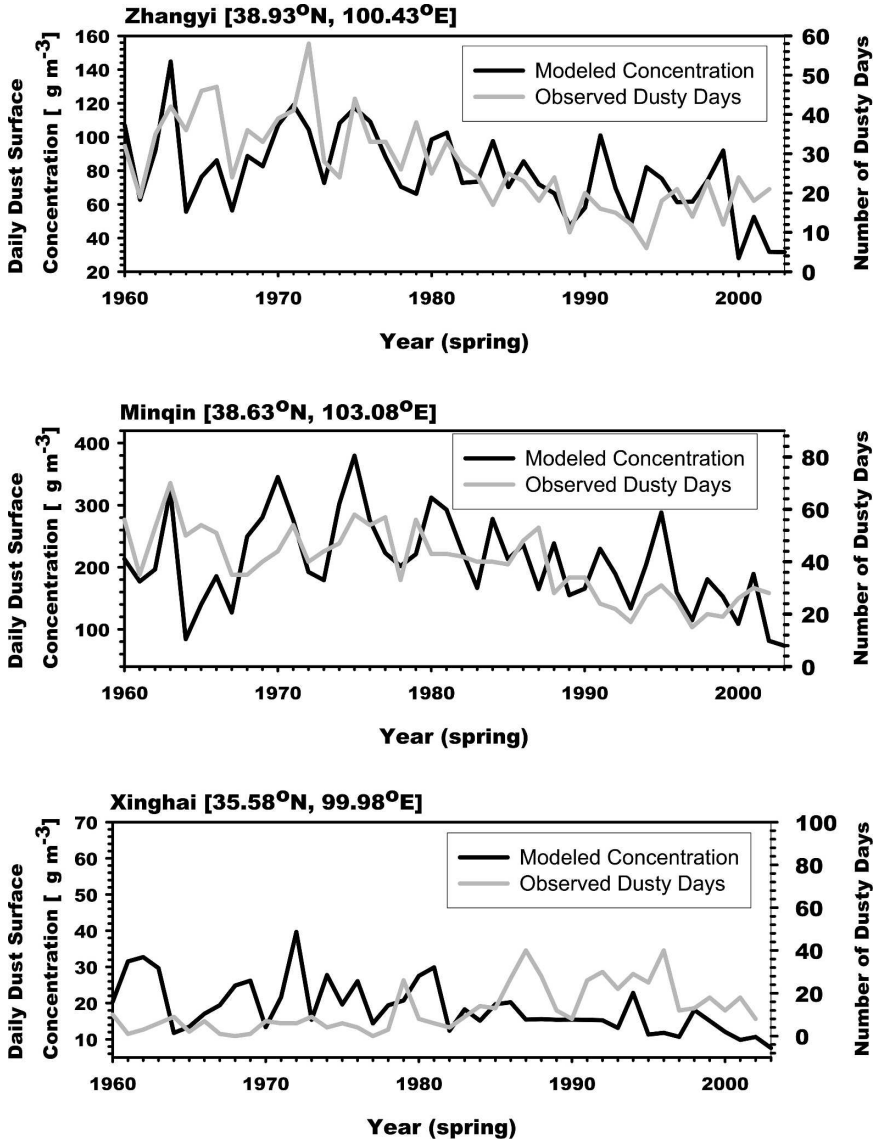

FIG. 4. (*Continued*)

tions and monthly evolution of Asian dust loading in spring correlated reasonably well with TOMS AI observations. On this basis, the climatological characteristics of Asian dust loading and long-range transport can be obtained with some confidence from the NARCM simulations.

The validation of modeled dust aerosol distributions is constrained by a lack of comprehensive observational data. However, based on comparison with several decades of available observations of the spatial and temporal distribution of surface dust aerosols and Asian dust loading (Figs. 1–6), together with validation of NARCM simulations during ACE-Asia, we are confident that NARCM can provide a realistic characterization of Asian dust aerosol and its trans-Pacific transport.

