Long range trans-Pacific transport and deposition of Asian dust aerosols

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Abstract

The deposition of Asian dust aerosols during their trans-Pacific transport might cause significant marine phytoplankton biomass increases. However, the knowledge of the trans-Pacific dust transport, deposition, and spatial distribution is still poor due to a lack of continuous and simultaneous observations in the Asian subcontinent, the north Pacific Ocean, and North America. The severe Asian dust storm during 6 to 9 April 2001 provided an opportunity to gain a better understanding of trans-Pacific dust transport and deposition, using a comprehensive set of observations from satellites, ground-based light detection and ranging, aircraft, and surface observation networks. The observations and model simulations outline the general pattern of dust transport, deposition, vertical profile, and spatial distribution. The following points were observed: (1) the surface dust concentration decreased exponentially with the increasing dust transport distance from 80°E to 120°W along the transport pathway; (2) the altitude of the dust concentration peak increased with increasing transport distance in the north Pacific region; and (3) the spatial distribution of dust deposition mainly depended on the trans-Pacific transport route.

Key words: dust aerosol; trans-Pacific dust transport and deposition; spatial distribution

Introduction

The iron hypothesis proposed by John Martin in 1990 (Martin, 1990) suggests that some oceans such as the north Pacific Ocean and equatorial Pacific Ocean are high in nutrient but low in chlorophyll content. Phosphate and nitrate concentrations are high in the surface of these oceans whereas their productivity is low. Iron from terrestrial dust is the primary limiting factor for the productivity of marine phytoplankton. The iron fertilization hypothesis indicates that marine phytoplankton biomass is important for the atmospheric carbon cycle (Coale et al., 1996; Watson et al., 2000; Ridgwell, 2002). It was also shown that trans-Pacific transport of Asian dust aerosols, which contributed approximately 95% of the iron to the biogeochemical cycle of the north Pacific Ocean (Duce et al., 1980; Rea and Hovan, 1995), caused a significant marine phytoplankton biomass increase as a result of dust aerosol deposition (Bishop et al., 2002; Gao et al., 2003; Han et al., 2006).

Although studies have been carried out to simulate and observe dust aerosols over the north Pacific Ocean (Duce et al., 1980; Chun et al., 2001; Takamura et al., 2002; Chung et al., 2003; Gao et al., 2003; Gong et al., 2003; Holzer et al., 2003; Liu et al., 2003; Zhao et al., 2003), the observational data are very short and sparse in the region. Trans-Pacific dust transportation, deposition, and spatial distribution are still poorly understood because of a lack of continuous and simultaneous observational data on dust, combined from central Asia, the north Pacific Ocean, and North America. If a typical dust event is identified, where dust is transported from central Asia to North America across the north Pacific Ocean, and a comprehensive observational data from that event is obtained, the spatial distribution of trans-Pacific Asian dust transport and deposition from the observation and simulation data might be characterized. Here, a dust storm event originating over central Asia on April 6 to 9, 2001, which was the strongest dust storm event over the last 20 years with long range transport as far as North America (Jaffe et al., 2003), was analyzed. The dust storm transported fine dust particles over the north Pacific Ocean and reached North America and even the Atlantic Ocean (Jaffe et al., 2003; Gong et al., 2003). This dust storm episode was well observed by satellites, ground-based LiDAR (light detection and ranging), and surface measurement networks such as the ACE-Asia experiment (Asian Pacific regional aerosol characterization experiment) and IMPROVE (interagency monitoring program for improved visual environments). This provided an opportunity to understand the Asian dust transport and deposition across the Pacific, as well as, the linkages between terrestrial dusts and climate. Although the changes in the surface dust fluxes with the transport distance over Pacific were analyzed by Han and his co-worker (2006),
no analysis of the spatial dust distribution was done during this dust storm. Whereas the dust column loading over 700 hPa for this dust storm event in the trans-Pacific was simulated by references (Gong et al., 2003; Zhao et al., 2003), and the spatial dust distribution was shown clearly, however, it requires the support of surface observation data. In this study, on the basis of the above references and results (Gong et al., 2003; Zhao et al., 2003; Han et al., 2006), the available observation data and the simulation results were used to determine the long range transport pattern of the dust storm from east Asia to North America during April 6 to 18, 2001. In addition, a skeleton map is presented by analyzing the features of dust transport and deposition, vertical dust distribution, and surface dust distribution in the north Pacific.

