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Long-range transport of yellow sand to Taiwan in Spring 2000: observed evidence and simulation

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Abstract

More than 10 Asian dust storms occurring in Spring 2000 were found to transport dust long distances, with some fallout reaching as far as Taiwan. An air quality data set from Taiwan clearly shows that long-range transport of yellow-sand results in air quality in Taiwan, which is categorized as "Unhealthy" or "Very Unhealthy". Backward trajectory analysis indicates that, for air parcels that arrived over Taiwan on 28 April, two or three days are required for transport from source regions, such as Inner Mongolia, a territory that is becoming a desert as a result of over-use and destruction of vegetation cover by human occupants. Furthermore, a 3-D long-range transport model for yellow sand, with an advanced size-dependent deflation module and driven by the NCAR/Penn State Fifth-Generation Mesoscale Model (MM5), is used to identify the long-range transport of yellow sand to Taiwan in April. Comparisons between observations and model calculations indicate that the model is able to reproduce some key features of the long-range transport. Transport of yellow sand to Taiwan is found to occur most easily when dust storms occurring in north China are accompanied by a high-pressure system located over the west of Japan. The high concentrations of yellow sand transported over Taiwan are usually between 500 and 1500 m high, not at the surface.

Keywords: Yellow sand; Observations in Taiwan; Transport; Modeling; Air quality

1. Introduction

The long-range transport of yellow sand has been observed over the last two decades (Duce et al., 1980; Tsunogai and Kondo, 1982; Parrington et al., 1983; Uematsu et al., 1983, 1985; Iwasaka et al., 1983; Murayama, 1988; Gao et al., 1992; Chung and Yoon, 1996). The yellow-sand phenomenon is dust storm occurring in East Asia, which is mainly from the Taklamakan, Gobi, and Ordos deserts and the Loess plateau and occurs most frequently in spring, between March and May, showing a clearly seasonal cycle. It plays an active role in the biogeochemical cycles of trace elements in the mid-latitude Northern Hemisphere (Okada et al., 1990; Preining, 1991; Zhang et al., 1998). The recorded instances of dust storms in Beijing have grown significantly in the second half of the 20th century, from 5 times in the 1950s, 8 in the 1960s, 13 in the 1970s, and to 14 in the 1990s. In 2000, more than 12 severe dust storms occurred in north China and some cases were found to transport dust long distances and as far as Taiwan. Yellow sand from north China has significant influence on the air quality of Taiwan, sharply increasing particulate matter (PM10) levels.

The purpose of the present study is to investigate the transport of yellow sand to Taiwan and to determine which aspects of this type of dust transport are important in April 2000. Observed evidence of yellow-sand events are shown in Section 2. Backward trajectory analysis is used to identify the transport paths of the pollutants in Section 3. Numerical simulation with a long-range transport model, and comparison with TOMS satellite retrievals of the absorbing aerosol index and the observed PM10 concentration in Taiwan, are

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used to estimate the source region of dust and to characterize the long-range transport of yellow sand to Taiwan.

2. Observational evidence of yellow-sand events in 2000

The Taiwan Air Quality Monitoring Network (TAQMN) has 72 air quality monitoring stations, including four traffic stations, four background stations, three industrial stations and two national park stations (see Fig. 1). The priority pollutants that can be monitored include particulate matter (PM10), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and ozone (O_3). To help the public understand air quality more easily, this formula of the Taiwan monitoring data is converted to a Pollution Standard Index (PSI) according to the law of EPA. For each pollutant, a sub-index is calculated from a segmented linear function that transforms the ambient concentration onto a scale from 0 to 500. The PSI is calculated as the maximum of these sub-indices. The index ranges from 101 to 199 and 200 to 299 are categorized as "Unhealthful" and "Very Unhealthful". The breakpoints of PM10 concentration for these two categories are 150 and 350 $\mu g/m^3$. When PM10 extends to 420 $\mu g/m^3$, the air quality is categorized as "Hazardous".

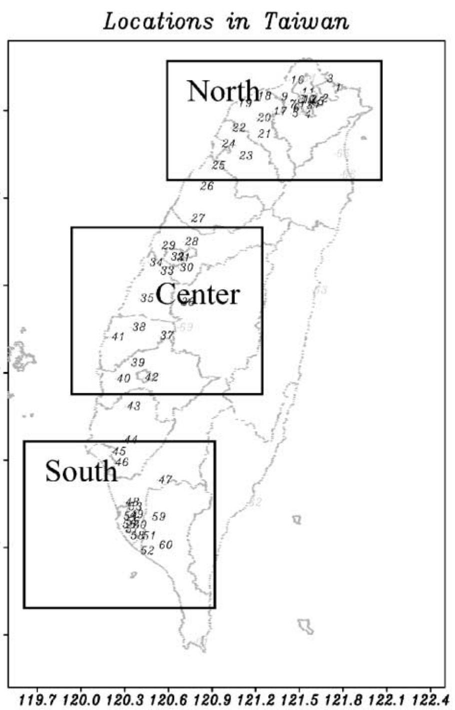

Fig. 1. The distribution of air quality monitoring stations at the Taiwan Air Quality Monitoring Network (TAQMN).

