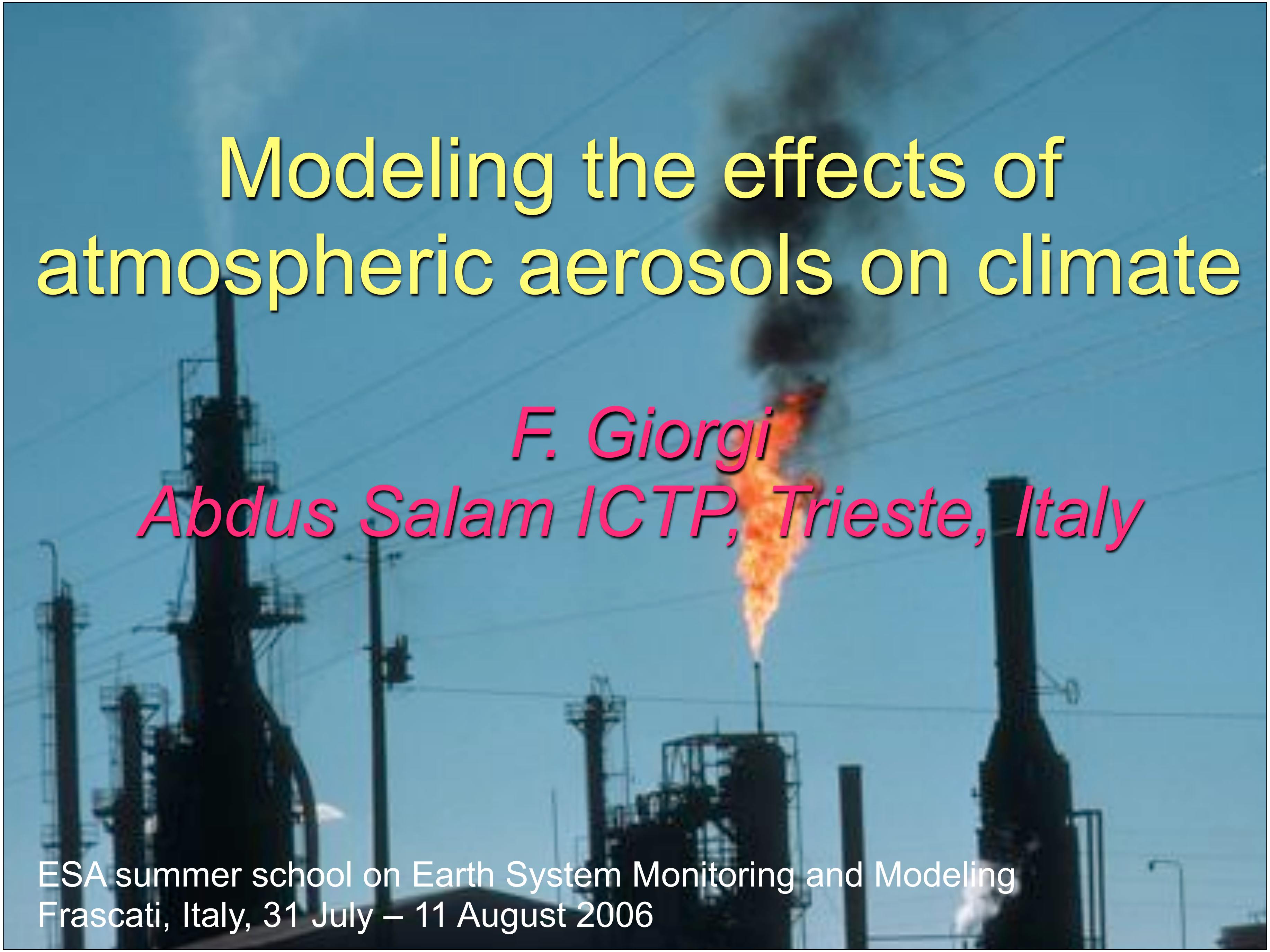
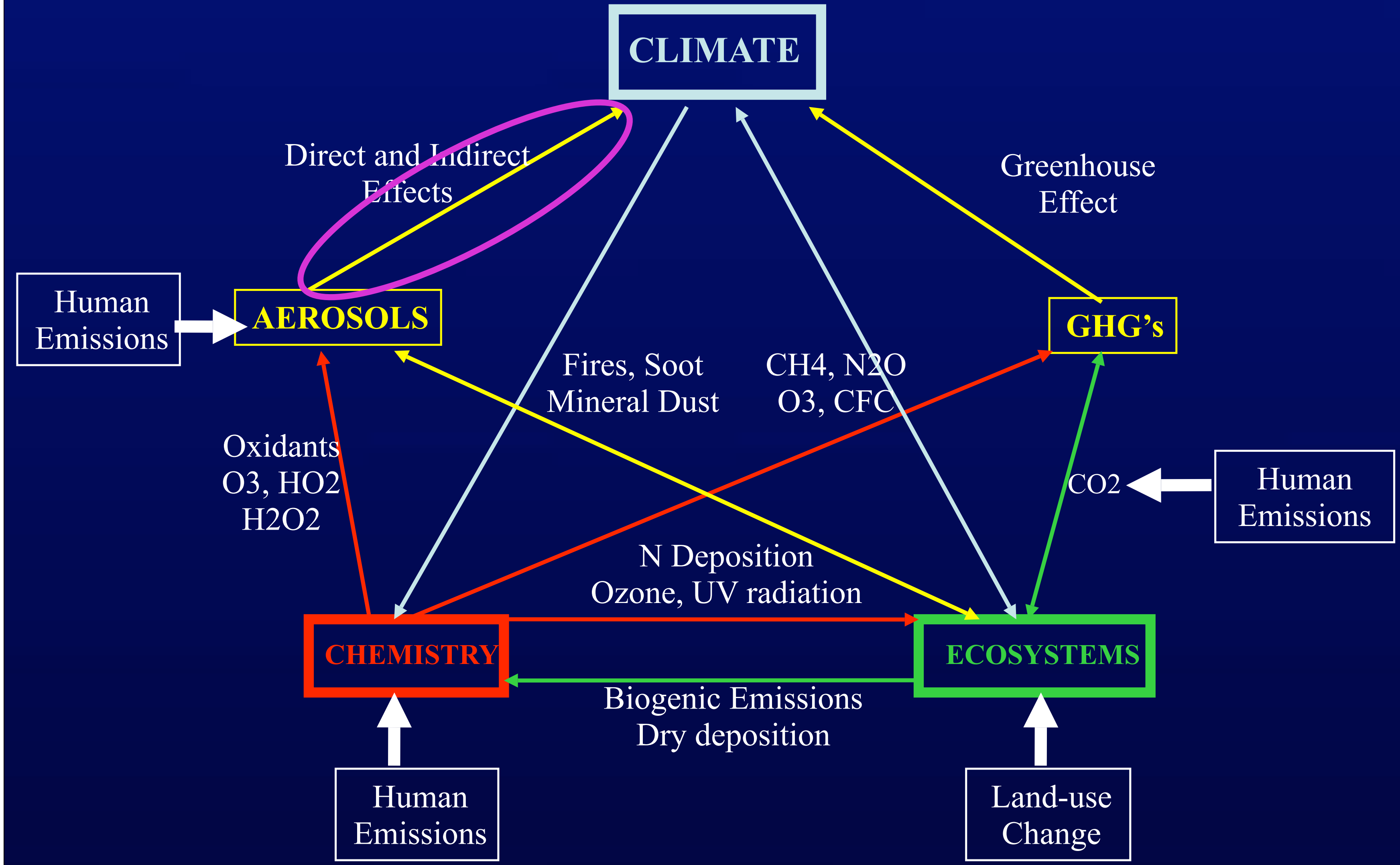


Modeling the effects of atmospheric aerosols on climate

F. Giorgi
Abdus Salam ICTP, Trieste, Italy

ESA summer school on Earth System Monitoring and Modeling
Frascati, Italy, 31 July – 11 August 2006

