Numerical Simulations of Asian Dust-Aerosols and Regional Impact on Weather and Climate- Part I: Control Case-PRCM Simulation without Dust-Aerosols

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ABSTRACT

Aerosol particles affect atmospheric radiation and cloud microphysics, and are considered a major uncertainty in climate forcing. At the same time, accurate simulation and prediction of meteorological conditions are necessary to simulate the distribution and chemical reaction of the aerosols. Distribution of pollutions can also be used to validate meteorological models. This paper consists of two parts: Part I: Numerical simulation of weather and soil conditions from the Purdue Regional Climate Model (PRCM); and Part II: Numerical modeling of online interaction between dust and weather/climate. Both parts were integrated continuously from April 08 to 24, 1998 without nudging or restarting. The detailed treatment of soil and the planetary boundary layer (PBL), using the semi-conserved ice-potential temperature and total water substance as prognostic variables, a local reference to calculate the pressure gradient, and the accurate advection scheme, allowed the PRCM to well reproduce the movements of the fronts/cyclones, downslope wind, upper/mid-level-jet, vertical mixing, and the low-level convergence over a complex terrain. They are crucial to the lift, dispersion, and transport of dusts over the Gobi Desert, the Taklimakan Desert, and the downstream regions. The dust model in Part II calculated the production, mixing, transport/removal, and radiative property of the dusts using the meteorology generated by the PRCM. The radiative effects of the dusts calculated from the dust model were then fed back to the PRCM. Because no nudging or restarting was applied during 17 continuous days of integration, the conservation laws of momentum, energy, and mass (including dry air, water substances and dusts) are valid. Hence, the PRCM provides data that are consistent for studying the movement of aerosols and the interactions among the aerosols, weather, and soil.

Keywords: Dust; PRCM; Transport; Cutoff low; Jet; Downslope wind.

INTRODUCTION

Integrating meteorological models and air quality models may be the best approach to study the interactions among air pollution, climate/meteorology, and soil condition. However, it also poses several major challenges. Meteorology is the main source of uncertainty in any air pollution and emergency preparedness model, because the emission, dispersion/mixing, transport and removal of aerosols depend upon meteorological conditions (Uno et al., 2006). At the same time, aerosols can also affect radiation, cloud, temperature, wind, and precipitation, as well as mesoscale and/or large scale circulations. Aerosols are also good indicators of wind, mixing and precipitation/washout in the real atmosphere and numerical models. Part I of this study presents the Purdue Regional Climate Model (PRCM) and simulations of the meteorological conditions in April 1998, when two severe dust storms developed in inner Asia. The dust plumes travelled across the Pacific Ocean and reached the U.S. within a few days.

The error of a predicted dust concentration can come from the errors in source regions, emission, transport, and deposition of dust, which mainly depend on the physics, dynamics, and numerical schemes of atmospheric and soil models.Observed wind, temperature, cloud, and soil conditions are more accurate than model simulations. However, the observed data is usually collected twice a day with a horizontal distance of a few hundred km between two stations, it is never dense enough in time or space to drive an air quality model, nor can it provide any forecasting data. Thus, a meteorological model is required, which can provide 4D meteorological field continuously, some of variables, (for example turbulent mixing) are not observed routinely but required in pollution models. Unfortunately, meteorology generated by a model also introduces the main source of uncertainty in air pollution modeling.