4. Mean climate

In this section, we use the comprehensive data from the 44-yr NARCM simulations to present a modeled climatology of the typical spatial and temporal distributions of Asian soil dust emission, column loading, deposition, trans-Pacific transport routes, and budgets.

a. Asian dust aerosol emission and surface concentrations

Using the same NARCM simulations from 1960 to 2002, Zhang et al. (2003a) examined spatial and tem-

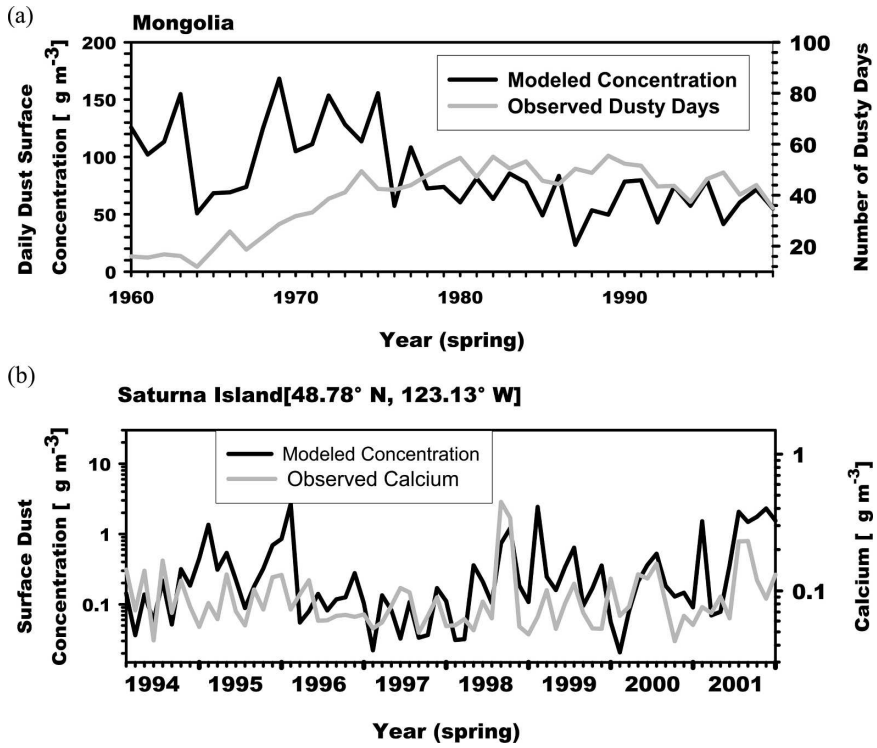

FIG. 5. Comparisons of the modeled surface dust concentrations in spring (a) with the observed number of dusty days per year in Mongolia from 1960 to 1999 and (b) surface measurements in Saturna Island by CAPMON monitoring network from 1994 to 2001.

poral distributions of Asian dust aerosol emission from 10 different desert regions in East Asia. Climatologically, major sources of Asian dust aerosol are the deserts in Mongolia, the Taklimakan Desert in western China, and the Badain Juran Desert in northern China with the averaged contribution of 29%, 21%, and 22% of the total Asian dust emission, respectively. The springtime dust emission from the major sources and the other desert regions in western China and Kazakhstan exhibited a decreasing trend over the last 20 yr after 1980, while the dust emission from some desert regions in northeastern China had an increasing trend over the last 20 yr (Zhang et al. 2003a). The climatological spatial distribution of Asian surface dust concentrations from NARCM simulations also confirmed that the arid and semiarid regions in East Asia were major areas of Asian dust storms with the dominant dust centers in the Taklimakan Desert in western China and the Gobi Desert including both the desert in Mongolia and the Badain Juran Desert in northern China (Fig. 1a).

The typical daily distribution of Asian dust emissions in spring from 1 March (Julian day 60) to 31 May (Julian day 151) is shown in Fig. 7. The monthly averaged rate of daily dust emission over the deserts in East Asian was 0.96, 1.58, and 1.36 Mt day^{-1} in March, April, and May, respectively. Asian dust emissions vary substantially from day to day, depending on the daily changes of surface wind and surface conditions in the desert areas (Gong et al. 2003a). Figure 7 also indicates that the Asian dust storms in spring occurred most frequently from early April to early May.

b. Asian dust aerosol loading

The averaged dust aerosol loading during spring from 1960 to 2003 is shown in Fig. 8. The quantity of dust loading reaches up to more than 500 kg km^{-2} over the dust source region in western China and downwind areas near the Gobi Desert in Mongolia and northern China. Asian dust aerosol emitted from the source regions contributes directly to local dust loading there. Over the East Asian subcontinent, the regional-scale transport of the Asian deserts is dominated by surface-level northwesterly winds associated with the Asian winter monsoon (An et al. 1990). Here, the spatial distribution of dust loading is influenced by the invasion of dry cold air masses from the northwest. Across the North Pacific a zonal axis of dust loading around 40°N