Time series of mean PM10 concentration in March and April 2000 are shown in Fig. 2 for the north, the center, and the south of Taiwan. SO_2 concentrations are also shown in the figure as an indicator of local pollutants. If the PM10 concentration is high and SO_2 is low, we can assume that the high level of PM10 is partly caused by the long-range transport of yellow sand. As seen in the figure there are two days, 25 March and 27–28 April, on which the long-range transport of yellow sand from north China to Taiwan may be clearly identified. In March 2000, there are at least five episodes of yellow-sand transport to Taiwan. They are on 4, 15, 20, 25 and 28 March, with the largest episode on 25 March, when the PM10 concentrations over most of Taiwan are more than 250 $\mu g/m^3$. Similar results can be seen for April. On 28 April, the observed PM10 levels are more than 400 $\mu g/m^3$ and result in "Very Unhealthful" and "Hazardous" air quality in north Taiwan, clearly showing the great influence of the long-range transport of yellow sand on public health.

3. Trajectory analysis

The transport paths of the pollutants were investigated by use of backward trajectory analysis for the high PM10 episodes in Spring 2000. Three-day isentropic back-trajectories are calculated using winds from NCEP reanalysis fields based on a statistical analysis of the latitude, longitude and height of the trajectory at 1 h intervals over 3 days. The analyses have a horizontal resolution of 1°, with 17 levels in the vertical and are archived every 6 h. The trajectories of particles were integrated backward in time by interpolating these four-dimensional (4-D) wind records to current particle positions, in time and space employing a fourth-order Runge–Kutta scheme. The particles' positions (latitude, longitude and height) were output every hour.

Two events with high levels of particulate matter (PM10) were observed by TAQMN on 25 March and 28 April. Backward trajectories for air parcels that arrived over Central Taiwan on these two days are shown in Fig. 3. The trajectories follow a northwest–southeast path due to the westerly flow coupled with a high-pressure system over Japan. On 25 March the air parcel moved via the Loess plateau from the arid lands of Mongolia to east China (Fig. 3a). The air parcel came from the west of the Mongolian Plateau, over the Gobi desert and the Loess Plateau, which are major source regions of yellow sand. On 23 March , it moved over the East China Sea and then southwest to central Taiwan. In contrast, the high levels of yellow sand on 28 April in Taiwan are transported over Inner Mongolia and the Hebei province close to Beijing, a territory that is recently becoming desert. Two or three days are needed for the transport of yellow sand from the source regions

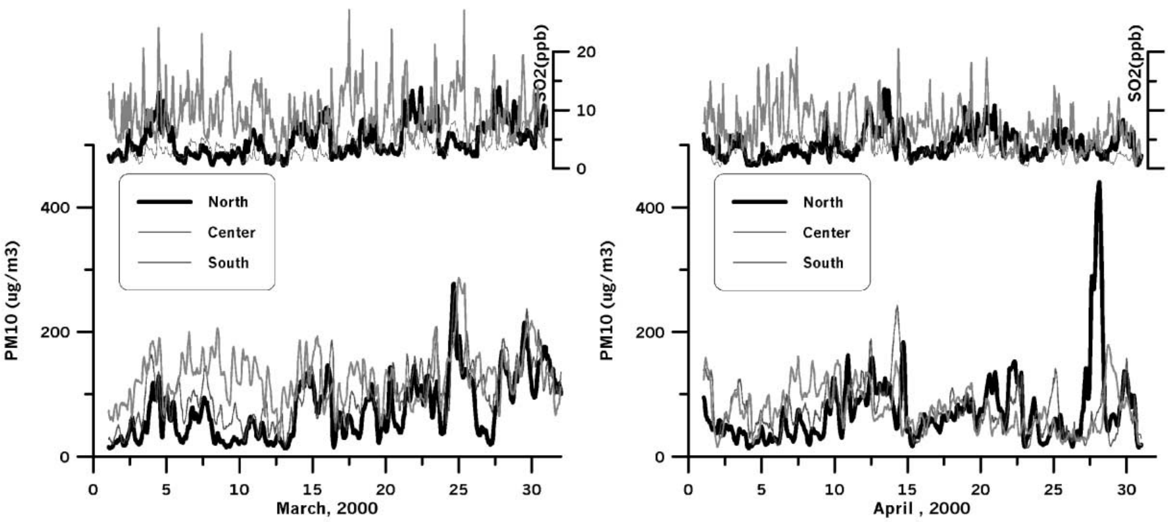

Fig. 2. Time series of observed PM10 ($\mu g\, m^{-3}$) and SO_2 (ppb) concentration averaged among the stations in the north, center, and south of Taiwan in March and April 2000. The stations in each area are shown in Fig. 1.

to Taiwan. In addition, both trajectories approached Taiwan over the Shanghai region, and crossed the East China Sea to Taiwan at levels below 2000 m. The trajectories agree well with the meteorological charts, yellow-sand observations and model simulations.