Asian dust frequently occurs during the spring in East Asia. However, April 1998 was one of most severe cases. The meteorological environment and soil conditions should
be quite special in order to support the lifting and transport of the dense dusts. It was noted that Taiwan EPA issued a severe warning for that event. Several numerical models, including PSU/NCAR mesoscale model MM5, also predicted the dusts carried by strong northerly wind in the PBL would reach Taiwan. Actually, most dusts stayed above the PBL, and were transported eastward by strongly winds in the mid-level jet (Sun et al., 2013a). In and Park (2002) applied a 3-D air quality model including a dust module, and used the MM5 meteorological outputs to study the dust storms of April 14–19, 1998 in China. Their simulated plumes stayed mainly below 2000 m and were extensively transported southward, which differed from observations. When observed in Seoul and Hefei the mean height of the plumes was about 4 to 5 km (Murayama et al., 2001). Murayama et al. (2001) and Uno et al. (2001) successfully applied an on-line tracer model to study the dust and aerosols transport between April 13 and 30, 1998. The tracer model was coupled to the Regional Atmospheric Modeling System (RAMS) (Pielke et al., 1992), with a build-in four-dimensional data assimilation (FDDA), based on European Centre for Medium-Range Weather Forecasts (ECMWF) global analysis data, being applied to their meteorological fields. FDDA involves the integration of effective time-dependent observational data into a predictive model. In RAMS this is done during the model running through the so-called Newtonian relaxation (“nudging”) scheme to force the simulated meteorological fields close to observations. Over Japan, the height of the simulated dust layer was about 3 km due to a descending motion in the region, but it was higher (4 to 5 km) in Seoul and Hefei (31°52′N, 117°17′E). A thin dust layer in the upper troposphere and the coexistence of dust and cirrus clouds were also commonly observed in Hefei and Japan. The trajectories derived from the ECMWF showed the apparent effect of the cutoff low at Hefei and Nagasaki when that cutoff low passed over those regions, e.g., a strong downward motion and a counterclockwise curved trajectory. Those studies reveal the difficulties for weather models to accurately simulate the evolution of weather systems and the associated wind fields, which control the horizontal transport of dusts. It is also difficult to formulate appropriate lifting in the source regions enhanced by low-level-convergence and downslope wind over complex terrain as well as turbulent mixing and deposition to simulate the dusts and clouds in the right altitude in the downstream regions. Finally, the precipitation and washout are another challenge in model simulations.

Although it is popular to use reanalysis to force the model simulations close to observations (i.e., nudging), or restart within a short period (1–3 days), because the errors of the model increase with time, as discussed in Otte (2008), Cheng et al. (2008), and others. However, either nudging or restart violates the conservation laws of the Navier–Stokes equations. Therefore, the numerical results generated from long-integrations without nudging or restart are important to study the environment for the development of dust storms, as well as interactions and feedbacks between dusts and meteorological fields.

Here, we integrate the Purdue Regional Climate Model continuously from April 08 to 24, 1998 without nudging or restart in Part I and Part II (Sun et al., 2013a). The control run without dust in Part I is to investigate what kind weather conditions and land surface can produce the most severe dust storms in years, which reached North America, as well as to compare with the simulations including dust to study the active interactions between dusts and weather. Some of the observed and/or simulated dusts are also used to validate the observed and simulated weather patterns discussed in Part I.

THE PURDUE REGIONAL CLIMATE MODEL (PRCM)

As discussed by Uno et al. (2006), the modeled wind over the Taklimakan area and Tibetan Plateau differ considerably between well-established meteorological models. Some models in these inter-model comparisons indicate very calm conditions in the Taklimakan Desert, whereas other models show a systematic easterly wind. The dust emission flux is fundamentally proportional to the third or fourth power of the surface friction velocity ($u^*$). Therefore even a small difference of say, 2–3 m/s will engender a factor of 2 or 3 times the difference in dust emission flux. This indicates that the differences in model results mainly lie within the meteorological parameters. However, each dust model is strongly connected to its own meteorological driver (model), and the participating groups consider the usage of unified meteorological conditions impractical (Uno et al., 2006). Hence, the detailed physics and numerical schemes of meteorological models are crucial for predicting the dust and aerosols in an air quality model. Improvement of the meteorological model is a key to reduce the differences and errors among dust models.

The PRCM is a hydrostatic primitive equation model that utilizes the terrain-following coordinate ($\sigma$) in the vertical direction. The major differences between the PRCM and other regional climate models (For examples: MM5 (In and Park, 2002), and Cloud Resolving Storm Simulator (CreSS, Tsuboki and Sakakibara, 2007; Sun et al., 2012, 2013b), etc.) are as follows. The ice-equivalent potential temperature $\theta_e$ and total water substance $q_w (= $ water vapor $+ $ cloud liquid water $+ $ cloud ice) are used as prognostic variables (Chern, 1994; Haines et al., 1997; Chen and Sun, 2002), which are also used in the turbulent kinetic energy equation (TKE) with an improved mixing length scale (Sun and Chang, 1986a, b). The model also includes multi-layers of snow, vegetation, and soil (Bosilovich and Sun, 1995; Sun and Chern, 2005), NASA radiation parameterizations (Chou and Suarez, 1994; Chou et al., 2001), and cumulus parameterizations (Kuo, 1965, 1974; Anthes, 1977), the fourth-order advection scheme (Sun, 1993) in the advection terms, and a local reference applied to calculate the pressure gradient force (Sun, 1995). The transport of dusts and an atmospheric chemistry module
were added by Yang (2004a, b).