Climate-Chemistry Interactions



CLIMATE

Direct and Indirect Effects

Greenhouse Effect

Human Emissions

AEROSOLS

GHG's

Fires, Soot Mineral Dust

CH4, N2O O3, CFC

Oxidants O3, HO2 H2O2

CO2

Human Emissions

N Deposition Ozone, UV radiation

CHEMISTRY

ECOSYSTEMS

Biogenic Emissions Dry deposition

Human Emissions

Land-use Change

Aerosol radiative effects

Direct effects

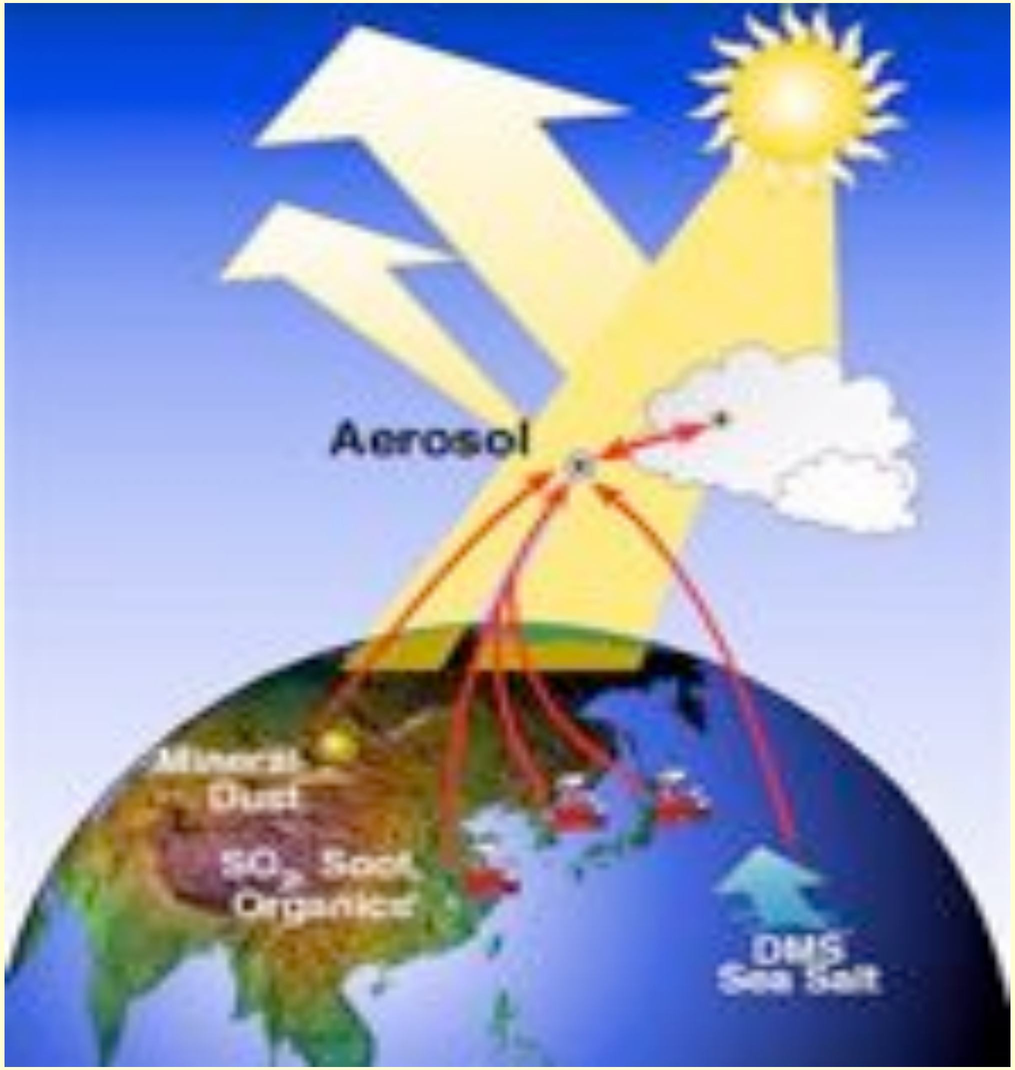
Aerosols absorb
and reflect solar radiation

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

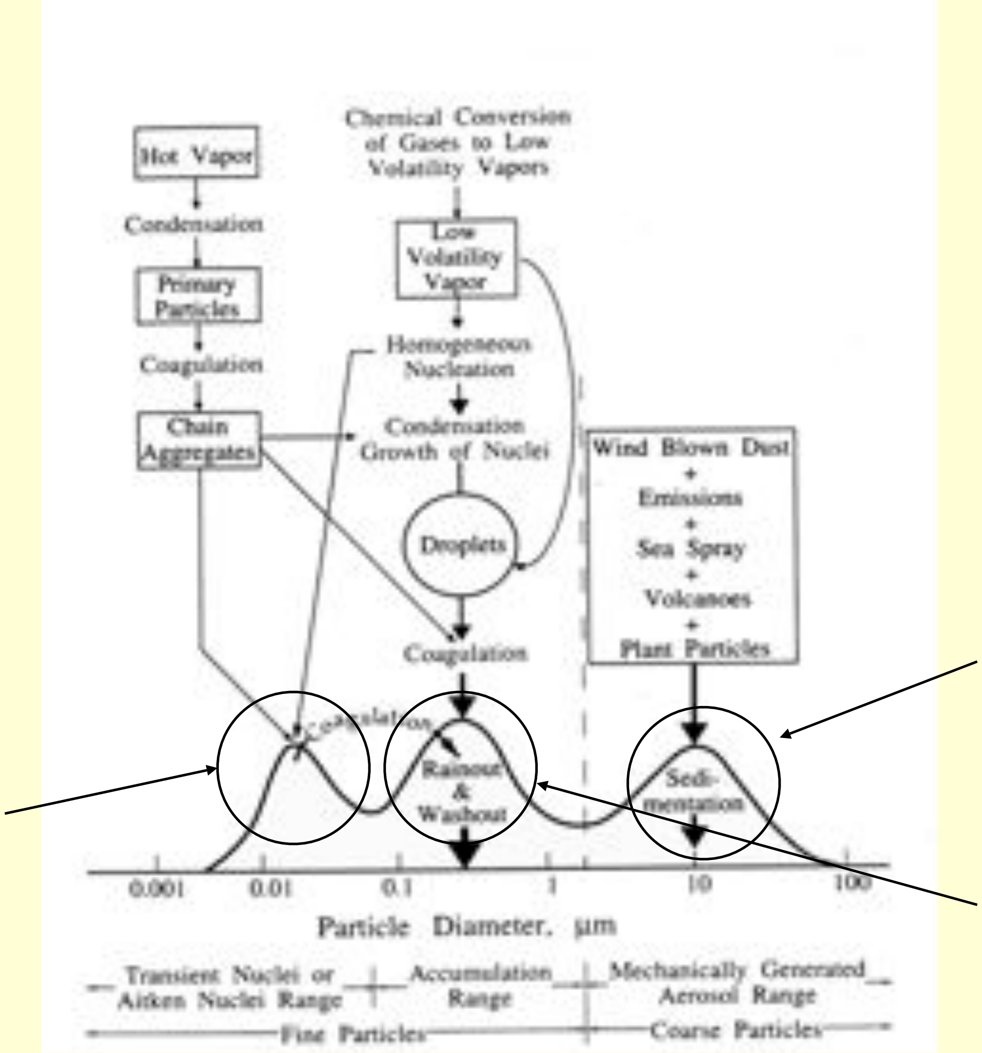


Many different types of aerosols are found in the atmosphere

- Sulfates
- Nitrates
- Organic Carbon (OC)
- Black Carbon (BC)
- Mineral Dust
- Sea Spray
- Volcanic