4. Model simulations

4.1. Model description

The long-range transport model system used here is an Eulerian transport, transformation and removal model which includes all the major processes such as emission, advection, diffusion, chemistry, dry deposition, wet deposition and micro-physical processes (Huang and Wang, 1998). It simulates time-varying three-dimensional distributions of trace gases and yellow-sand particles, as well as the temporal and spatial distribution of dry and wet deposition of atmospheric tracer species. The yellow-sand particles are divided into nine particle size bins from 0.5 to 90 μm in the model. A deflation module of soil and sand dust loading has been coupled with the model to provide explicit information on the emission intensity of yellow sand over East Asia (Wang et al., 2000). In contrast to previous modules for Sahara and Australian deserts, it includes three major predictors: the friction velocity, the surface humidity, and the dominant weather system. Chinese dust storms are initiated by strong winds in dry conditions and travel behind the cold fronts associated with moving low-pressure systems. We assume that deflation only occurs when the potential source areas are controlled by these kinds of systems. In the module, the change of surface air temperature during the previous 6 h is used to address the dominant weather system. Comparison of the deflation module results, with observed data on dust deflation in April and July 1988 using these three parameters together or separately, shows that the best estimate can be obtained by considering the three predictors together. It indicates that the last two predictors provide a limitation for deflation and can decrease the number of false declarations, especially in the wet season. The model results show a reasonable agreement with the observations during yellow-sand episodes in the spring of 1988 and 1998 (Wang and Ueda, 1999, 2000).

The current model domain covers East Asia from 16°N to 60°N, and from 75°E to 145°E with a horizontal resolution of $1^\circ \times 1^\circ$. It includes the Himalayas and Tibet to the west, Korea and Japan to the east, south Siberia to the north, Taiwan and Hong Kong to the south, and the Gobi and Taklamakan deserts and the Loess plateau at the center. The vertical extent consists of 18 layers from the surface to the tropopause with a terrain-following height coordinate.

Meteorological fields were obtained from the NCAR/Penn State Fifth-Generation Mesoscale Model (MM5). MM5 has been used for a broad spectrum of theoretical and real-time studies (Grell et al., 1995). It includes a multiple-nest capability, nonhydrostatic dynamics and a 4-D data assimilation capability. An interpolation module considering the mass conservation is used to transfer the meteorological fields from the MM5 coordinate system to that of our model system. The Mercat map projection selected for our simulation

