Direct radiative forcing of aerosol in Asia and its impact on the meteorological fields

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Roles of aerosols:
- Provide reaction sites for atmospheric chemical species
- Serve as carriers for many condensed or sorbed species
- Change the global climate system by
  - changing atmospheric radiation balance,
  - directly by absorption, scattering and emission of solar and terrestrial radiation
  - indirectly by changing the albedo and the life time of clouds by acting as cloud condensation nuclei
Wind-blown mineral dust from desert and semiarid regions is an important source of tropospheric aerosols

- contributes 1000-3000 Tg yr\(^{-1}\) to global atmospheric emission
- a distinct feature in East Asia, West Africa, South America

In East Asia, Asian dust (Hwangsa in Korean)

- frequently occurs in Sand desert, Gobi desert and Loess plateau in northern China and Mongolia
- reported to be transported to the western part of USA
- increases the albedo over the cloudless ocean and land by up to 10-20%
- reduces the direct solar radiation by 30-40%
Radiative effects of aerosols
Purpose:

• To estimate direct radiative forcing of Asian dust aerosols and anthropogenic aerosols for the period of March 2002, using ADAM model, Aerosol dynamic model, NCAR column radiation model (CRM) with the MM5 meteorological model.

• To estimate impacts of direct radiative forcing of Asian Dust on meteorological fields.
Model Description
Aerosol model system

- Emission (SO₂, NOₓ, NH₃, VOC, CO, BC, OC, PM₁₀)
- Gas Chemistry (CIT, 32 species, 53 chemical reactions)
- Meteo. Model (MM5, 60x60 km² horizontal resolution)

Aerosol Dynamic Model + Asian Dust Aerosol Model

Radiation Model CCM CRM
Effects of radiative forcing of aerosols on Meteorological fields

Coupled model (CMM5) (with Radiative Forcing)

Non-Coupled model (NMM5) (without Radiative Forcing)

CMM5 — NMM5 — Impact
### Meteorological Model

- MM5 version 3 nonhydrostatic model
- 60 km x 60 km horizontal resolution
- 20 Vertical layer in coordinate
- Moisture : simple ice explicit scheme
- Convection : Kain-Fritsch scheme
- PBL : Medium Range Forecasting (MRF)
- Period : March 2002

### Gas Chemistry

- CIT (California Institute of Technology, Russel)
- Adds (SO$_2$+OH) reaction and NH$_3$ (52 → 53 chemical reactions, 29 → 32 species)
- 8 photolytic reaction (cloud effect)
- SO$_2$ oxidation : 3 path (O$_3$, H$_2$O$_2$, Fe$^+$, Mn$^+$)
- NH$_3$/HNO$_3$ dissolution
**Aerosol Dynamics Model**

- Gas-Aerosol mass transfer (Hybrid scheme)
- Nucleation: critical value of the gas-phase sulfuric acid
- Condensation/evaporation: concentration difference between the particle surface and the bulk gas
- Dry and wet deposition
- Hygroscopic growth
- Coagulation: Brownian motion, Turbulent shear, Sedimentation

**Asian Dust Aerosol Model**

- Specification of Dust source region
- 12 bins (0.02~77 μm in diameter)
- Statistically derived dust emission conditions in Sand, Gobi, Loess, mixed soil surface
- Dust emission flux \( \propto u^4 \)
- Dust emission modification by the land-use types
- Log-normal distributions of the suspended particles in the source region with minimally and fully dispersed particle-size distribution
Radiation model

National Center for Atmospheric Research (NCAR) column radiation model (CRM) of the community climate model (CCM)

Mineralogical composition in Asian Dust [from soil samples in the source regions (Park, 2002)]

6 mineral component selected
Model Domain & Asian Dust Source Region

- Gobi
- Mixed
- Sand
- Loess
Anthropogenic emission over Asia

a) SO$_2$

b) NO$_x$

c) NH$_3$

d) VOC

e) PME

f) BC+OC

(unit: t grid$^{-1}$ month$^{-1}$) Streets et al., 2000
Results
Daily mean surface concentration over South Korea