1 Observation and simulation data

To determine the long-range transport and deposition of Asian dust over east Asia, the north Pacific, and North America, we used the following observational data: (1) the geopotential height, the vertical speed ω, wind vector, and precipitation reanalysis data (2.5°×2.5°), from National Center for Environmental Prediction and National Center Atmospheric Research, during 10 to 20 April 2001; (2) the data of surface dust aerosol particulate matter of 10 microns in diameter or smaller (PM$_{10}$), from the ACE-Asia experiment and IMPROVE network (Chin et al., 2003; Gong et al., 2003; Jaffe et al., 2003; Zhang et al., 2003); (3) aerosol index (AI) data, from total ozone mapping spectrometer (TOMS) (Richard, 2007); (4) the vertical profiles of dust concentration by a C-130 aircraft in the region of the Yellow Sea and the Sea of Japan (April 11, 2001, Chin et al., 2003), and by an aircraft, in the north Pacific coast in Washington (April 14, Price et al., 2003).

The NARCM model (northern aerosol regional climate model) used in this study has been applied extensively to simulate dust storms during ACE-Asia (Gong et al., 2003; Zhao et al., 2003). The modeling results showed reasonable agreement with the soil dust strength and frequency in China, as well as, with downwind transport to North America in 2001 (Gong et al., 2003; Zhao et al., 2003). In NARCM a size-segregated multicomponent aerosol mass conservation equation is expressed as follows (Gong et al., 2003):

$$\frac{\partial ip_i}{\partial t} = \left( \frac{\partial ip_i}{\partial t} \right)_{\text{Transport}} + \left( \frac{\partial ip_i}{\partial t} \right)_{\text{Surface}} + \left( \frac{\partial ip_i}{\partial t} \right)_{\text{Clear air}} + \left( \frac{\partial ip_i}{\partial t} \right)_{\text{DR}} + \left( \frac{\partial ip_i}{\partial t} \right)_{\text{In-cloud}} + \left( \frac{\partial ip_i}{\partial t} \right)_{\text{Below-cloud}}$$

(1)

where, the rate of change in mixing ratio of dry particle mass $p_i$ in a size range, $i$, is divided into factor terms (or tendencies) for transport, sources, clear air, dry deposition (DR), in-cloud and below-cloud processes. Details of the method were provided by Gong et al. (2003), where the NARCM simulation of dust aerosols for the period of April 6 to 18, 2001 was discussed, together with the observation data.

2 Transport facts of the dust storm

During April 6 to 9, 2001, a strong dust storm event originating from the Xinjiang Regional Municipality (XMR) swept over northern China and midwest Mongolia. On April 7, 2001 (at local time), a vigorous cold surface front was located at the Balkhash Lake at 05:00, which moved to the northwestern XMR at 08:00 and the northern XMR at 14:00, and then passed the Tianshan Mountains at 20:00. The cold front was separated into two branches because of the blocking of the Tianshan Mountains. The northern branch moved quickly on to midwestern Mongolia and the Hexi Corridor of Gansu Province at 05:00 on April 8, to southern Ningxia and Gansu Province at 14:00, and finally to the Yellow Sea before fading away on April 9, 2001. The southern branch moved slowly into the Tarim Basin, and then moved from west to east into the Qaidam Basin at 05:00 on April 8, 2001. As the cold front crossed over north China and Midwest Mongolia, gale force winds exceeding 20 m/s triggered the strong dust storm, which moved eastward through the northeast part of China and produced a widespread region of poor visibility. A severe dust storm occurred in the northeast of China, where the visibility was less than 1 km (Han et al., 2006). According to the GMS-5 weather satellite and surface station visibility observations this dust storm event spread through an area covering approximately 3.9×10$^5$ km$^2$ (Han et al., 2005). The TOMS image clearly showed the long-distance dust transport process over Korea, Japan, the north Pacific and North America, and even the Atlantic (Gong et al., 2003; Han et al., 2006). The dust cloud passed over Japan on April 11, and then the western coast of North America, before moving steadily eastward over the North American continent. On April 18, the dust cloud gradually disintegrated into the Atlantic as the fine dust particles cleared from the atmosphere by a cloud (Han et al., 2005). The NARCM simulation was used to describe the dust column loading over 700 hPa for the dust storm event in the trans-Pacific. The results showed a good agreement between the spatial and temporal distributions of model-predicted dust loading and the observed TOMS -AI (Gong et al., 2003).