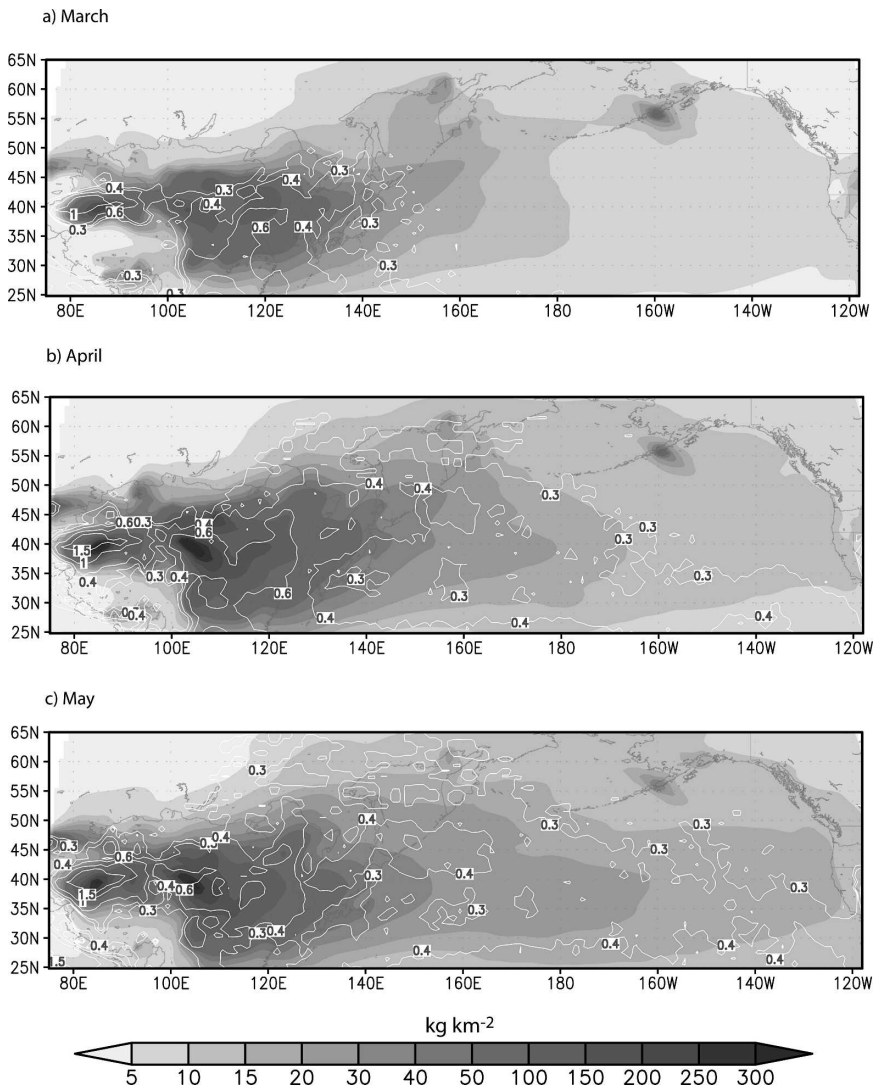

FIG. 6. Monthly averaged dust column–loading contours (kg km^{-2}) and the monthly averaged TOMS AI (contour lines) from the *Nimbus-7* during 1979–92 and from the *Earth Probe* satellites during 1996 and 2003 in (a) March, (b) April, and (c) May.

stretches from the western Pacific into western North America along the prevailing free-tropopheric apparent wind in the midlatitude spring. The pattern of Asian dust loading is a consequence of the Asian dust emissions from the source regions in East Asia, the regional transport with surface northwesterly winds in the lower troposphere across the Asian subcontinent, the trans-Pacific transport of Asian dust aerosol with the midlatitude westerlies, and deposition along the transport pathways. This pattern implies that significant changes in radiative forcing, atmospheric chemistry, and the sediments in land and ocean may be expected over large areas of the Northern Hemisphere due to Asian dust aerosol and its transport. Furthermore, Asian dust aerosol contributes most of the dust aerosol loading in the troposphere over the midlatitude regions from East Asia to western North America during springtime.