The atmospheric aerosol cycle

T

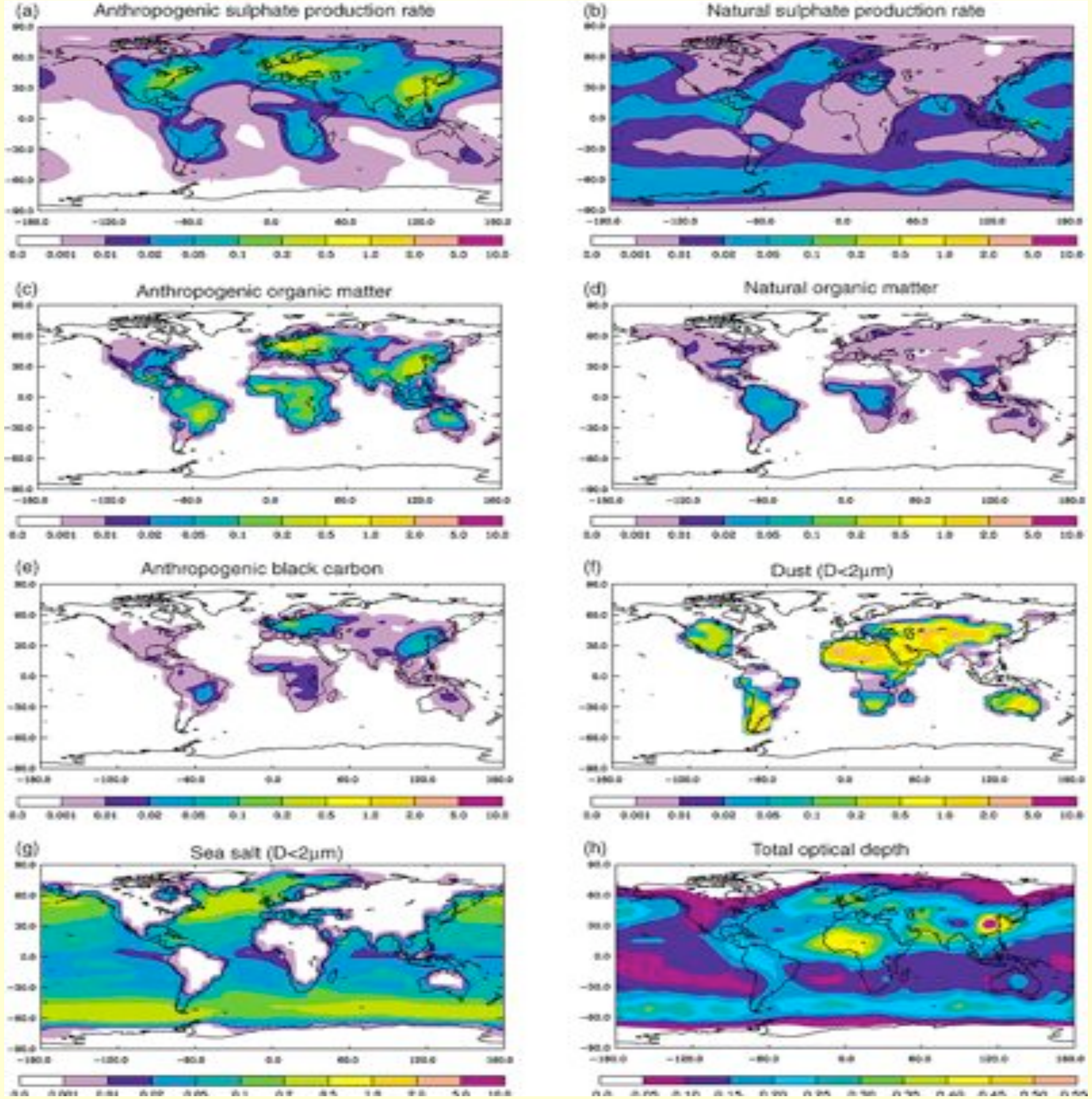


Short lived
(< 1 day)

Short lived
(< 1 day)

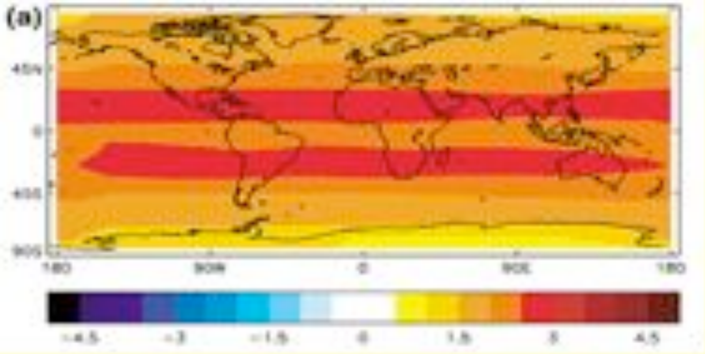
Long lived
(days to weeks)

Production rate of different aerosols

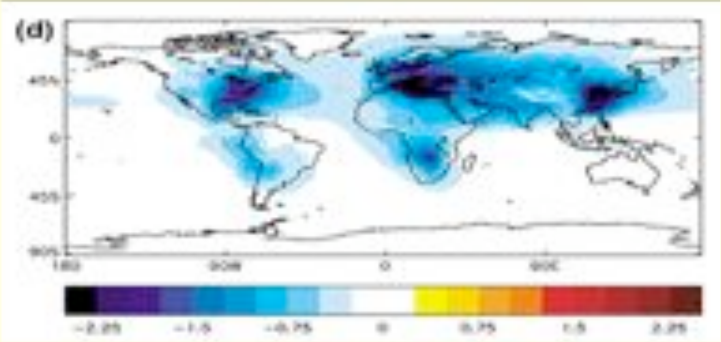


Radiative Forcing of GHG and Aerosols

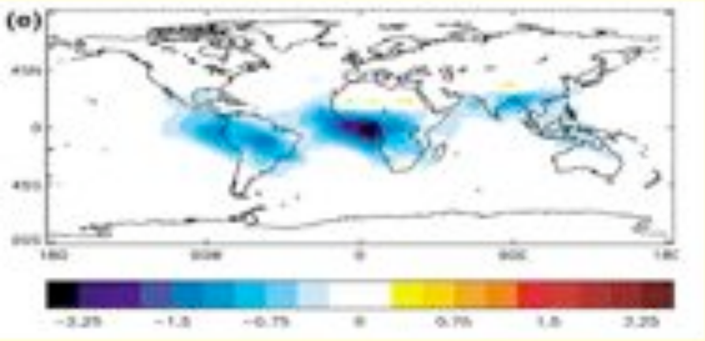
GHG



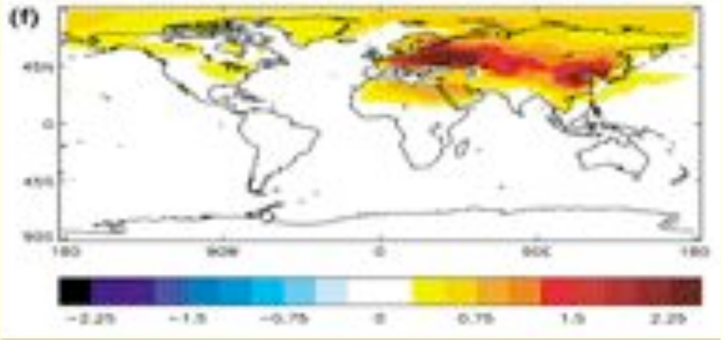
Sulfat



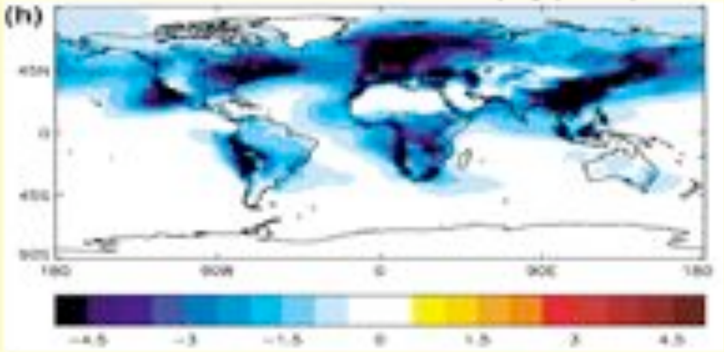
Biomass Burning OC and BC



Fossil Fuel Burning OC and BC

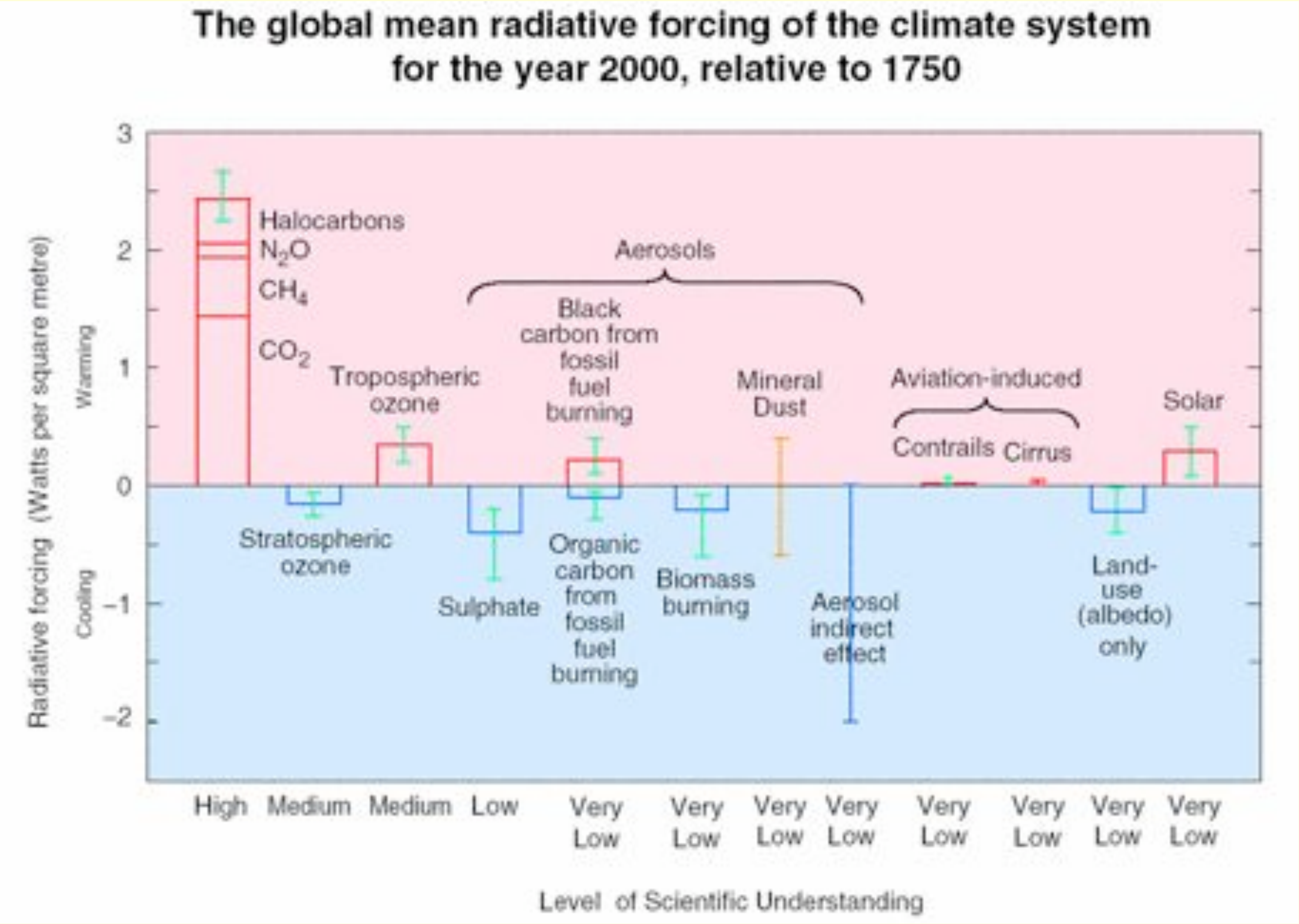


Sulfate Indirect Effect (Type I)