(a) TPM\(_{10}\)

(b) PM\(_{10}\)

(c) Relative Humidity

March 2002

OBS
MODEL

CONC (µg m\(^{-3}\))

CONC (µg m\(^{-3}\))

RH (%)
Location of monitoring sites of EANET

1. Guanyinqiao
2. Jinyunshan
3. Shizhan
4. Weishuiyuan
5. Hongwen
6. Xiang Zhou
7. Richiri
8. Tappi
9. Sado-seki
10. Happo
11. Oki
12. Yusuhara
13. Ogasawara
14. Hedo
15. Ijira
16. Banryu
17. Petaling Jaya
18. Tanah Rata
19. Terelj
20. Metro Manila
21. Los Banos
22. Kanghwa
23. Cheju
24. Irnisi
25. Mondy
26. Listvyanka
27. Irkutsk
28. Primorskaya
29. Mae Hia
30. HaNoi
Comparison of observed and modeled aerosol concentration in Asia

(a) Sulfate
- $y = 0.89x - 0.19$
- $R^2 = 0.86$

(b) Nitrate
- $y = 0.97x - 0.12$
- $R^2 = 0.82$

(c) Ammonium
- $y = 0.59x + 0.58$
- $R^2 = 0.36$

(d) PM$_{10}$
- $y = 1.05x + 11.31$
- $R^2 = 0.71$
Column integrated Asian dust and secondary inorganic aerosol

Asian dust concentration ($\mu g \text{ m}^{-2}$) expressed in common logarithm scale

SIA concentration ($\mu g \text{ m}^{-2}$) expressed in common logarithm scale

(\mu g \text{ m}^{-2})
Spatial distribution of aerosol concentration

Column integrated monthly mean concentration ($\mu g \, m^{-2}$) expressed in common logarithm scale

- Dust + PM
- BC
- OC
- SIA
- MIX
- TOTAL

(\mu g \, m^{-2})
Direct radiative forcing (W m$^{-2}$) at the surface
Direct radiative forcing (W m$^{-2}$) at the TOA
Direct radiative forcing (W m\(^{-2}\)) at the atmosphere
Fractional contributions of each type of aerosols

(a) Total Mass

(b) ADRF at SFC

(c) ADRF at TOA

(d) ADRF at ATM
## Radiative intensity

<table>
<thead>
<tr>
<th>Aerosol</th>
<th>Surface (W mg(^{-1}))</th>
<th>TOA (W mg(^{-1}))</th>
<th>Atmosphere (W mg(^{-1}))</th>
<th>Total mass con. (mg m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asian dust</td>
<td>-0.03</td>
<td>-0.02</td>
<td>0.01</td>
<td>51.48</td>
</tr>
<tr>
<td>SIA</td>
<td>-0.20</td>
<td>-0.18</td>
<td>0.01</td>
<td>8.58</td>
</tr>
<tr>
<td>Mixed type</td>
<td>-0.19</td>
<td>+0.01</td>
<td>0.19</td>
<td>10.92</td>
</tr>
<tr>
<td>BC</td>
<td>-5.67</td>
<td>+1.35</td>
<td>6.21</td>
<td>0.16</td>
</tr>
<tr>
<td>OC</td>
<td>-0.31</td>
<td>-0.25</td>
<td>0.07</td>
<td>1.56</td>
</tr>
<tr>
<td>Sea salt</td>
<td>-0.04</td>
<td>-0.04</td>
<td>0.00</td>
<td>5.46</td>
</tr>
</tbody>
</table>
Impacts of aerosol radiative forcing on meteorological fields

vertically integrated DUST concentration and WIND VECTOR (coupled)
Affected temperature

sfc TEMPERATURE (coupled - non-coupled)

(a) 18 March

(b) 19 March

(c) 20 March

(d) 21 March

(e) 22 March

(f) 23 March

-1.5 \ -1 \ -0.5 \ -0.1 \ 0.1 \ 0.5 \ 1 \ 1.5
Pressure anomaly

Difference of SLP (Coupled – Non-Coupled)