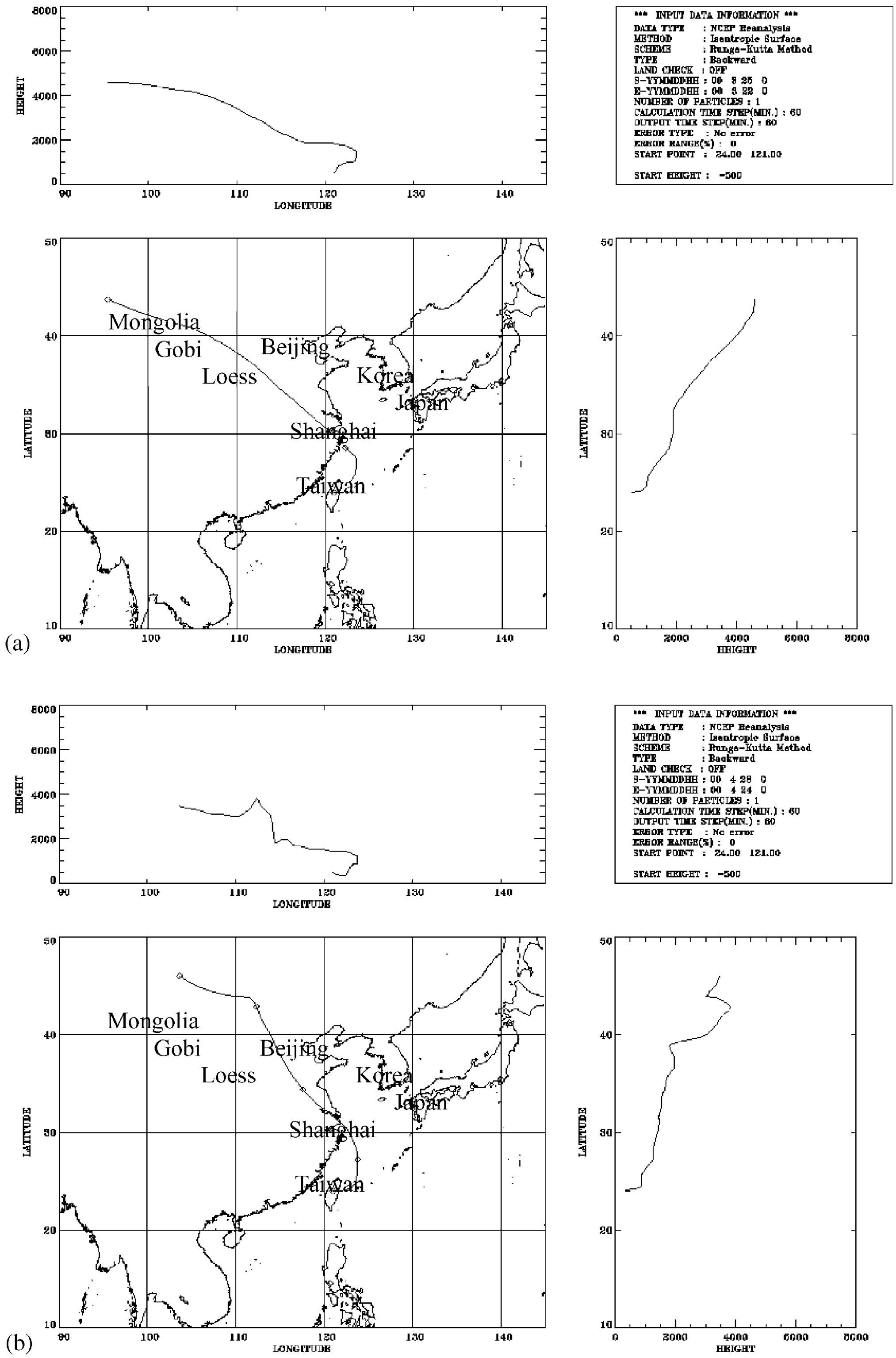

Fig. 3. Three-day backward isentropic air trajectory from Taiwan using winds from NCEP analyses at 00Z on 25 March (a) and 00Z on 28 April 2000 (b), respectively.

reduces the error in this interpolation. For each time step the emission intensity was computed by the deflation module using the surface winds, temperature, and relative humidity linearly interpolated from the MM5 output.

4.2. Simulation results

A one-month simulation of the transport of yellow sand was carried out for April 2000. Fig. 4 compares the observed PM10 concentration with the simulated yellow-sand levels in north and south Taiwan. The model shows five dust events reaching north Taiwan, with two heavy episodes, on 11 and 27 April, but only reaching south Taiwan three times. The influence of yellow sand on south Taiwan is small, with concentrations of yellow sand less than 100 $\mu g\,m^{-3}$. The predicted peaks of yellow sand are reasonable, as is the arrived time of the yellow sand. Comparing with observations, the two heavy episodes are reproduced well by the model, but the amount is still difficult to predict well. The predicted surface concentration on 27 April 2000 is more than 230 $\mu g\,m^{-3}$; the strongest transport of yellow sand, has reasonable agreement with observations in Taiwan if we take into account the local sources of PM10. The concentrations of PM10 in south Taiwan are high throughout the year due to the heavy industry located in the area (Liu et al., 1999). It is therefore difficult to separate the influence of the transport of yellow sand from that of local PM10 sources, and would require a detailed chemical composition analysis of PM10 during the spring.

There are clear indications that the dust is transported horizontally over long distances with a multi-layered profile, one layer near the ground, and the other in the middle troposphere (Uematsu et al., 1983). The vertical distributions of the simulated yellow-sand concentrations over the East China Sea, the north, the center and the south of Taiwan in April are shown in Fig. 5. The high concentration of yellow sand over Taiwan was usually between 500 and 1500 m high, not at the surface. Over the East China Sea, more than seven dust storms arrive, more than over Taiwan. This indicates that the main paths of yellow sand are associated with westerly flow, located around 30°N. From the analysis of backward trajectories, we found that the air parcels arrived over Taiwan were transported from the East China Sea at levels below 2000 m. Fig. 5 clearly shows a similar tendency in the model. The concentration of yellow sand decreased from north Taiwan to south. The closer the source region, the higher is the level seen. For 27 April, in north Taiwan the height is about 1 km, but for south Taiwan it is only 300 m high.

Here, we focus on discussing the simulation results for the episode of high PM10 levels greater than 400 $\mu g\,m^{-3}$ on 27, 28 April in Taiwan. Synoptic analyses of the episode show that the path of the transport of yellow sand is controlled by a high-pressure system located to the west of Japan when the dust storm occurred in north China on 25 April. This kind of synoptic system forces the yellow sand to move southeastward from the source region along the western edges of the high-pressure system, making the eastward transport of yellow sand very difficult. The dust loading was calculated with the deflation module for 24–27 April (Fig. 6). The deflation