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 & Precipitaion:
  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)
  Zeng et al (1998)
- 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.)

$$\frac{\partial\chi}{\partial t} = \underbrace{-\bar{V}\times\nabla\chi + F_H + F_V + T_{CUM}}_{\text{Transport}} + \underbrace{\underbrace{S_\chi}_{\text{Primary Emissions}} \underbrace{- R_{w,ls} - R_{w,cum} - D_{dep}}_{\text{Removal terms}} + \underbrace{\sum Q_p - Q_l}_{\text{Physico – chemical transformations}}}_{\text{Strongly dependent on the nature of the tracer}}$$

- **Particles and chemical species considered (“anthropogenic compounds”)**

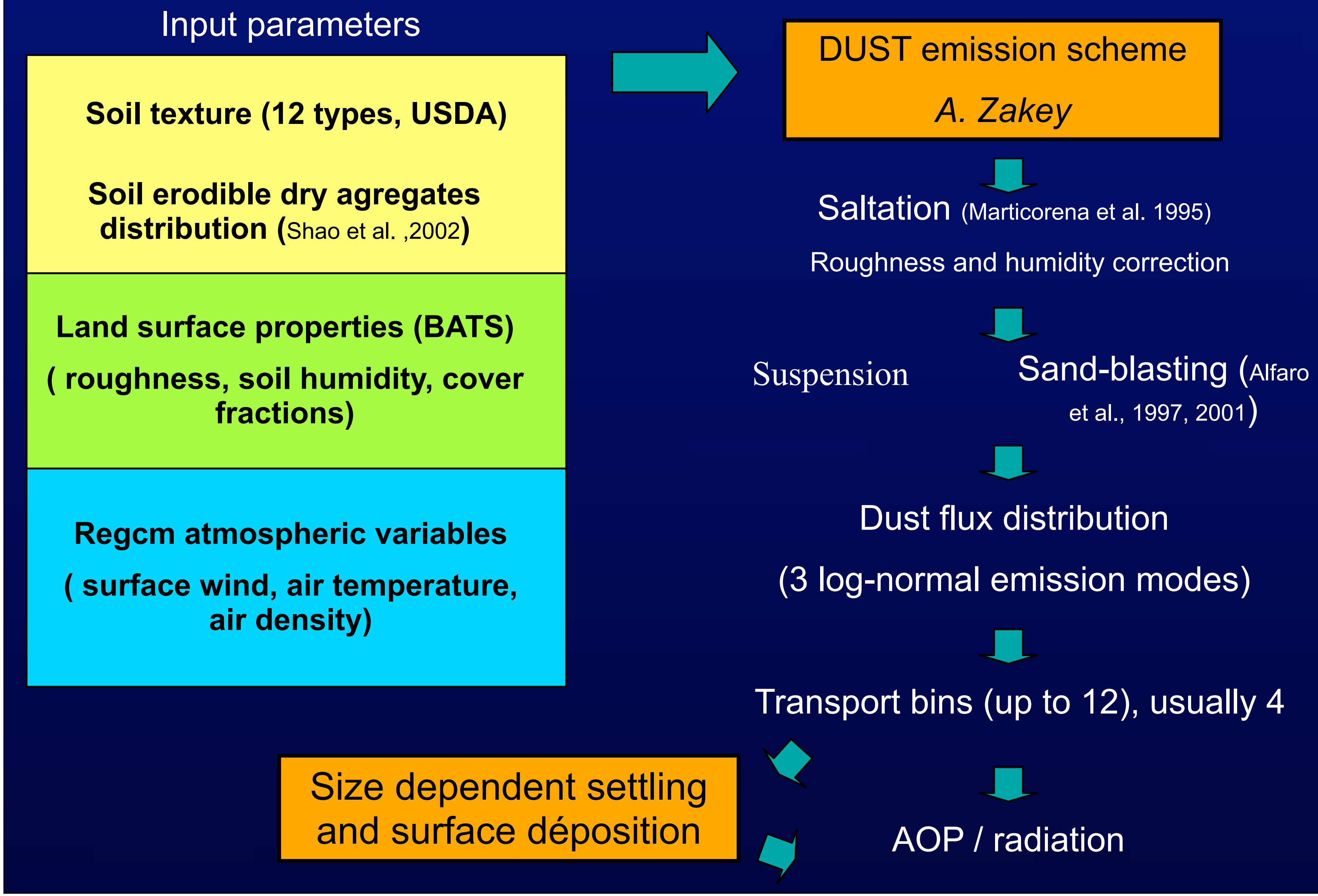
SO_2 ⇔ SO_4^-

BC (soot) → Hydrophilic ⇕ Hydrophobic

6 Tracers

OC_T (primary + secondary) → Hydrophilic ⇕ Hydrophobic

Aerosol dust model in RegCM



Input parameters

Soil texture (12 types, USDA)

Soil erodible dry agregates 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

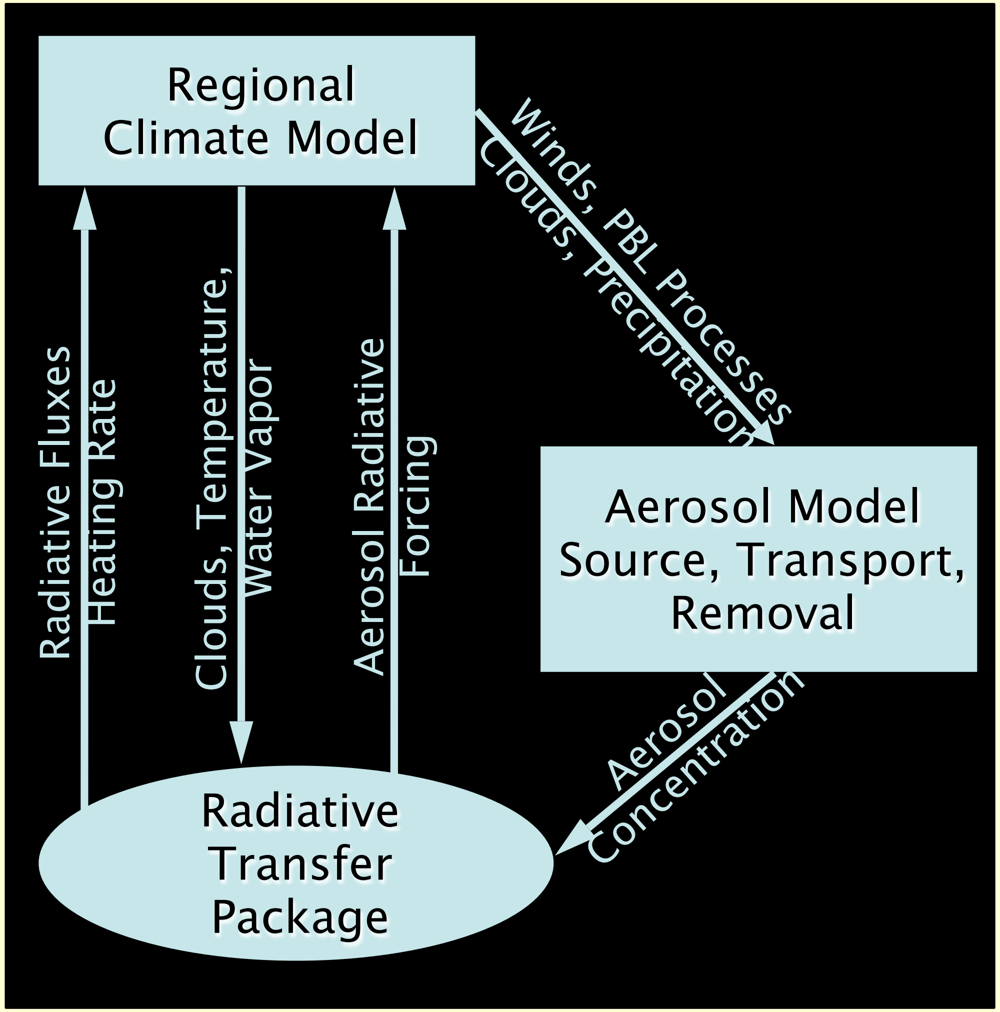
(3 log-normal emission modes)

