Numerical Simulation of Dust Storms in Asia

By

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April 1998: Long-range transport of Asian dust (Husar et al. 2001)
Asian Dust Storms

SeaWiFs Satellite Image
(April 16, 1998)

Dust Storm in China, 2001 (NASA/Jesse Allen, Robert Simmon/MODIS science team)
March 31, 2009 -- Powerful dust storms that whip across China's north and ...

Seoul, April 2007

Pictures show sand storms in Heilongjiang Province, northeast of China, May 12, 2011.

Jun 20, 2011

A cow herder during a dust storm at the coal ash disposal site of the Yuanbaoshan Power Plant, Chifeng, Inner Mongolia.

March 22, 2010: Osaka

1500 µg/m³
Osaka dust storm from China

Pei-king, 2010

Osaka dust storm from China
Dust-storm in Iran originated from China. 2014.06.04.

Background

- Global modeling approaches have routinely been adopted to investigate the climatic impacts due to various kind of aerosols, including man-made aerosols (such as sulfate and carbonaceous aerosol) and naturally occurred aerosols (such as mineral dusts and biomass burning aerosols).

- The productions and distributions of atmospheric aerosols and climate-aerosol interactions are still not well known.

- The determination of the climatic effects of aerosols relies on the detailed information of atmospheric aerosols and on the honest representation of the radiative effects.

- Global climate change due to atmospheric aerosols should be considered from the regional-scale.
Challenges to Dust Storms Simulations:

1. Accurate weather system
2. Location and passage of fronts & cyclones over source regions
3. Wind, upslope & downslope wind over complex terrain
4. Soil moisture
5. Lifting of dusts from soil
6. Convergence and vertical mixing
7. Transport, dispersion & depositions
   (dry & wet- washed out by snow/rain)
8. Interactions among precipitation, cloud, dust and radiation
9. Active interactions between aerosols & weather without nudging or restart.
• Observed & simulation of June 1988 drought in USA at 500 mb

Sun et al. (2005)
Observed and simulated monthly precipitation over 1993 Midwest flooding area of USA (Bosilovich and Sun 1999)
Observed (green circle) and simulated (red x for Case A, blue line for Case B) of snow depth during 1 November 1969 and 31 May 1974.

Observed (green circle) and simulated (red x for Case A, blue line for Case B) for snow density.
Fig. 4a: Observed and simulated ground temperatures at layer 1-5 during 1 November 1969 and 1 November 1970


Fig. 4d: Same as Fig. 4a except during 1 November 1972 and 1 November 1973

Sun & chern 2005
Fig. 5d: Same as fig. 5a except during November 1972 and May 1997

Comparison between ECMWF (green dots) and PRCM simulations (lines) for mean sea-level pressure (MSLP) and surface air temp. (Tsfc) in Red River Valley of USA in March 1997 (Min & Sun 2011)
10 Summers Simulation Evaluation
(1991-2000 summer: May-August)

Climatological Mean (Yu et al., 2004; Hsu et al., 2004)

Bias  -0.15mb  RMSE  0.60mb  Pattern correlation  0.95

Climatological Mean:  from Yu et al. 2004

Bias  0.47K  RMSE  0.72K  Pattern correlation  0.99
Observed surface wind & model wind at $z=25$ m at 20Z May 16, 1987 (Sun and Chern 1993)

- Lee vortex and Land-sea breeze in Taiwan during TAMEX in 1987

Observation (a) and model simulation (b) of lee-vortex and blocking of mountains at 900 mb during TAMEX at 0200 LST 17 (1800 UTC 16) May 1987. (Sun and Chern 1993)
A portion set of 1° x 1° global source function data set.
2.3.4 Dust Emissions

The flux $F_p$ of particle size $p$ can be approximated by the following expression:

$$F_p = \begin{cases} 
    C S S_p U_{10m}^2 (U_{10m} - u_r), & \text{if } U_{10m} > u_r \\
    0, & \text{otherwise}
\end{cases} \quad (2.6)$$

where $C$ is a dimensional factor equal to $1 \mu g s^2 m^{-2}$, $S$ is the source function (the function of alluvium available for wind erosion), $U_{10m}$ is the horizontal wind speed at 10 m, $u_r$ is the threshold velocity, and $s_p$ is the fraction of each size class.

Relationship of the threshold friction velocity ($U_t$) to particle diameter ($D_p$). (From Marticorena and Bergametti, 1995)

2.5.1 Aerosol Optical Thickness

The optical thickness $\tau$ can be calculated from the dust mass load by the following relation

$$\tau(\lambda) = \sum_{i} \frac{3 Q_{ext}(\lambda, r_i) M_i}{4 r_i \rho_i}$$ \quad (2.10)

where

- $Q_{ext}(\lambda, r_i) =$ the extinction efficiency factor at wavelength $\lambda$ and effective radius $r_i$ (no unit)
- $M_i =$ column mass loading of the size class $i$ $(kg/m^2)$
- $\rho_i =$ mass density of the size class $i$ $(kg/m^3)$
(1) ECMWF reanalysis and (2) PRCM control run modeled mean sea level pressure (Pa) on 0000UTC April 14, 1998. The model results shown were obtained after 6-day simulations.

As in Fig. 4.1, except for 500mb wind field and vectors (m/s²) after 6-day simulations.

00Z April 14, 1998
Top: simulated surface air temperature at 00Z15, 00Z16, and 00Z17 April. Bottom: same as top except for 700hPa wind.