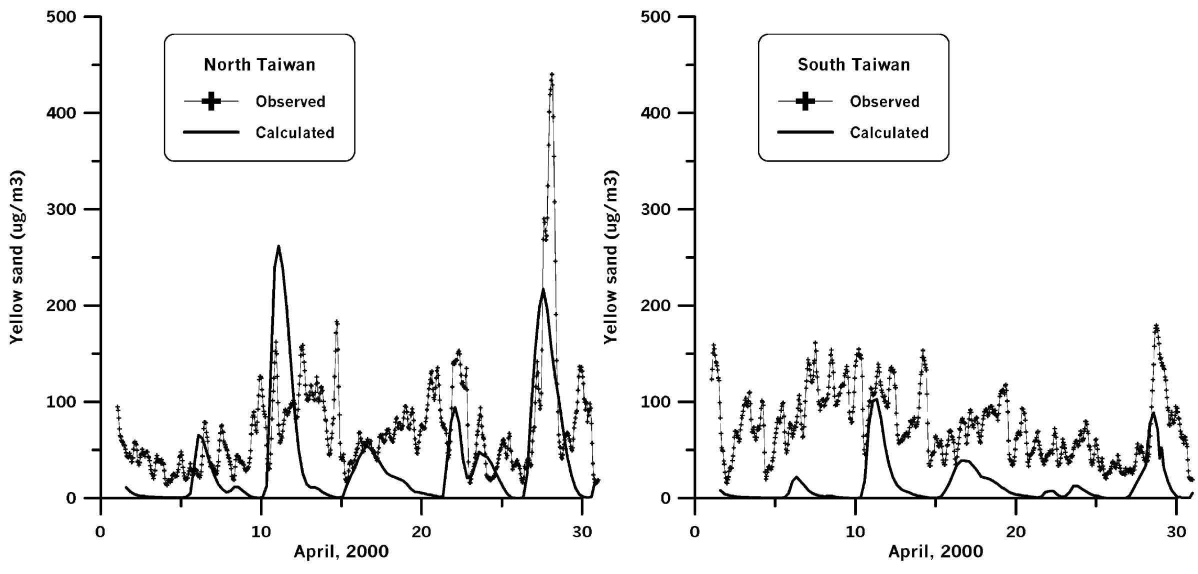

Fig. 4. Comparison of observed and calculated surface concentrations of yellow sand at north Taiwan and south Taiwan, respectively.

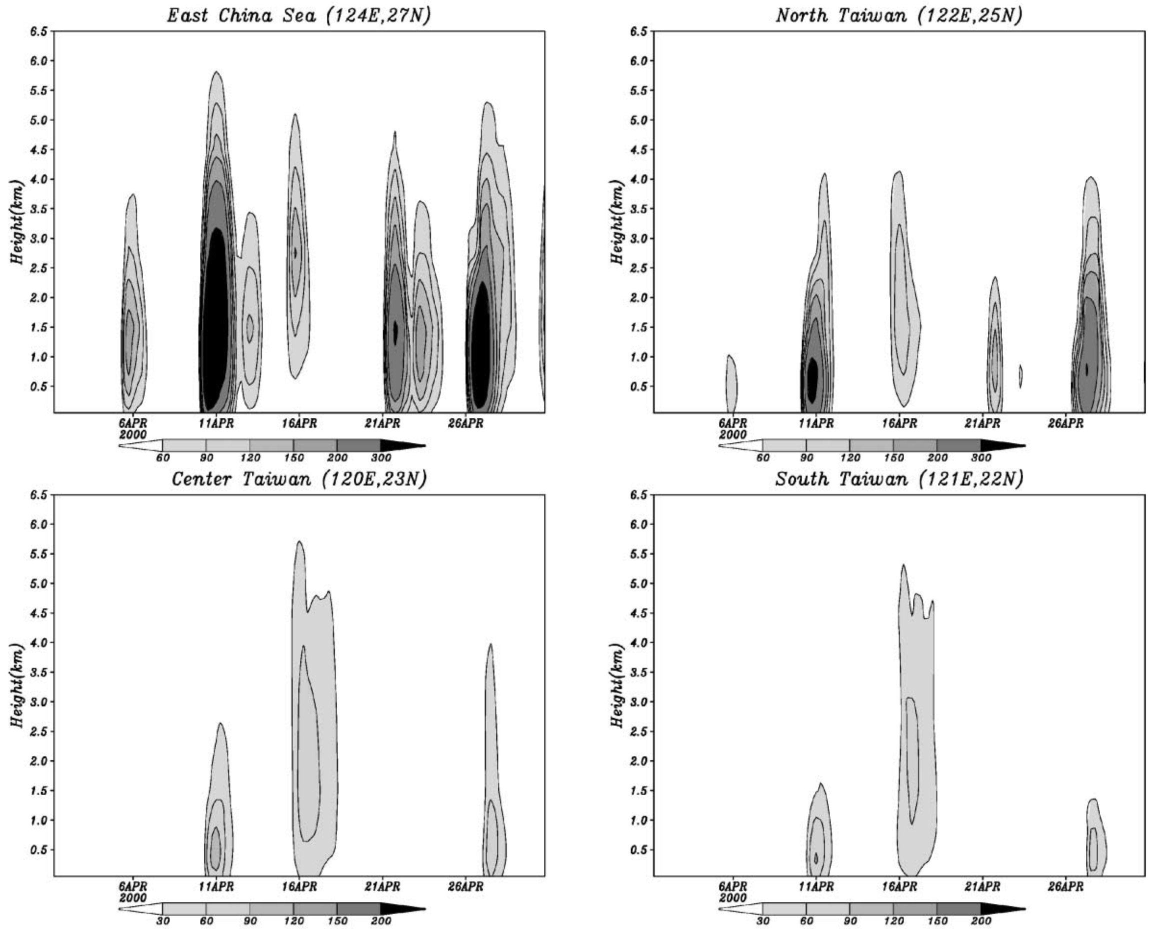

Fig. 5. Vertical distribution of yellow-sand concentration in east China, the north, the center and the southern parts of Taiwan in April 2000.

area on 24 April covered Inner Mongolia, the Gobi desert, and the Loess Plateau. It moved to the Loess Plateau and Hebei province on 25 April, but weakened on 26 April. On 27 April, another heavy deflation event occurred in the Taklamakan, and on the Mongolia Plateau.