Transport bins (up to 12), usually 4

Size dependent settling and surface déposition

AOP / radiation

Climate-aerosol model coupling



Regional Climate Model

Aerosol Model Source, Transport, Removal

Radiative Transfer Package

Winds, PBL Processes Clouds, Precipitation

Aerosol Concentration

Radiative Fluxes Heating Rate

Clouds, Temperature, Water Vapor

Aerosol Radiative Forcing

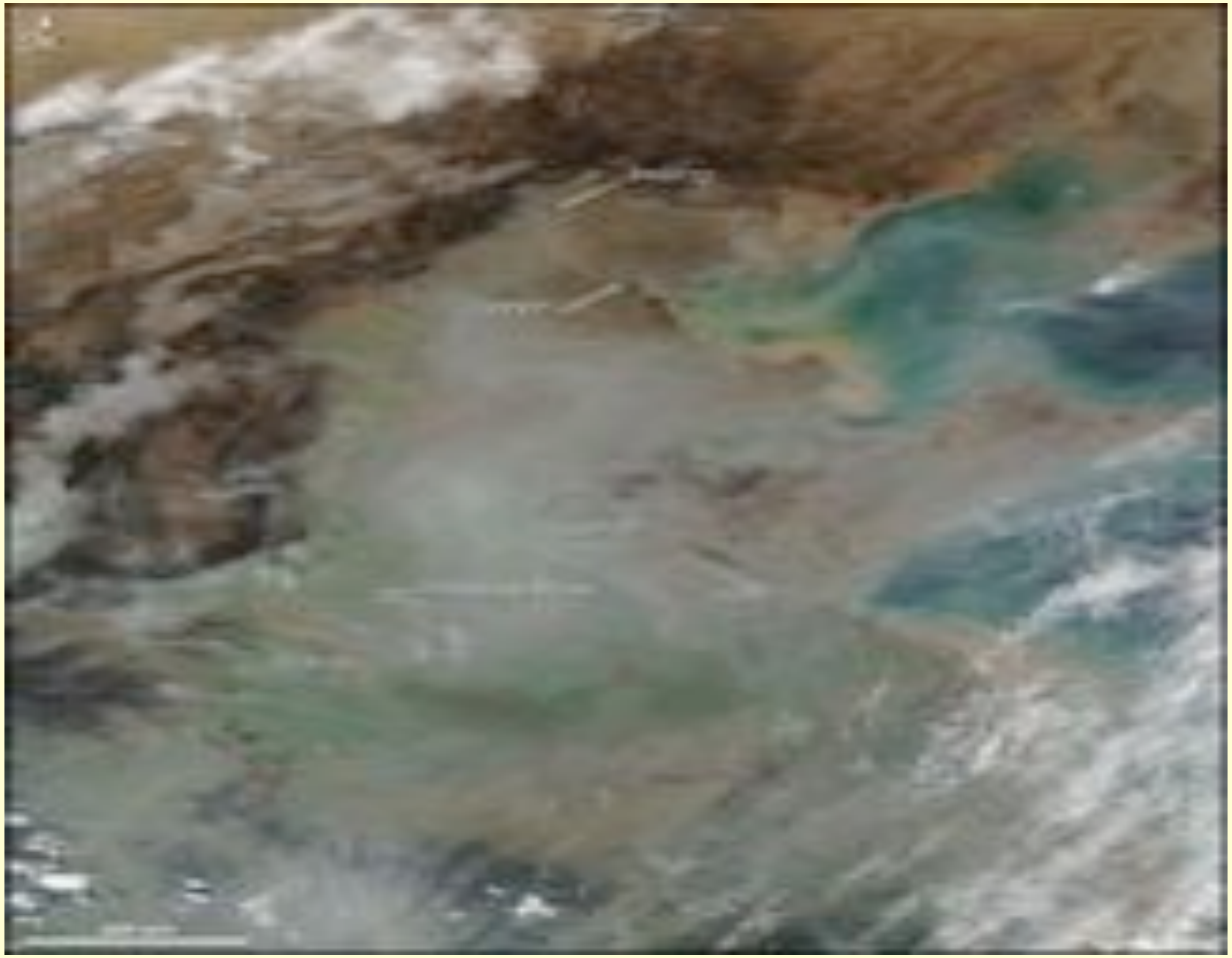
The case of East Asia

- 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
  - Qian and Giorgi (1999,2000), Qian et al. (2001, 2003), Chameides et al. (1999,2002),Streets and Waldhoff (2000),Kaiser and Qian (2002),Giorgi et al. (2002,2003)