c. *Asian dust deposition*

Deposition is the major removal process for aerosol from atmosphere. In NARCM, deposition includes gas and particle dry and wet deposition with below-cloud and in-cloud scavenging, which were considered in the size-segregated aerosol mass balance equation (Gong et al. 2003b). The climatological distribution of Asian dust deposition and ratio of wet to dry deposition of the dust aerosol in spring is shown in Fig. 9. The total dust mass from dry and wet deposition during spring ranged

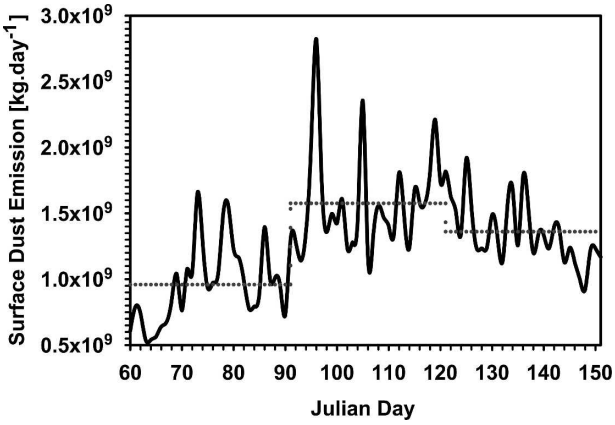

FIG. 7. The 44-yr-averaged daily distribution of modeled dust emission from the deserts in East Asia from 1 March to 31 May, 1960–2003. The dotted lines are the monthly mean in March, April, and May.

between 0.05 and 500 tons km^{-2} over the NARCM domain from East Asia across the northern Pacific to western North America. Maximum deposition was over the dust source regions with most of the emitted dust redeposited onto the dust source areas. Over Asian dust source regions, which are arid or semiarid with low precipitation, dry deposition is the dominant removal process. Over the entire model domain, total dry deposition was also greater than wet deposition with respect to dust mass deposition because a major part of dust deposition occurred over source areas (Table 1). Nevertheless, on the pathway of trans-Pacific dust transport far from the source regions, wet deposition exceeded dry deposition by a factor of ~20 (Fig. 9). Wet deposition as a function of precipitation is the major process of soil dust removal from the atmosphere to ocean in the North Pacific. Climatologically, dry deposition is a dominant removal process of Asian dust aerosol near the source areas whereas the removal of dust particles by precipitation is the major process of dust deposition during the trans-Pacific transport of Asian dust.

d. Asian dust transport

As the prevailing midlatitude free-tropospheric winds in spring are westerly, most trans-Pacific transport of Asian dust aerosol could be expected to be zonal. Therefore, the product of dust aerosol concentration and zonal wind component U (i.e., zonal dust transport flux) can be used to estimate the amount and direction of Asian dust trans-Pacific transport. Positive (negative) zonal dust transport fluxes indicate eastward (westward) transport of dust aerosol. Figure 10 illustrates the averaged transport flux of Asian dust aerosol from Asian dust sources to western North America along 40°N, where the zonal axis of dust loading exists (Fig. 8). Climatologically, the regional-scale transport of Asian dust from the desert regions to East Asian offshore regions in the western Pacific extends to an elevation of <3 km. Before Asian dust from the source regions under the influence of northwesterly winds and the cold surge of winter monsoon reaches the Pacific Ocean or South China, it is lifted to the free troposphere and carried by the midlatitude westerlies. Most trans-Pacific dust transport occurs in the middle troposphere between 3 and 10 km, where the zonal dust transport fluxes are at a maximum. The averaged height of Asian dust inflow entering North America from 140° to 120°W ranged from 5 to 10 km in spring. The monthly averaged transport fluxes of Asian dust also indicate that most Asian dust export occurs in the lower troposphere between 1 and 3 km with the center of dust export moving from about 38°N in March to 40°N in April to 43°N in May. Figure 11 shows the

