Modeling the effects of atmospheric aerosols on climate

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Climate-Chemistry Interactions

CLIMATE

CHEMISTRY

ECOSYSTEMS

AEROSOLS

Human Emissions

Oxidants
O3, HO2, H2O2

Fires, Soot
Mineral Dust

CH4, N2O
O3, CFC

N Deposition
Ozone, UV radiation

Biogenic Emissions
Dry deposition

Land-use
Change

GHG’s

Greenhouse Effect

Direct and Indirect Effects

CO2

Human Emissions
Aerosol radiative effects

**Direct effects**
Aerosols absorb and reflect solar radiation

**Indirect effects**
Aerosols change the properties of clouds (increase in reflectivity and lifetime)

Aerosols with the longest atmospheric lifetime ($d=0.1-1$ micron) are also the most radiatively active.

Aerosol effects are particularly important at the regional scale because of their short lifetime.
Many different types of aerosols are found in the atmosphere:

- Sulfates
- Nitrates
- Organic Carbon (OC)
- Black Carbon (BC)
- Mineral Dust
- Sea Spray
- Volcanic
The atmospheric aerosol cycle

- Short lived (< 1 day)
- Long lived (days to weeks)
Production rate of different aerosols
Radiative Forcing of GHG and Aerosols

GHG

Sulfate Indirect Effect (Type I)

Biomass Burning OC and BC

Fossil Fuel Burning OC and BC
Climatic Impacts of Aerosols

- Surface and atmospheric cooling (reflecting aerosols)
- Atmospheric warming (absorbing aerosols)
- Modification of the vertical temperature profile and stability, with an effect on convection
- Modification of the precipitation efficiency in cloud systems
- Modification of the cloud structure, chemical composition and related radiative forcing
- Modification of large scale and regional circulations (e.g. Monsoons)
The global mean radiative forcing of the climate system for the year 2000, relative to 1750.
Some case studies of aerosol climatic effects
(using the regional climate model RegCM3)
The RegCM3 model

- **Dynamics:**
  - MM5 Hydrostatic (Grell et al 1994)
- **Radiation:**
  - CCM3 (Kiehl 1996)
- **Large-Scale Clouds & Precipitation:**
  - SUBEX (Pal et al 2000)
- **Cumulus Convection:**
  - Grell (1993)
  - Anthes-Kuo (1977)
  - Emanuel (1991)
- **Boundary Layer:**
  - Holtslag (1990)
- **Tracers/Aerosols/dust:**
  - Qian et al (2001); Solmon et al (2005); Zakey et al. (2006)
- **Land Surface:**
  - BATS (Dickinson et al 1993)
  - SUB-BATS (Giorgi et al 2003)
  - CLM (Dai et al. 2003)
- **Ocean Fluxes**
  - BATS (Dickinson et al 1993)
- **Computations**
  - Parallel Code (Bi, Gao, Yeh)
  - Multiple Platforms
  - User-Friendly Code
Simple “on-line” Aerosols in RegCM3

- General approach ↔ Tracer model / RegCM3 (from Giorgi et al., Qian et al.)

\[
\frac{\partial \chi}{\partial t} = -\vec{V} \times \nabla \chi + F_H + F_V + T_{\text{CUM}} + S_\chi - R_{w,ls} - R_{w,\text{cum}} - D_{\text{dep}} + \sum Q_p - Q_l
\]

- Transport
- Primary Emissions
- Removal terms
- Physico – chemical transformations

Strongly dependent on the nature of the tracer

- Particles and chemical species considered ("anthropogenic compounds")

\[
\begin{align*}
\text{SO}_2 & \quad \leftrightarrow \quad \text{SO}_4^- \\
\text{BC (soot)} & \quad \rightarrow \quad \text{Hydrophilic} \\
\text{Hydrophobic} & \\
\text{OC}_T & \quad \rightarrow \quad \text{Hydrophilic} \\
& \quad \rightarrow \quad \text{Hydrophobic}
\end{align*}
\]

6 Tracers
Aerosol dust model in RegCM

Input parameters

- Soil texture (12 types, USDA)
- Soil erodible dry aggregates distribution (Shao et al., 2002)
- Land surface properties (BATS) (roughness, soil humidity, cover fractions)
- Regcm atmospheric variables (surface wind, air temperature, air density)

DUST emission scheme

A. Zakey

- Saltation (Marticorena et al. 1995)
- Roughness and humidity correction
- Suspension
- Sand-blasting (Alfaro et al., 1997, 2001)
- Dust flux distribution (3 log-normal emission modes)
- Transport bins (up to 12), usually 4
- Size dependent settling and surface déposition
- AOP / radiation
Climate-aerosol model coupling

Regional Climate Model

Radiative Transfer Package

Radiative Fluxes, Heating Rate

Clouds, Temperature, Water Vapor

Aerosol Radiative Forcing

Winds, PBL Processes

Clouds, Precipitation

Aerosol Model Source, Transport, Removal

Aerosol Concentration
The case of East Asia

- During the last decades East Asia has been one of the most rapidly developing regions of the world.
- As a result, anthropogenic aerosol emissions and concentrations over the region have considerably increased, thereby (possibly) affecting the climate of the region.
- In a series of studies we investigated the possible regional climatic effects of anthropogenic aerosols over East Asia:
Sources of airborne pollution in Asia are many: home cooking, power generation, industry, traffic, and biomass burning.
Aerosols: Brown cloud over China