Maps of daily TOMS satellite retrievals of the absorbing aerosol index (http://toms.gsfc. nasa.gov) are used for model validation. Comparisons of the TOMS' aerosol index with the simulated distribution of yellow sand at 150 and 3000 m on 25 and 26 April are shown in Fig. 7. The predicted distribution shows a reasonable agreement with the observations. Dust deflation occurred in Inner Mongolia, Gansu, and Shaanxi provinces on 24 April (Fig. 6). The yellow sand was transported southeast and covered north and northeast China on 25 April, and then moved eastward to the coastal areas of Bohai Sea and southward to central and east China on 26 April. When we compare the distribution of yellow sand at low level (150 m) and high level (3000 m), the distribution patterns fit the TOMS satellite maps very well. On 25 April, there is a high-pressure system located over the Korea peninsular and west Japan accompanied by very strong south winds along the east coast of China. At the same time, the wind fields are weak over east China. This kind of pattern may cause the yellow sand to be transported south-westerly rather than easterly. On 26 April, there is nearly no dust over north China, and no new dust storms occurred. However, the wind fields changed, with a strong north wind over east China from the surface to high levels resulting in floating dust that covered most of China and being transported southeasterly to Taiwan. The results for 27 and 28 April are shown in Fig. 8. Comparing the observation and the simulation, the calculated distribution patterns fit the TOMS satellite maps very well. On 27 April, TOMS could not retrieve the high concentration of yellow sand in the Mongolia

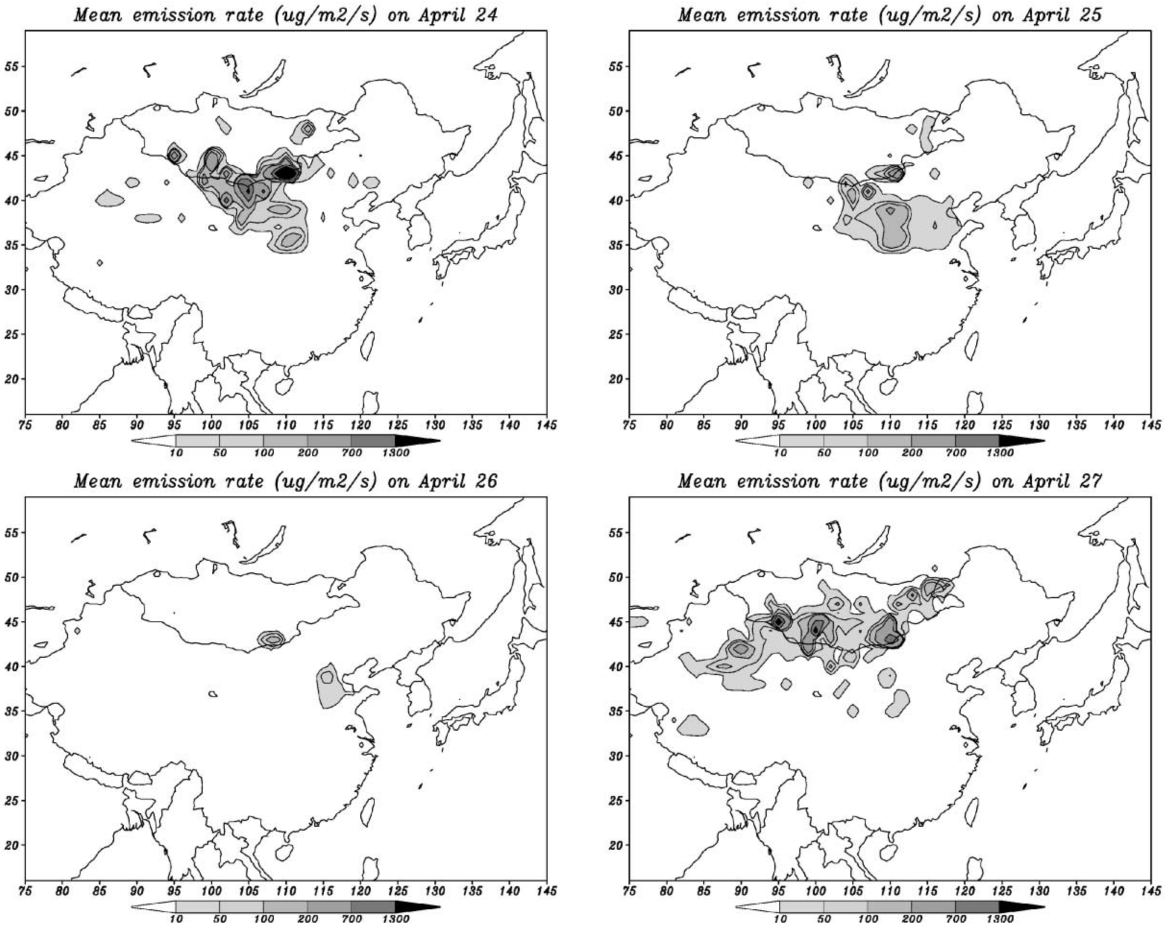

Fig. 6. Emission intensity of yellow-sand deflation on 24–27 April calculated by the model. Contours are 10, 50, 100, 200, 700, 1300 $\mu g\,m^{-2}\,s^{-1}$.