**Column Dust Loading**

Satellite Images from SeaWiFS Project on April 16, 1998

Total Column Dust Loading (×10^3 mg/m^2) on April 15 and 16, 1998
(1) ECMWF reanalysis and (2) PRCM control run modeled mean sea level pressure (Pa) on 0000UTC April 19, 1998. The model results shown were obtained after 11-day simulations.

except for 500 mb wind field and vectors \((\text{m/s}^2)\). on 0000UTC April 19, 1998. after 11-day simulations.
Simulate mixing ratio near 550 hPa (left) and TOM AI maps (right) at 00Z April 22.

Fig. 8: Isentropic trajectory back in time from Seoul at 4 km altitude: April 14-18 (left), April 19-23 (right) (Choi et al. 2001).
Isentropic trajectory back in time from Seoul at 4 km altitude: April 14-18 (left)

Modeled 700 mb wind & total column dust mass loading (102 mg m^-2) at 00Z April 16, 1998.

Isentropic trajectory back in time from Seoul at 4 km altitude: April 19-23 (Choi et al. 2001).

Simulate mixing ratio near 550 hPa (left) and TOM AI maps (right) at 00Z April 22.
Column Aerosol Optical Depth
Dalanzadgad, Mongolia, Lat=43.577, Long=104.419

(Measurement date source: AERONET)

Vertical Transport
Vertical cross-sections used in vertical transport analysis

Source Region
1200km downwind
Vertical distributions (1000 hPa to 200hPa) of modeled dust mixing ratios (mg kg$^{-1}$) by size at 1200km downwind region at 00Z April 22.
Fig. 12: A: PRCM(Dust)–PRCM(Control) daily mean surface temperature at 00Z for April 8-24, B: ECMWF April 1998 monthly mean surface temperature bias from 10-year mean.
Mean 850mb-geopotential m²/s² (April 8-24, 1998):

ECMWF reanalysis          PRM Model Output

17-day continuous integration without nudging or restart

As in Fig. 4.7, except for 700mb wind field and vectors (m/s²).
Fig. 1: the vertically integrated daily mean TSP concentration expressed in common logarithm (μg m⁻²) with the wind vectors at the height of 1500 m (In and Park 2002).
Our total columnar dust mass loading reached 3000 mg /m$^2$ on April 15-16, 1998 (Fig. 8), which may be comparable with the dust loading of 2967 mg /m$^2$ with concentration of 989 mg /m$^3$ (with a depth of 3.0 km) observed in Korea on January 25, 1999 (Chung et al.), and the mean column loading around 1500 mg m$^{-2}$ in Beijing simulated from the models in April of 2002 (Uno et al. 2006). While both MM5 and WRF failed to reproduce the concentration in the downstream regions. MM5 also produced cooling in high concentration areas.

Over the weekend, the Korea Meteorological Association (KMA) issued a dust warning for all of South Korea. Warnings are issued any time dust levels exceed 800 micrograms per cubic meter of air -- enough to pose a serious health hazard to anyone breathing in the stuff. Record measurements topped out at 2,847 micrograms per cubic meter. Yuck.
An intercomparison study of dust emission/transport models over Asia (DMIP) for two dust episodes in 2002 were performed utilizing 8 dust models based on the output of global or regional meteorological models with objective analysis results (including NCEP, ECMWF, JMA, and NOGAPS) (Uno et al, 2006). The model correctly captured the onset and cessation timing of the major dust event at the observation site. However, the maximum concentration of each model differed by a factor of 2–4 times. The modeled wind over the Taklimakan area and Tibetan Plateau differed considerably between meteorological models. Some models indicate very calm conditions in the Taklimakan Desert, whereas other models showed a systematic easterly wind. The dust emission flux is fundamentally proportional to the third or fourth power of the surface friction velocity (u*). Thus, even small differences (say, 2–3 m s⁻¹) will result in a difference in dust emission flux of a factor of 2 or 3 times. Their results indicated that the difference in model results may be due to the meteorological parameters. Improvement of the meteorological model is a key to reducing the differences among the dust models.

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Thank you very much


ECMWF-reanalysis (a) wind vector (arrow indicates wind speed of 9.45 ms\(^{-1}\)), and (b) streamline at 06Z15 at \(z = 25\) m.

Simulated (a) wind vector (arrow indicates wind speed of 14.4 ms\(^{-1}\)), and (b) streamline.
Wind Barbs: Purdue/NTU NH Model
Dark Arrows: Observed Winds

201x201 grid
1km Grid spacing. This plot shows the central part of the model domain.

Color contours show the model terrain in m asl.

Grid number west to east direction

(a) wind in White Sands after 4-hr integration, (dx=dy=2km, and dz=300m). initial wind U= 5 m/s;  (b) Streamline (white line) and virtual potential temperature (background shaded colors) at z=1.8km, warm color (red) indicates subsidence warming on the lee-side, and cold (blue) color adiabatic cooling on the windward side of the mountain.
Conclusions:

The PRCM with Dust seems able to reproduce the observed Weather and dust distribution during 18-days integration without restart or nudging.

The distributions of dusts and radiative effects strongly depend on detailed simulated wind, stratification, precipitation, turbulences and soil conditions as well as the passage and evolution of weather systems.

A model requires restart or nudging cannot be applied to study the interactions between aerosols and weather, although it is a popular approach.

Fig. 5: (a) Surface weather maps at 0000 Z15 April of 1998. The black circle indicated observed blowing dust or the dust emission (after In and Park 2002). (b) simulated mean sea level pressure