The PRCM, with the comprehensive soil-vegetation-snow module provides an accurate prediction of soil moisture and temperature, the passage of cyclones/fronts, and the enhanced downslope wind and convergence over complex terrains in the source regions. Soil property, wetness, and wind speed are crucial to the lift of dusts. The semi-conserved \( \theta_q \) and \( q_w \) used as prognostic variables and also applied to the TKE equation, provide a better treatment of the conservation of heat and water substance as well as the turbulence parameterization, as discussed in Sun and Chang (1986a, b), Sun (1986, 1988, 1989), and Chern (1994). We are incorporating the mass-conserved, positive-definite semi-Lagrangian scheme (Sun et al., 1996; Sun and Yeh, 1997; Sun and Sun, 2004; Oh, 2007; Sun, 2007), the sea-ice-mixed layer ocean module (Sun and Chern, 2010), and a new semi-implicit scheme (Sun, 2010, 2011) into the PRCM. The model has been applied to study the observed cyclogenesis and winter storms over the complex terrain in the western USA (Chern, 1994); formation and propagation of lee-vortices in Taiwan (Sun et al., 1991, Sun and Chern, 1993, 1994); winter storms and vortices in the Rocky Mountains (Haines et al., 1997); interactions between cold front and mountains in Taiwan and China (Sun and Chern, 2006), etc. It has also been integrated from a few weeks to a few months continuously without nudging to study the East Asia climate for 10 summers (from May 1 to August 31) between 1991–2000, the bias of the mean-sea-level pressure is –0.15 hPa; the bias of the surface temperature is 0.47 K, and RMSE is 0.72 K (Hsu et al., 2004; Yu et al., 2004; Yu, 2007). It has also been applied to study the 1993 flood in the USA (Bosilovich and Sun, 1999a, b); 1998 drought in the USA (Sun et al. 2004); and 1998 flooding in China and Korea (Sun et al. 2011); the Red River flooding due to snowmelt in the US (Min, 2005). Detailed model descriptions and applications can be found in Sun et al. (2009). This paper is to study the favor conditions for the development of severe dust storms, as well as why some models predict that dust storms would reach Taiwan. The ECMWF reanalysis and some observational data, including plume concentrations will be used to validate the meteorological variables. Similar approaches are used in other case studies, including: Murayama et al. (2001), Uno et al. (2001), In and Park (2002), Otte (2008), Cheng et al. (2008) and others. Although the PRCM has been validated against several observational data and reanalysis, more cases studies and validations are needed in order to have a better understanding of the model performance when it is applied to predict the weather and pollutions of dust storms, as well as how to improve the model.

NUMERICAL RESULTS

The domain discussed in this study covers an area of 7740 km × 6180 km as shown in Fig. 2, consisting of 129 and 108 grid points in the x- and y- directions, respectively. The horizontal resolution for each grid is 60 km × 60 km. There are 28 vertical levels in a sigma coordinate system, and 4 levels in soil. The integration time step used for the atmospheric modeling was 2.5 minutes. The radiation calculations were performed every 30 minutes. During the PRCM-Dust runs (in Part II), the aerosol optical properties of dust aerosols in each vertical layer were updated in the radiation module during the PRCM modeling. The initial and boundary conditions of the meteorological fields were from the ECMWF Operational Reanalysis data sets, and have a resolution of about 1.125 degrees. The boundary conditions were provided every 6 hours by the ECMWF. The model also includes the U.S. Navy 10-Minute Global Elevation and Geographic Characteristics and the Wilson, Henderson-Sellers’ 1-Degree Global Vegetation and Soils data. As discussed previously, an accurate simulation of the meteorological fields and soil conditions are needed before we can predict the dust concentration from an air quality model (Uno et al., 2006). Here, we will first present the results from the PRCM without Dust model, which is referred to as the Control Run.