3 Transport and deposition of dust aerosols in the north Pacific

3.1 Surface PM$_{10}$ distribution

Twenty one stations with PM$_{10}$ observations were selected from the regions of central Asia, Korea, Japan, and North America, all lying in the dust storm transport pathway in April 2001 (Fig 1). Note that data is absent from the north Pacific (Fig 1). A scatter diagram of the PM$_{10}$ peak values versus longitude at each station (adding the stations from IMPROVE), during this dust storm, is shown in Fig. 2. The results showed that the surface dust concentrations decreased gradually along the transport pathway. The peak surface PM$_{10}$ values reached approximately 700–900 µg/m$^3$ in north China, approximately 230–450 µg/m$^3$ in...
Therefore, in the north Pacific, the dust particles in the dust source region by dry deposition (Zhao et al., 2003) with a confidence level obtained as follows:

$$y = 4336.5e^{-0.0223x}$$

where, $y$ is the value of $\text{PM}_{10}$, $x$ is degrees longitude, and the correlation coefficient between $x$ and $y$ is $R^2 = 0.9104$.

The dust concentrations decrease exponentially with increasing longitude from $80^\circ$E to $120^\circ$W (i.e., with an increase of dust transport distance) with a confidence level of 99%. Coarse dust particles are removed quickly near the dust source region by dry deposition (Zhao et al., 2003). Therefore, in the north Pacific, the dust particles in the atmosphere become uniform and consist mainly of fine particles of less than 10 $\mu$m, which has been proved by the marine dust deposition results and $\text{PM}_{10}$ records (Rea and Hovan, 1995; Jaffe et al., 2003). The relationship between dust concentration and transport distance is consistent with the Fe-concentration variation curve from the north Pacific Ocean surface (Gao et al., 2003).

### 3.2 Vertical distribution of dust aerosol concentrations

During the intensive observation period of March 31 to May 4, 2001, in ACE-Asia, a C-130 aircraft was used to measure dust aerosol concentrations in the region of the Yellow Sea and the Sea of Japan (Chin et al., 2003). Nineteen research flights (RF) were conducted, and recorded vertical dust concentration profiles on April 11, 2001, when the dust storm passed over the region (Chin et al., 2003). The vertical profiles of observed dust concentrations from the RF (Fig. 4a1) show two clear layers: a lower layer from the surface to 500 m with a dust concentration peak of approximately 80–100 $\mu$g/m$^3$, and the upper layer located at an elevation of 2000–3000 m with a peak concentration of approximately 80 $\mu$g/m$^3$ (Chin et al., 2003). The simulation (Gong et al., 2003) and LiDAR (Chung et al., 2003) results also showed the existence of two clear layers. At a similar time, the total aerosol scattering of green light (TSG) was measured using an aircraft off the coast of Washington (Price et al., 2003) on April 14, 2001, the time when the studied dust storm from Asia arrived at the west coast of North America. The observed TSG profiles exhibited a higher peak, at over 6 km (Fig. 4a2) (Gong et al., 2003; Price et al., 2003). On the basis of these two observed profiles over the coastal areas in the east Pacific and west Pacific, it was conjectured that the altitude of dust concentration peak ascended with the increase of transport distance in the north Pacific region.