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

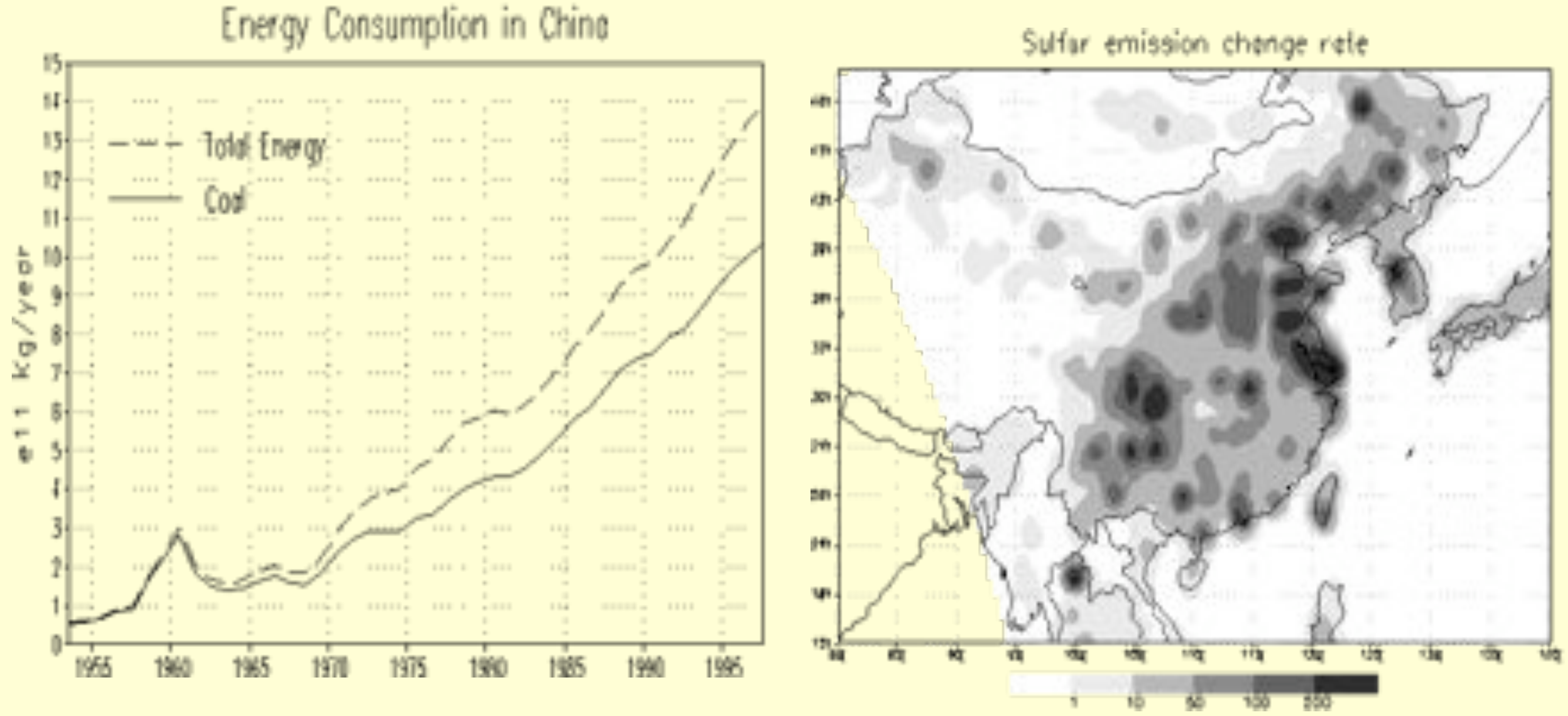


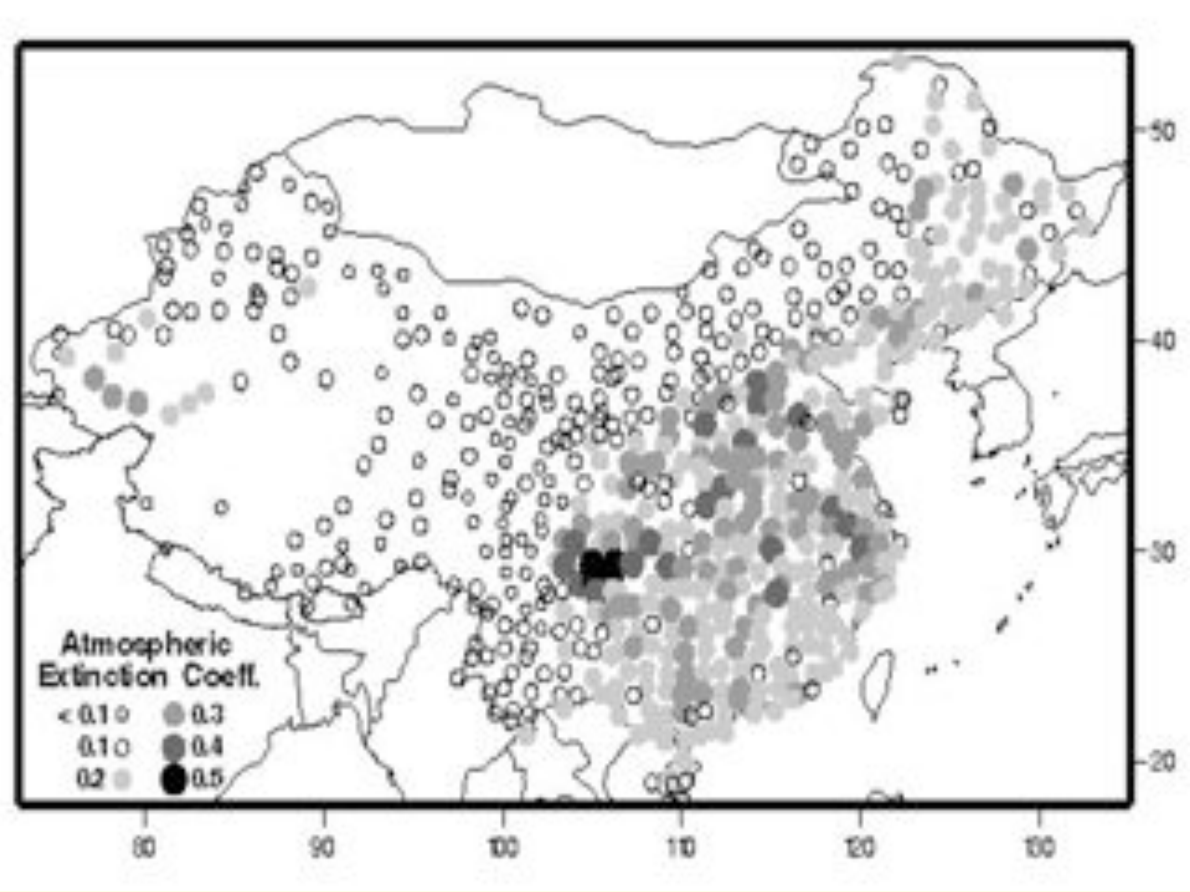
Some observational evidence of aerosol effects over East Asia

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.



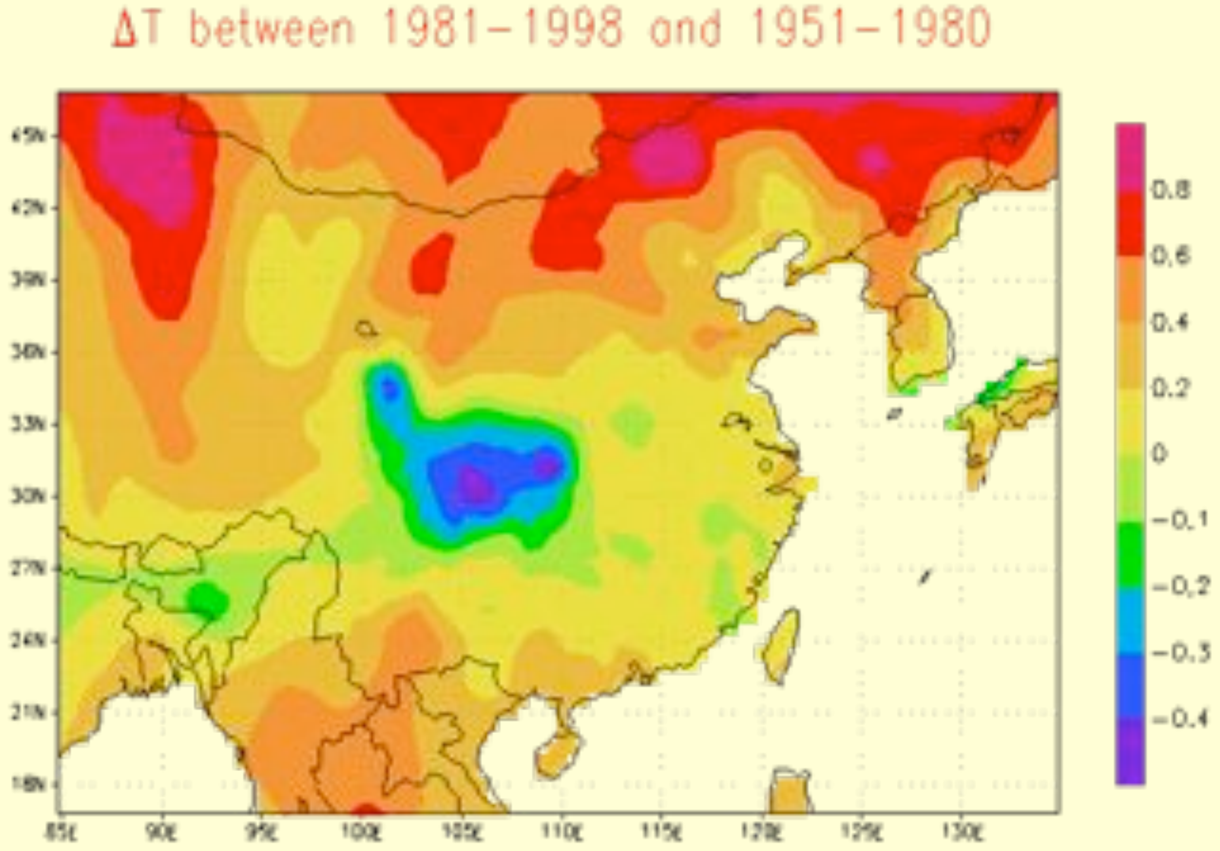


Aerosol extinction coefficient averaged for 1981-1998

Kaiser and Qian (2002)

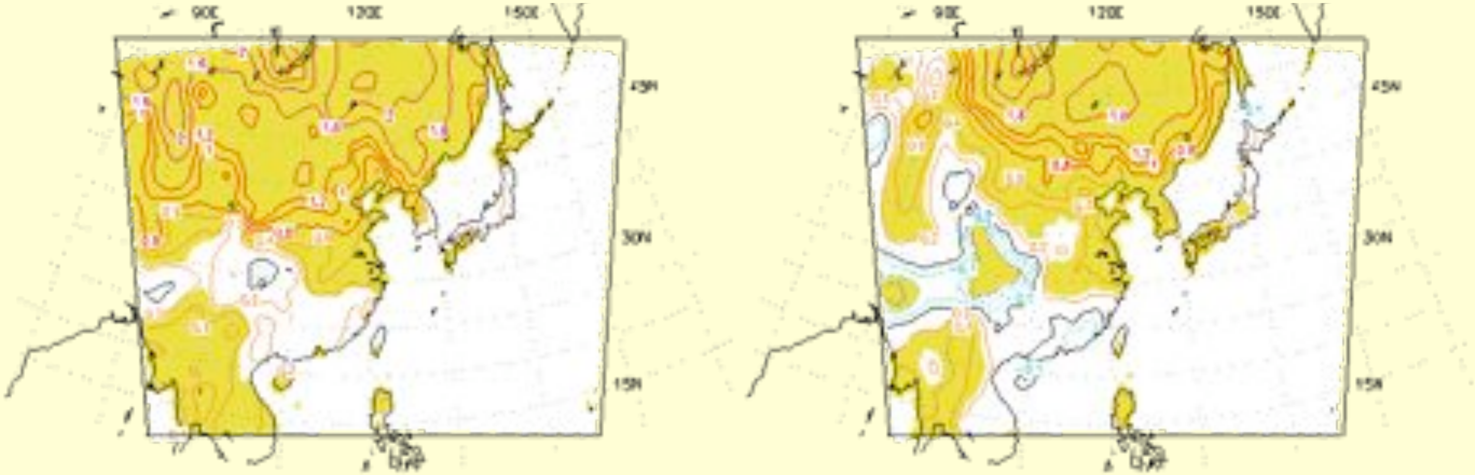
Change of observed mean temperature (^oC) in China

Qian and Giorgi (2000)