The mean-sea-level pressure and 500-hPa wind on April 14 from the ECMWF and model simulations after 6 days of integration are shown in Figs. 3 and 4. On April 14, both reanalysis and simulations show a cyclone located around 57°N and 85°E in the lee of the Altai Mts., which is composed of 3–5 km high barriers. It should be noted that the lee slope of mountains is a favorite area of cyclogenesis in Asia. A strong cyclonic wind around the low enhanced by the downslope wind on the lee side of the Altai Mts. lifted the dust from the Taklimakan Desert. There was another low located around 55°N, 117°E and a pressure gradient zone near 107°E, which is clearer in the simulations than in the ECMWF reanalysis. This might be due to the coarse resolution in the reanalysis. The strong wind, around the deep cyclone near the Taklimakan Desert and the cold front along the edge of the simulated high pressure were responsible for

Fig. 1. Long-range transport of Asian dust (Husar et al., 2001).
Fig. 2. Model Domain with 10 lateral boundary nudging band.

Fig. 3. (a) ECMWF mean sea level pressure (unit: 0.1 hPa); (b) Wind at 500 hPa at 00Z 14 April (unit: m/s).

Fig. 4. (a) Simulated mean sea level pressure after 6 days integration at 00Z 14 April (unit: 0.1 hPa); (b) Wind at 500 hPa (unit: m/s).
the initiation of the first dust event at the source regions and will be discussed in Part II. The wind at 500 hPa was stronger than 20 m/s over the dust source regions. The area of wind speed greater than 20 is indicated by orange color and wind direction closely follows the direction of the strong-wind-band. This area of strong wind gradually moved toward the southeast following the trough in the upper level, where baroclinicity was well developed. At the 500-hPa surface, a strong wind belt existed along the baroclinic region and around a cyclonic vorticity near 43°N and 120–125°E, as shown in the reanalysis and simulation at 500hPa (Figs. 3–4). This is a characteristic pressure pattern for maturing cyclonic vorticity (Chun et al., 2001; Chung et al., 2003), which deepened when it moved eastward.

On April 15, a deep low pressure was situated in northeastern Mongolia, as shown in the surface map in Fig. 5(a) and the model simulation in Fig. 5(b). The high pressure was located from western Mongolia extending to Tibet; there was also a high pressure over North Korea and northern Japan as well as over the Pacific Ocean; and there was a low pressure over southern Japan extending southwestward to Taiwan and the Philippines in the surface map (Fig. 5(a)). They are well reproduced by the model. The occurrence and passage of strong surface winds along the surface pressure gradient zones are also indicated by the wind-blown dusts observed to the southwest and southeast of Mongolia shown by black dots near (120°E, 40°N) and (100°E, 40°N) in Fig. 5(a) (In and Park, 2002). Those pressure gradient zones are also shown in numerical simulations in Fig. 5(b). Dusts at 95–100°E and 40°N originated from the Taklimakan Desert, and dusts at 120°E and 40°N originated from the Gobi Desert. The sands lifted in the Gobi Desert (from the 1000 to 1500 m elevation) and the Taklimakan Desert (from the 1500 m elevation) were transported eastward and southeastward by the low-level jet stream (LLJ) at 700 hPa (Fig. 6), or by the stronger wind above. The simulated surface-air temperature and wind at 700 hPa on April 15–17 (Figs. 6–8) reveal the advancement of cold fronts, cyclones,