To study the reasons for changes in the dust concentration profile, the vertical speed, $\omega$, was calculated for the period when the storm passed over the north Pacific region. During the period of 11 to 14 April, there were two uplift centers in the west Pacific and east Pacific in the 850 to 200 hPa altitude range between 40$^\circ$N and 70$^\circ$N, and their locations corresponded with the east Asia trough and North American trough. From the average vertical speed, $\omega$, at 500 hPa from 11 to 14 April, it was seen that the ascending movement prevailed and linked the two uplift centers (Fig. 4b). On comparing this with the dust transport pathway (Han et al., 2005), it was found that the ascending movement often prevailed over the northern side...
of transport pathway, which is consistent with the general pattern of the 500 hPa wind vector (Fig.4c). In the west and east Pacific, the fine dust particles can be raised over East Asia, for example over Japan, and can be re-raised and east Pacific, the fine dust particles can be raised over the east Asia, for example over Japan, and can be re-raised and east Pacific, the fine dust particles can be raised over the east Asia, for example over Japan, and can be re-raised and east Pacific, the fine dust particles can be raised over the east Asia, for example over Japan, and can be re-raised and east Pacific, the fine dust particles can be raised over the east Asia, for example over Japan, and can be re-raised and east Pacific, the fine dust particles can be raised over the east Asia, for example over Japan, and can be re-raised and east Pacific, the fine dust particles can be raised over the east Asia, for example over Japan, and can be re-raised and east Pacific, the fine dust particles can be raised over the east Asia, for example over Japan, and can be re-raised

3.3 Spatial distribution of trans-Pacific dust aerosols

In the north Pacific region, the spatial distribution of surface dust aerosols only can be estimated from the available upper level dust aerosols loading from TOMS because of the lack surface observations. Numerical simulation is one of the best means by which to reconstruct the distribution. Gong et al. (2003) simulated the dust column loading over 700 hPa for this dust storm event in the trans-Pacific. A good agreement between the spatial and temporal distribution of model-predicted dust loading and the TOMS AI was achieved, and the trans-Pacific dust transport was also shown from the NARCM-simulation (Gong et al., 2003).

There were two severe dust events in central Asia in April and May, 2001 (Han et al., 2005). The strongest dust storm on April 6 to 9, 2001 was transported over the north Pacific and reached North America; the other dust storm from April 29 to May 4 with a northward pathway arrived in the Pacific region in May (Gong et al., 2003). The spatial distribution of zonal transport at 6000 m from the NARCM-simulation clearly showed that the fine dust particles from central Asia can be transported to Korea, Japan, and the north Pacific and North America by the westerly jet (Zhao et al., 2003). In the north Pacific region the spatial distribution of dust deposition showed the following features: (1) the dust transport pathway from 38°N in East Asia turned towards 42°N in the north Pacific region; (2) the greatest dust deposition occurred over the trans-Pacific transport pathway and (3) the dust transport fluxes decreased with the increase of transport distance from the west Pacific to east Pacific. This result agrees with the conclusion that dust concentration decreases exponentially with increasing transport distance, based on the available surface PM10 observations.

4 Conclusions

This study provides an outline of the trans-Pacific transport, deposition, vertical profile, and spatial distribution of Asian dust aerosols during the period of April 11 to 18, 2001, through the integration of model simulation results and a comprehensive observation data from satellites, ground-based lidar, aircraft, and surface observation networks. The results showed: (1) the surface dust concentrations decreased exponentially with the dust transport distance; (2) the altitude of the dust concentration peak became higher with increasing transport distance in the north Pacific region and (3) the spatial distribution of dust deposition mainly depended on the trans-Pacific transport route.

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