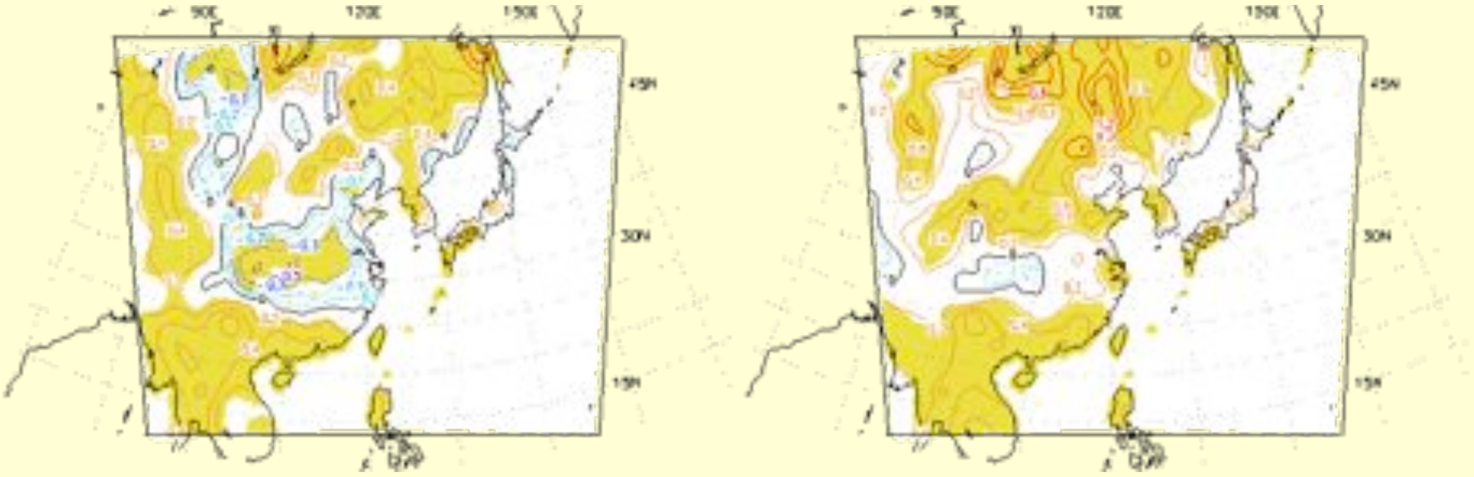
Change of observed mean temperature (oC) in China

Giorgi et al. (2002)