![Fig. 5.](image-url)
and jet at 700 hPa, because the wind at 700 hPa came from cold air and was almost perpendicular to the cold front. The modeled surface winds near the Gobi and Taklimakan Deserts were over 10 m/s, and the winds were over 20 m/s at 700 hPa, and the observed wind of LLJ was greater than 20 m/s (Chung et al., 2003). The strong surface winds were above the threshold wind speed (5–6 m/s) for dust suspension (Gillette, 1978). Dust clouds form when the friction from the high surface wind speed (> 5 m/s) loses dust particles into the atmospheric boundary layer and above. Once sand is pushed and lifted by the strong downslope wind and/or gusty wind, the vertical mixing and the cold air in a convergent flow of a cyclone can lift the sand and dust up higher. It is crucial to accurately simulate the spatial and temporal evolution of the cold front, cyclone, as well as the horizontal and vertical winds in the source regions over a complex terrain (Uno et al., 2006), because the gusty cold air in the rear side of a cold front and a strong cyclonic flow around the intense surface low play an important role in enhancing the downslope wind to produce sandstorms. Soil moisture and temperature directly affects surface albedo and stratification in the lower atmosphere. The threshold velocity in the dust emission module of the PRCM-Dust is also a function of soil moisture and property, which will be discussed in Part II. Consequently, it affects the surface temperature, wind, low-level-convergence, turbulent mixing, and dust emission, etc. They are crucial to both weather forecasting and aerosols/dusts modeling. The detail of the soil-snow model used in this study is presented in Sun and Chern (2005), which was validated against the 5-years observational data collected at Sleepers Experiment in Vermont. On April 16, a cyclone was situated in the southern portion of Bohai Bay, as shown by the surface temperature and wind at 700 hPa at 00Z16April (Fig. 7), which provides a steering flow for plume of dusts moving around the cutoff low, centered at 40–45°N and 115–120°E at 700-hPa. The maximum observed surface wind speed near this cold front was 15 m/s (Uno et al., 2001; Chung et al., 2003).
simulated wind pattern at 700 hPa matched excellently with the observed wind and the simulated U-shape high concentration at 00Z 16 April. More discussions will be presented in Part II. On April 17, a surface cyclone of 1008 hPa was located over the Yellow Sea (not shown). The simulated wind at 700 hPa (Fig. 8) shows that a deep trough moved eastward, from Bohai at 00Z 16 April to Korea at 00Z 17 April, and sand dust was observed in Cheju, Korea and in the Hebei and Henan Provinces of China. On 18 April, a pressure trough over the Japan Sea and Korea, followed by an eastward-moving anticyclone of 1018 hPa, pushed the dust storm over a wide area. As a result, on 18–20 April dusts occurred extensively over Korea, Okinawa (~25°N) and Japan, etc. (Chung et al., 2003).

Figs. 9–10 show that at 00Z 19 April, the observed new low pressure located near the border between Russia and Mongolia was well numerical simulations after 11 days of continuous integration. A major storm swept through Mongolia and north central China on April 19–20, when a cold front entered western Mongolia and swiftly moved eastward. The modeled surface winds near the Gobi Desert were over 13 m/s, and 700-hPa winds over 27 m/s. The strong wind zone at 700-hPa also moved eastward during April 19–21, as shown in Figs. 9–11. Meanwhile, a strong zonal wind belt developed at 500-hPa (Fig. 10), which was a perfect condition for dust to be transported eastward (Chun et al., 2001). Dusts were transported to Korea, Japan, and the North Pacific Ocean, and then advected to the West Coast of North America. This was clearly monitored by the SeaWiFS (Sea-viewing Wide Field-of-view Sensor, http://oceancolor.gsfc.nasa.gov/SeaWiFS/BACKGROUND/SEAWIFS_BACKGROUND.html) and TOMS aerosol index, as shown in Fig. 1. It was also noted that on April 19–21, the near west-east orientation of the wind field was consistent with the west-east oriented dust concentrations and plume-trajectory derived from the reanalysis that will be discussed in Part II. It is noted that the concentration of dusts can be used to validate the vertical and horizontal velocities, as well as mixing and stratification generated from the numerical model.

Fig. 8. Same as 6, except at 00Z17April.

Fig. 9. (a) ECMWF mean sea level pressure at 00Z19April (unit: 0.1 hPa); (b) wind at 500 hPa (unit: m/s).
The 17-day mean 850 hPa geopotential height and 700 hPa wind field from the ECMWF reanalysis and the PRCM result (Figs. 12 and 13) reveal that the PRCM is capable of simulating the observed meteorological fields during 17 days of integration, which creates a sound foundation for studying the life cycle of dust. In addition, the control run
SUMMARY

The PRCM was integrated continuously for 17 days from April 8 to 24, 1998 to simulate the environment when two huge dust storms occurred in Asia. The model well reproduced the observed meteorological field, especially the intensification and movement of the cyclone and the cutoff low, passage of cold fronts, strong downslope winds enhanced by cyclones and fronts, as well as the soil condition in the source regions. These characteristics are crucial to the onset of dust storms, and the lift, transport, dispersion, and removal of the dust. The distribution of dusts can also be used to validate the simulated wind, stratification, and mixing, etc. The detailed distribution of the dust will be discussed in Part II. Because no nudging or restarting was applied in this study, no artificial source/sink terms were added in the model, and thus the conservation laws of momentum, energy, and mass are valid according to the equations of motion. The PRCM can also provide a detailed 4-D evolution of the meteorology and dusts for studying the interaction between weather and dusts.

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