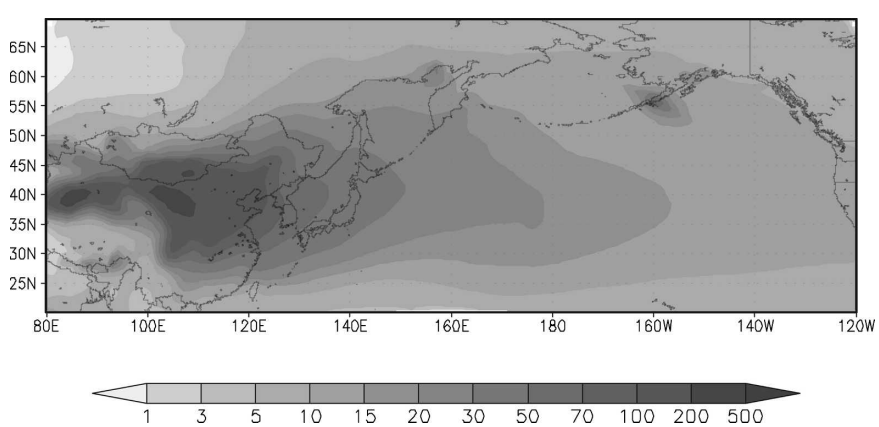

FIG. 8. Distribution of 44-yr-averaged dust column loading (kg km^{-2}) in spring from 1960 to 2003.

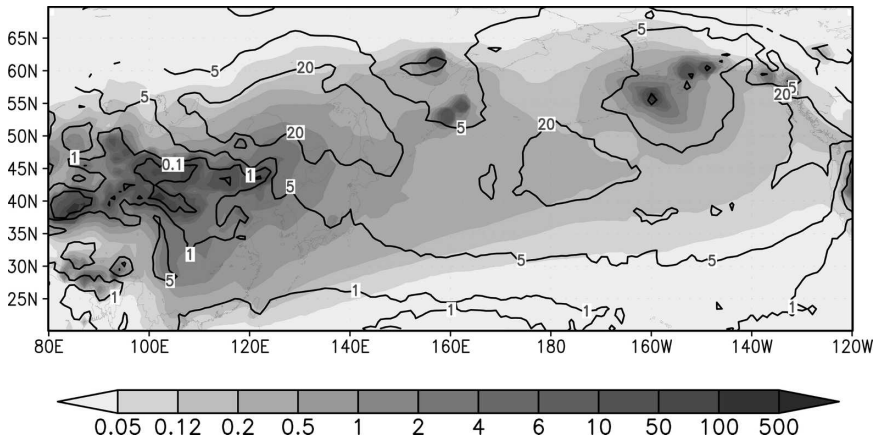

FIG. 9. The 44-yr-averaged depositions (tons km^{-2}) and ratio of wet and dry depositions (contour lines) in spring from 1960 to 2003.

distribution of averaged zonal transport fluxes between 3 and 10 km in the middle troposphere in spring. During springtime, Asian dust aerosol is transported eastward over the northern Pacific with a zonal transport axis around 40°N. This is the typical pathway for trans-Pacific transport of Asian dust (Husar et al. 2001). It should be noted in Fig. 11 that only Asian dust was engaged in this high-level long-range transport across the Pacific; dust from the other emission sources on the Pacific coast regions only influenced surface level concentrations.

Climatologically, Asian dust storms are closely associated with the activity of frontal cyclone in East Asia. The most favorable atmospheric circulation pattern for Asian dust storms is when intense cold fronts associated with cyclones sweep across Mongolia and northern China (Chun et al. 2001; Qian et al. 2002). The Asian dust transport over East Asia is governed by both the zonal and meridional airflows associated with such circulation patterns. The divergence of both zonal and meridional dust transport flux was computed to investigate the dust aerosol transport in East Asia. A positive (negative) dust transport flux divergence indicates a net export (input) of dust aerosols in the atmosphere. As discussed above, the regional-scale transport of Asian dust from the desert regions to East Asian offshore regions near the western Pacific occurred below 3 km, while trans-Pacific dust transport in the middle troposphere was between 3 and 10 km. The dust transport flux divergences below 3 km and between 3 and 10 km are shown in Fig. 12. Regional-scale transport of Asian dust is dominated by dust emission sources and northwesterly winds from cold frontal activity in East Asia. The major dust aerosol export regions in the atmosphere are associated with positive dust flux divergences over Asian desert regions, and the major dust input (sink) regions in the atmosphere have a negative dust flux divergence in the downwind areas near the desert regions during regional-scale transport of Asian dust (Fig. 12a). In the free troposphere from 3 to 10 km, the pattern of dust flux divergences forms a circulation cell over Mongolia and northern China with the dust flux convergence areas located from South China, to Korea, to the western Pacific (Fig. 12b). The cyclonic

TABLE 1. The 44-yr-averaged mass budget of dust emission, deposition, and trans-Pacific transport (in Mt) and percentage of deposition and transport relative to East Asian dust emission in spring from 1960 to 2003.