Plateau at 150 m, showing that the deflation processes occurred at low levels. Predicted yellow-sand concentrations decreased continuously and yellow sand was transported eastward to the Korean peninsula and west Japan, and southward to south China, reaching Taiwan on 27 April. On 28 April, TOMS observed high levels of aerosols in Takalamakan desert, Mongolia and central Inner Mongolia, Henan and Shandong province (south to Beijing). The model is capable of reproducing this result. But the satellite did not retrieve the high aerosols around the Beijing regions and eastern Inner Mongolia, in which the model predicted high levels of yellow sand. This is possibly due to the occurrence of strong cloud cover resulting in the strong dust maximum missing in TOMS. During the period, south China and Taiwan are controlled by a high-pressure system, causing the floating dust to be deposited to the surface over east and south China, the East China Sea and Taiwan.

5. Conclusions

Air quality data gathered in Taiwan provide clear evidence of the long-range transport of yellow sand in Spring 2000 with sharply increased PM10 levels. On 28 April, the observed PM10 levels are more than 400 $\mu g/m^3$ and result in air quality categorized as "Very Unhealthful" and "Hazardous" in north Taiwan, clearly showing the great influence of the long-range transport of yellow sand on the health of the public. Back-trajectory analysis indicates that the high levels of yellow sand originate from Mongolia, the Gobi desert and the Loess Plateau, and require two or three days for transport from the source area to Taiwan. From these two cases in Spring 2000, we found that the episodes of yellow-sand transport southeastwards to Taiwan are associated with a high-pressure system located over the west of Japan when dust particles are lifted over north China. This kind of synoptic system forces the yellow