(a) 18 March

(b) 19 March

(c) 20 March

(d) 21 March

(e) 22 March

(f) 23 March

$\left(10^{-2} \text{ hPa}\right)$
Wind affected by radiative forcing

Difference of SLP and WIND VECTOR (Coupled – Non-Coupled)

(a) 18 March

(b) 19 March

(c) 20 March

(d) 21 March

(e) 22 March

(f) 23 March

1.5
Radiative forcing

(a) Daily Total Emission

(b) Column Concentration

(c) D SRF (W m$^{-2}$)

(d) D T (°C)

(e) D SLP (Pa) & D WV

(f) Daily Total Emission Diff.

- 20 (m s$^{-1}$) (g m$^{-2}$ day$^{-1}$)
- 50 (m s$^{-1}$)
- 10$^6$ µg m$^{-2}$
- 1.5 (m s$^{-1}$)
- (g m$^{-2}$ day$^{-1}$)
Daily total emission difference
Diurnal variation of affected meteorological fields

REGION I [95–103E, 40–45N]

(a) VER. INT. CON.
(b) SRF and SHF
(c) T
(d) SLP
(e) WS
(f) Emission
(g) Stability (2 km height)
(h) Stability (surface layer)
Diurnal variation of affected meteorological fields
Conclusion

- **Time-area averaged column integrated total aerosol concentration in the analysis domain is**
  
  78 mg m\(^{-2}\)
  - 66 % by Asian dust
  - 14 % by mixed type aerosol
  - 11 % by SIA
  - 7 % by Sea salt

- **Time-area averaged direct radiative forcing at the surface is**

  \(-6.8 \text{ W m}^{-2}\)
  - 30 % by mixed type
  - 25 % by SIA
  - 22 % by Asian dust
  - 13 % by BC
  - 7 % by OC

<table>
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<tr>
<td>-0.19 W mg(^{-1})</td>
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</tr>
<tr>
<td><strong>-5.67 W mg(^{-1})</strong></td>
</tr>
<tr>
<td>-0.31 W mg(^{-1})</td>
</tr>
</tbody>
</table>
Time-area averaged direct radiative forcing
at the top of atmosphere is

-2.9 W m\(^{-2}\)  
- 43 % by SIA  
- 31 % by Asian dust  
- 11 % by OC  
- 6 % by Sea salt  
+ 6 % by BC  
+ 3 % by mixed aerosol

Radiative intensity
-0.18 W mg\(^{-1}\)  
-0.02 W mg\(^{-1}\)  
-0.25 W mg\(^{-1}\)  
-0.04 W mg\(^{-1}\)  
+1.35 W mg\(^{-1}\)  
+0.01 W mg\(^{-1}\)

Time-area averaged direct radiative forcing
in the atmosphere is

+3.8 W m\(^{-2}\)  
+ 55 % by mixed aerosol  
+ 26 % by BC  
+ 13 % by Asian dust

Radiative intensity
+0.19 W mg\(^{-1}\)  
+6.21 W mg\(^{-1}\)  
+0.01 W mg\(^{-1}\)
**Effects of radiative forcing of Asian dust on meteorological fields**

- With vertically integrated Asian dust aerosol concentration of 15 g m⁻² produces -200 W m⁻² surface radiative forcing, which in turn reduces the surface temperature of -2 °C.

- In the mean time it produces a positive pressure anomaly (about 0.8 hPa) with the negative pressure anomaly toward the synoptic low pressure center forming a dipole shape of pressure anomaly.

- The associated secondary circulation reduces the mean wind speed (about 3 m s⁻¹) in the upstream part of the high dust concentration region resulting in dust emission reduction, while in the downstream region it enhances the low-level wind speed, which in turn, enhance the dust emission. However, the enhanced dust emission is smaller than the reduced dust emission, resulting in overall reduction.

- Lower level cooling due to Asian dust aerosol enhances stable stratification in the lower layer. Reduction of turbulence intensity reduces dust emission.
Thank you!