Groups		Mar	Apr	May	Spring
East Asian dust emission		29.74	47.28	42.43	119.46
	Dry deposition	14.35 (48.25%)	22.89 (48.41%)	18.72 (44.12%)	55.96 (48.84%)
East Asian deserts	Wet removal	0.59 (1.99%)	1.30 (2.75%)	0.92 (2.17%)	2.80 (2.34%)
	Dry deposition	4.28 (14.39%)	5.63 (11.91%)	5.93 (13.98%)	15.84 (13.26%)
Nondesert regions in East Asian subcontinent	Wet removal	1.72 (5.78%)	3.81 (8.06%)	3.97 (9.36%)	9.50 (7.95%)
	Dry deposition	4.02 (13.52%)	2.76 (5.84%)	2.27 (5.35%)	9.05 (7.58%)
North Pacific	Wet removal	3.39 (11.40%)	3.58 (7.57%)	3.33 (7.85%)	10.30 (8.62%)
Outflow from East Asian continent		8.46 (28.45%)	12.33 (26.08%)	10.54 (24.84%)	31.33 (26.23%)
Inflow into North American continent		0.68 (2.29%)	1.82 (3.85%)	1.07 (2.52%)	3.57 (2.99%)

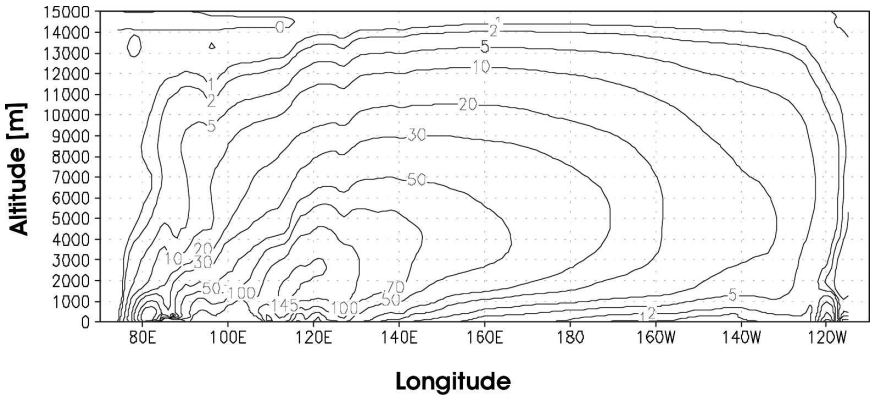

FIG. 10. The 44-yr-averaged zonal dust transport flux (μg m^{-2} s^{-1}) along 40°N in spring.

circulation is characterized by strong uplift in the lower troposphere and a divergence field in the upper troposphere (Ding 1994). The pattern of dust flux divergences in the free troposphere from 3 to 10 km suggests that the dust raised by cyclonic circulation over Mongolia and northern China is the supply of Asian dust aerosol for trans-Pacific transport.

e. Asian dust aerosol budgets

Table 1 presents 44-yr-averaged budgets of Asian dust aerosol during trans-Pacific transport over the model domain in spring. During the months of March, April, and May, an averaged total of 120 Mt dust from the Asian dust source regions was emitted into the atmosphere of the model domain. Although about 51% of the emitted dust particles were redeposited onto the source regions with dry deposition of 56 Mt and wet deposition of 2.8 Mt in spring, the Asian dust sources had the major contribution of tropospheric dust aerosol to the atmosphere. Asian dust emissions are widely considered to be the major sources loess matter deposited on the Loess Plateau and marine sediments in the North Pacific (Merrill et al. 1989, 1994; Prospero 1981; Zhang et al. 1996a). About 21% of Asian dust emission was deposited onto the nondesert regions in the Asian subcontinent with the strongest dust sink in the Loess Plateau, situated immediately downwind of the Gobi Desert. The climatological estimation indicates that 26% of Asian dust is exported eastward from the East Asian subcontinent to the western Pacific, 16% of Asian dust production is deposited into the North Pacific, and ~3% of Asian dust production flowed into the atmosphere over North America via the trans-Pacific transport. Asian dust aerosol and its trans-Pacific transport therefore likely play an important role in climate variation, atmospheric chemistry, and biogeochemical links between land, atmosphere, and ocean in the Northern Hemisphere.