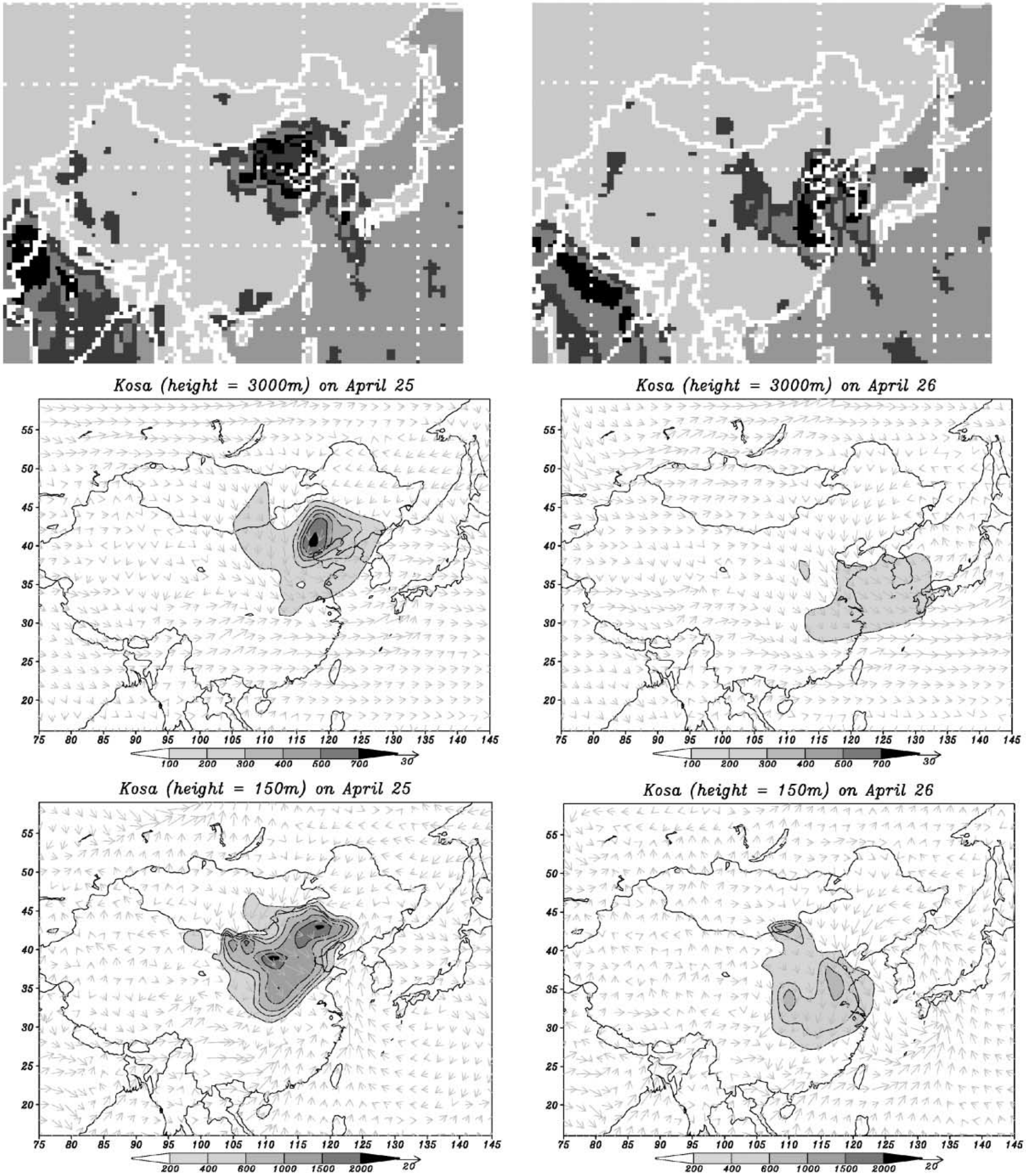

Fig. 7. Comparison of the TOMS satellite retrievals of the absorbing aerosol index with the distribution of simulated yellow-sand concentration ($\mu g\,m^{-3}$) at heights of 150 and 3000 m in East Asia on 25 April (left) and 26 April (right).

sand to move southeastward from the source region along the western edges of the high-pressure system. The model simulation results show a reasonable agreement with TOMS observations. High PM10 levels on 27, 28 April 2000 in Taiwan are mainly due to the long-range transport of yellow sand and the transport was usually between 500 and 1500 m high, not at the surface.

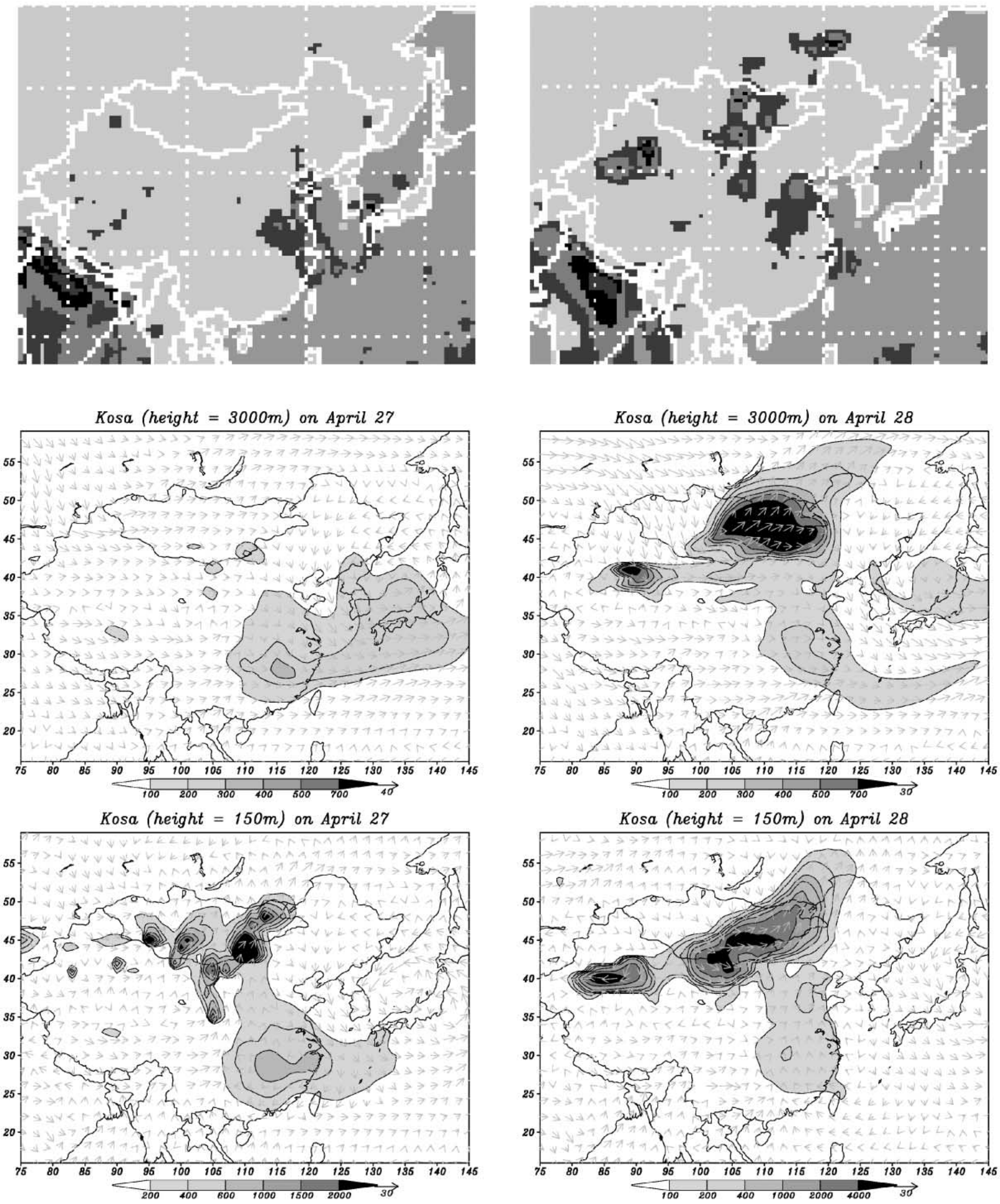

Fig. 8. Same as Fig. 7, but for 27 (left) and 28 (right) April.

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