17 November 2004
Some observational evidence of aerosol effects over East Asia
Yearly coal and total energy consumption in China from 1953-1997 (left)
Spatial distribution of SO$_2$ emission yearly change rate during 1953-1997 (right).
Data from Ren et al., 1997.
Aerosol extinction coefficient averaged for 1981-1998
Kaiser and Qian (2002)
Change of observed mean temperature (°C) in China
Qian and Giorgi (2000)
Change of observed mean temperature (°C) in China

Giorgi et al. (2002)

1981-98 minus 1951-80, DJF

1981-98 minus 1951-80, MAM

1981-98 minus 1951-80, JJA

1981-98 minus 1951-80, SON
Trend of summer mean daily maximum temperature for 1954-1998
Kaiser and Qian (2002)
Annual mean and daily maximum temperature anomaly trend over the Sichuan Basin for 1954-1998
Simulation of direct and indirect effects of anthropogenic sulfate over East Asia using RegCM
Model and experiment design

• Use of an interactively coupled regional climate-chemistry model (RegCM)
  – Inclusion of a simplified sulfur model
  – Realistic emissions of sulfur dioxide

• Intercomparison of a series of experiments with and without direct and indirect effects of sulfate
  – CONT: Aerosols not radiatively active
  – DIR1: Direct effects only; current emissions
  – DIR2: Direct effects only; doubled emissions
  – IND1: Direct + Indirect effects; current emissions
  – IND2: Direct + Indirect effects; doubled emissions

• Simulation period: 1993-1997
• Domain covering East Asia at 50 km grid spacing
Aerosol model components

• **Transport**
  – Advection by resolvable scale winds
  – Horizontal and vertical turbulent diffusion
  – Vertical transport by deep convection

• **Removal**
  – Wet removal by both resolvable scale and cumulus clouds
  – Dry deposition (constant dry deposition velocity)

• **Direct effects**
  – Specification of sulfate optical properties (absorptivity, scattering coefficient, asymmetry factor)

• **Indirect effects**
  – Cloud droplet radius expressed as an empirical function of the aerosol mass concentration
Sulfur Emission (g S/m²/yr)
Temperature, DJF, DIR1-CONT

Temperature, MAM, DIR1-CONT

Temperature, JJA, DIR1-CONT

Temperature, SON, DIR1-CONT
Temperature, DJF, IND2-CONT

Temperature, MAM, IND2-CONT

Temperature, JJA, IND2-CONT

Temperature, SON, IND2-CONT
Conclusions

• **Anthropogenic sulfates (and other aerosols) have a significant impact on the surface climate of China**
  - Surface cooling
  - Decrease in precipitation

• **Direct effects dominate in the cold (and dry) season, indirect effects dominate in the warm season and in inhibiting precipitation**

• **The simulated aerosol-induced surface cooling is consistent with the observed record over some regions of China, most noticeably the Sichuan Basin of southwest China**
Dust simulation over East Asia
(Preliminary results; 1 hour interval output)

Column burden (mg/m²) dust size: 0.10~1.00
Dry deposition of dust over 330,000 t in Beijing
The case of the Europe/Africa region
Example I: SO2 and SO4 burden, DJF 2000

Shading = SO4
Isocontour = SO2

Average $\text{SO}_4^{2-}$ concentration field ($\mu$g.m$^{-3}$) and column burden
Example II:
BC burden
DJF 2000
JJA 2000

Example II: BC burden
Preliminary case study: Dust storm of 20-28 February 2000

SeaWIFS (NGSFC)  
TOMS (aerosol index)  
RegCM  
(0.1-10 μm dust burden)
Simulation of northern Sahara dust outbreak (March 13-16, 2002)
Long term dust simulation, JJA 2000
Total AOD

Dust AOD JJA 2000

RegCM

MISR
Long term dust simulation, JJA 2000
Cross sections

RegCM Dust (JJA 2000)
extinction profiles

East-west
North-South
Effects of aerosols and dust on the African monsoon

Total AOD, JJA, 1998-2002
Effects of aerosols and dust on the African monsoon

Surface temperature, control - aerosol
Effects of aerosols and dust on the African monsoon
Effects of aerosols and dust on the African monsoon

Precipitation control - aerosol

Conclusions

• Aerosols and especially Saharan dust can have significant effects on the African monsoon
  – Cooling in the continental interior
  – Decrease of the land-ocean temperature gradient
  – Weakening of the monsoon circulation
  – Reduction of the inland penetration of the monsoon rain band
• Dust feedbacks might have contributed to the Sahel drought which occurred in the 1960-90s.
Summary

• Atmospheric aerosols can have important effects on climate, especially at the regional scale

• Regional climate models are especially useful tools to study aerosol effects

• Interactive coupling of chemistry/aerosol and regional climate models is still in its beginning stages
  - More comprehensive models need to be developed (excellent area of research for young scientists)