The monthly average of Asian dust budgets in spring from 1960 to 2003 indicates that 30, 48, and 42 Mt was produced from the source regions in March, April, and May, respectively. The relative monthly percentage of deposition and transport to Asian dust emission showed that dust deposition on the nondesert regions

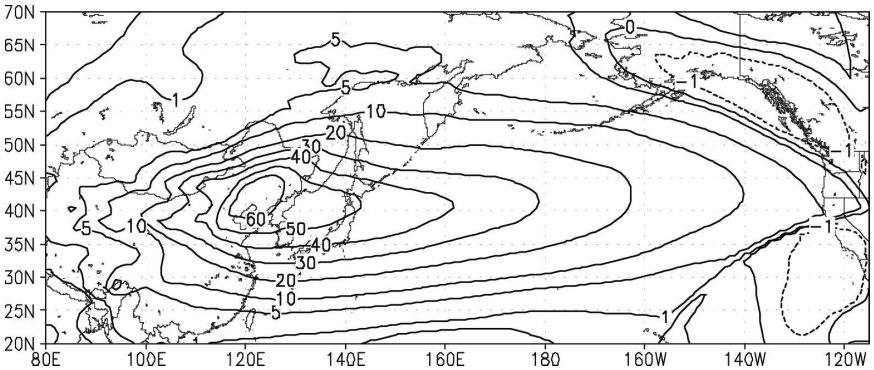

FIG. 11. Averaged distribution of zonal dust transport flux (μg m^{-2} s^{-1}) between 3 and 10 km in spring from 1960 to 2003.

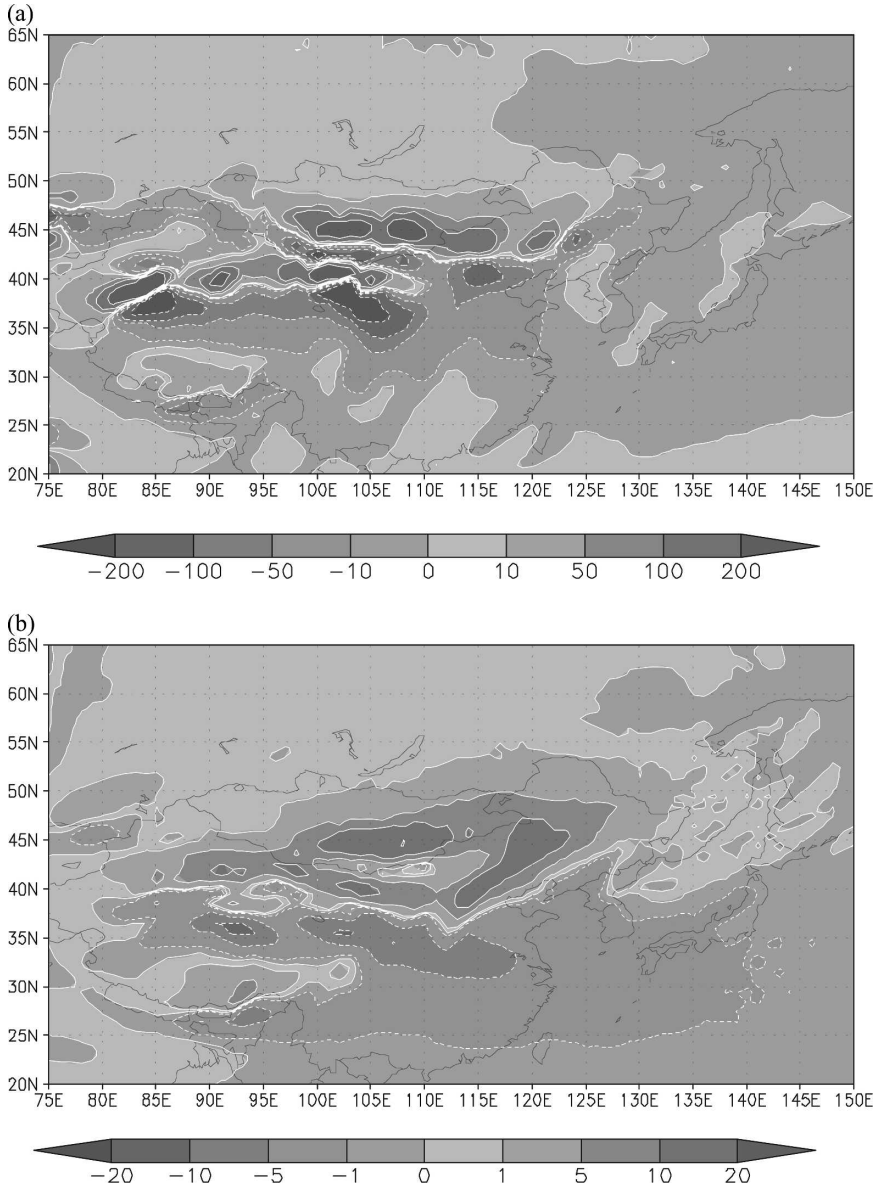

FIG. 12. Averaged distribution of Asian dust flux divergence ($\times 10^{-5}$ μg m^{-3} s^{-1}): (a) below 3 km and (b) between 3 and 10 km in spring from 1960 to 2003. The positive and negative dust flux divergence contours are also identified with solid and dashed lines, respectively.

of Asian continent peaked in May with 23%, outflow from the continent peaked in March with 28%, Asian dust deposition into the Pacific peaked in March with 25%, and the inflow into North America atmosphere peaked in April with 4%. These monthly variations of Asian dust budgets among dust emission from the source regions, dust deposition in Asian continent, and the North Pacific and trans-Pacific dust transport depend on the changes of the Asian dust transport patterns. The transport patterns are closely associated with the global-scale evolution of atmospheric circulation, especially of westerlies in the midlatitudes (Gong et al. 2003a). In March, the strongest cold surge of the Asian winter monsoon carried the most outflow of Asian dust to the west Pacific, and Asian dust was transported eastward across the North Pacific, but not sufficiently far to reach North America, and most was deposited into the Pacific Ocean. In April, zonal transport around 40°N was well developed over North Pacific with the most inflow of Asian dust to North America. In May, Asian transport was separated into two pathways: an eastward zonal path over the North Pacific and a me-

ridional path from China to the northeast Asian continent. This meridional path caused the most dust deposition over the nondesert regions of the Asian continent in May.

5. Conclusions

The climatology of Asian dust aerosol and its trans-Pacific transport for the period from 1960 to 2003 described herein is based on surface measurements of dust frequency and satellite observations of TOMS AI and from 44-yr NARCM simulations. Model validation was conducted as rigorously as the available observational data allow and leads to the following conclusions.

1) The deserts in Mongolia and in western and northern China (mainly the Taklimakan and Badain Juran, respectively) were the major areas of Asian dust storms The monthly averaged rate of daily dust emission (<41 μm in diameter) over the deserts in East Asia was 0.96, 1.58, and 1.36 Mt in March, April, and May, respectively.
2) Dust loading reaches up to more than 500 kg km^{-2} over the dust source region in western China and downwind area near the Gobi Desert. The spatial distribution of dust loading over the East Asian subcontinent is consistent with the tracks of cyclonic storms with intense cold frontal activity. Across the North Pacific, a zone of heaviest loading stretches along a zonal axis around 40°N corresponding to the prevailing westerly winds of the free troposphere.
3) Total dust mass from dry and wet deposition during spring ranged between 0.05 and 500 tons km^{-2} from East Asia to the North Pacific to western North America. Over Asian dust source regions, dry deposition is the dominant removal process. On the pathway of dust transport far from the source, wet deposition exceeded dry deposition by a factor of ~20. Wet deposition is the major process of soil dust removal from the atmosphere to ocean in the North Pacific.
4) Regionally, Asian dust transported from the deserts to East Asian offshore regions was entrained to an elevation of <3 km and was strongly influenced by northwesterly winds associated with activity of a cold frontal cyclone in East Asia. The cyclonic circulations in Mongolia and northern China raised and supplied dust aerosol to trans-Pacific transport. Most trans-Pacific dust transport occurs in the middle troposphere between 3 and 10 km along a zonal transport axis around 40°N.
5) An averaged total of 120 Mt of dust aerosol from the Asian dust source regions was emitted into atmosphere in spring. Relative to Asian dust emission, 51% was redeposited onto the source regions, 21% was deposited onto the nondesert regions in the Asian subcontinent, 26% outflowed eastward from East Asia to the western Pacific, 16% was deposited into the North Pacific, and about 3% flowed into the atmosphere over North America via trans-Pacific transport.

This paper characterizes the mean climate of Asian dust aerosol using the comprehensive data from the 44-yr NARCM simulations with comparisons between the simulations and available observations. As both model predictions and observations exhibited significant interannual variability, a companion paper focuses on the links between important climatic indices and interannual variability of Asian dust aerosol production, loading, deposition, and transport.

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