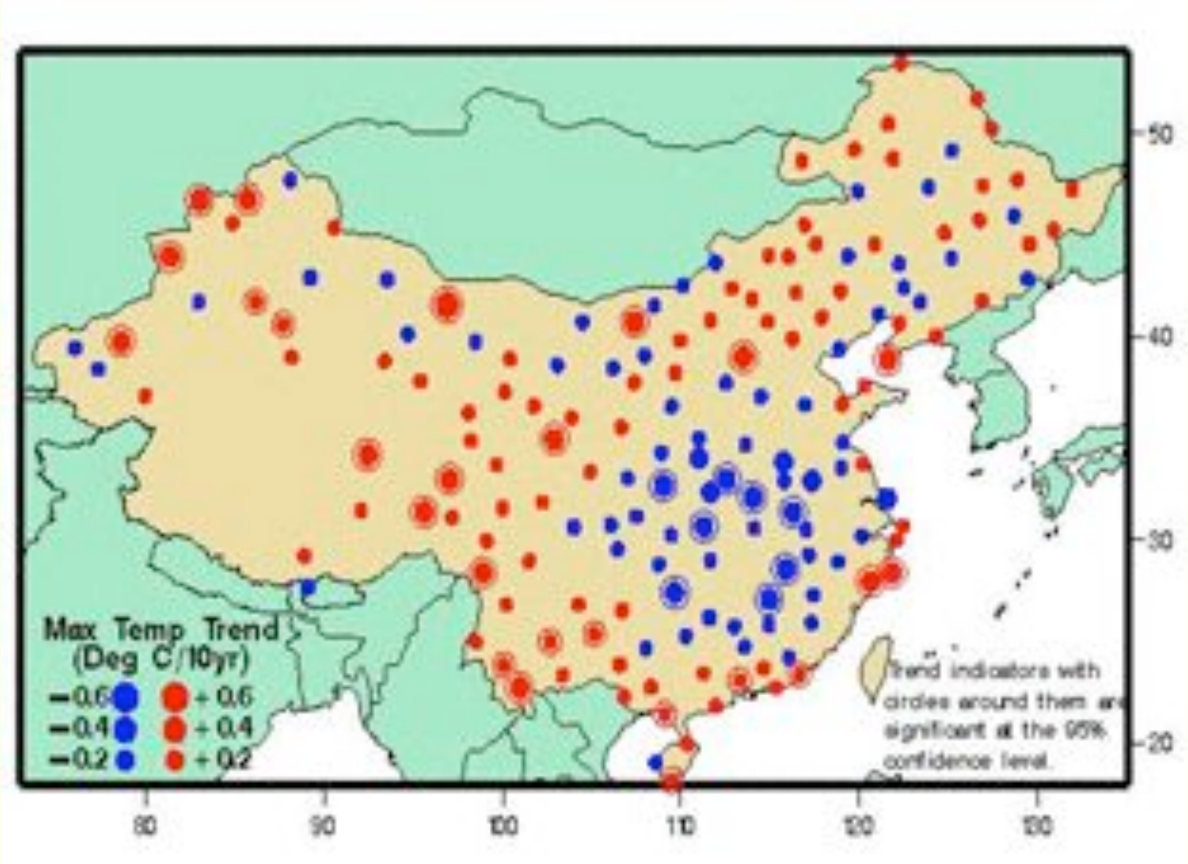
1981-98 minus 1951-80, DJF

1981-98 minus 1951-80, MAM

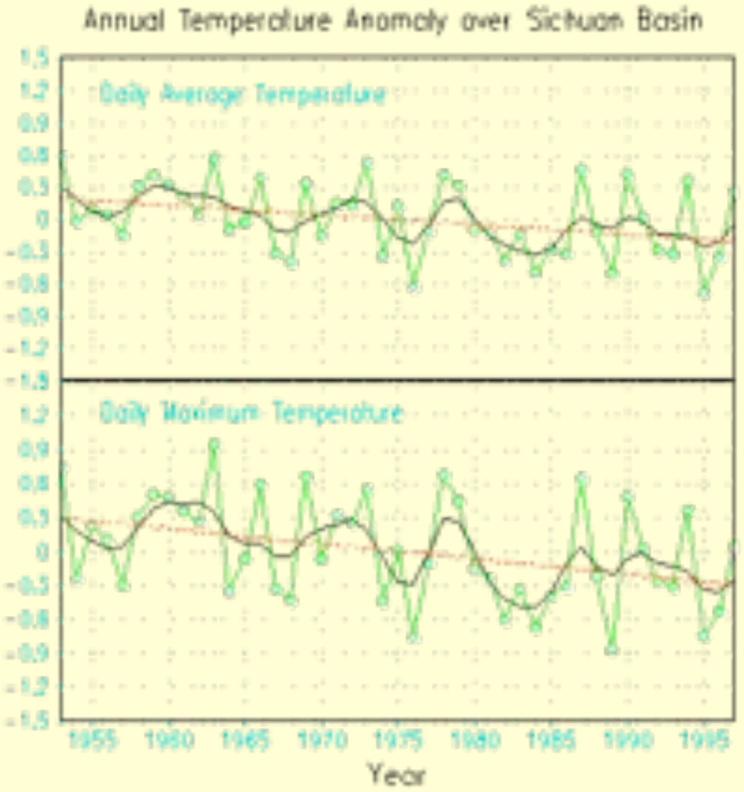


1981-98 minus 1951-80, JJA

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

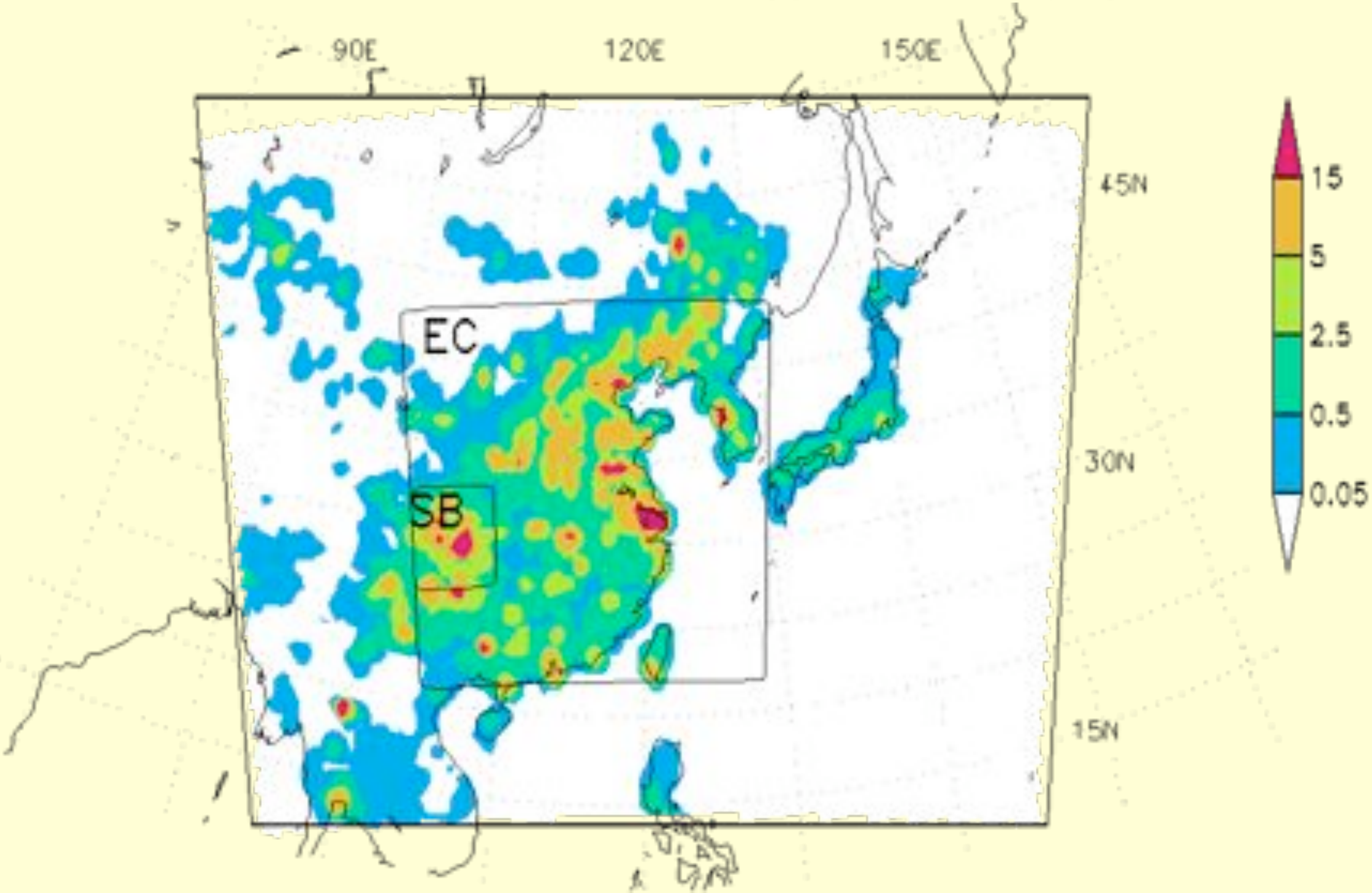
Model and experiment design

- 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

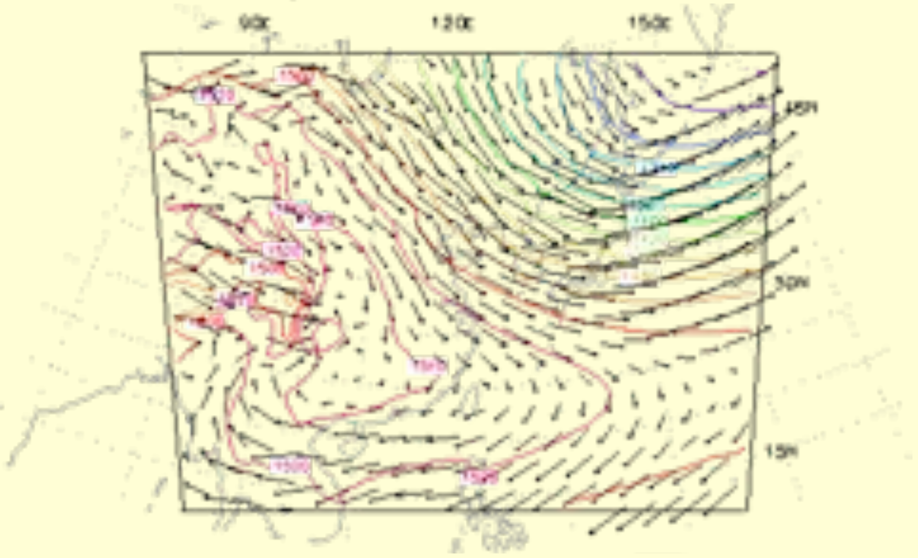
Aerosol model components

- 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 (absortivity, scattering coefficient, asymmetry factor)
- Indirect effects
  - Cloud droplet radius expressed as an empirical function of the aerosol mass concentration

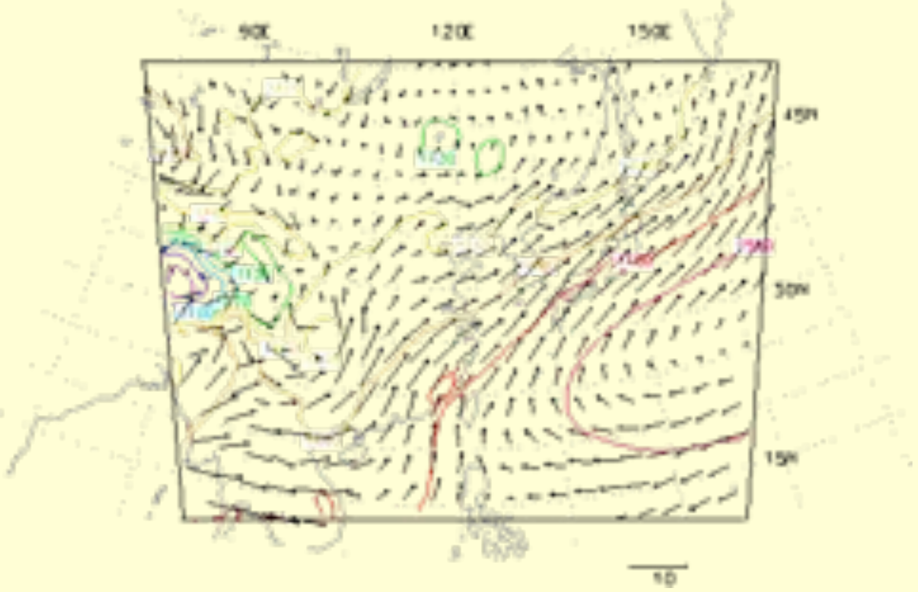
Sulfur Emission (g S/m2/yr)



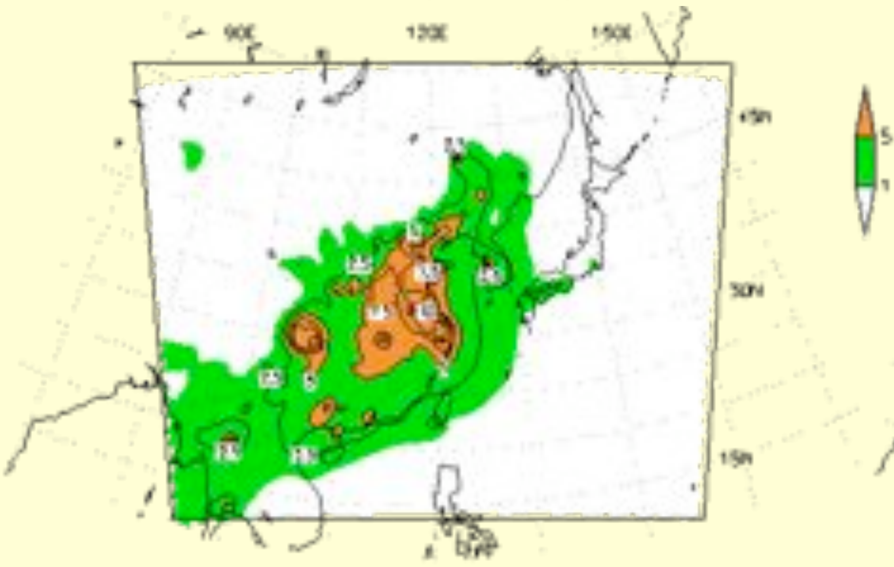
850 mb Gph and Wind, DJF, CONT



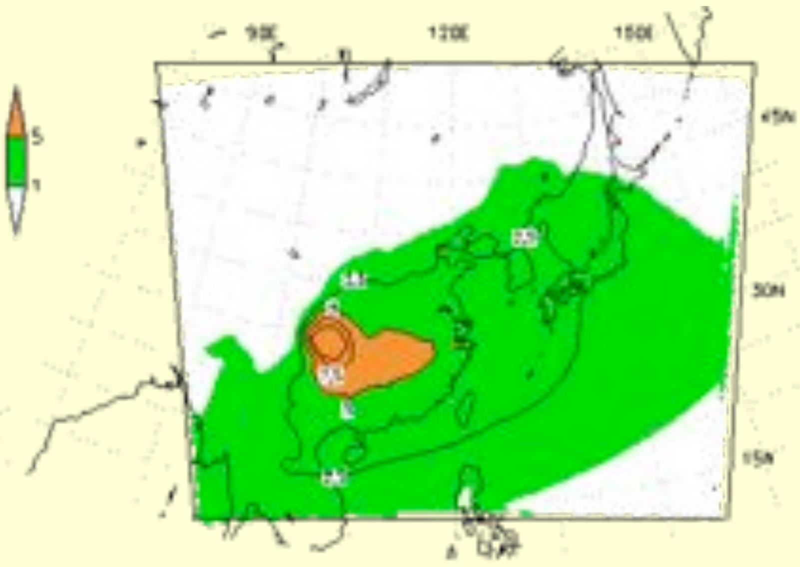
850 mb Gph and Wind, JJA, CONT



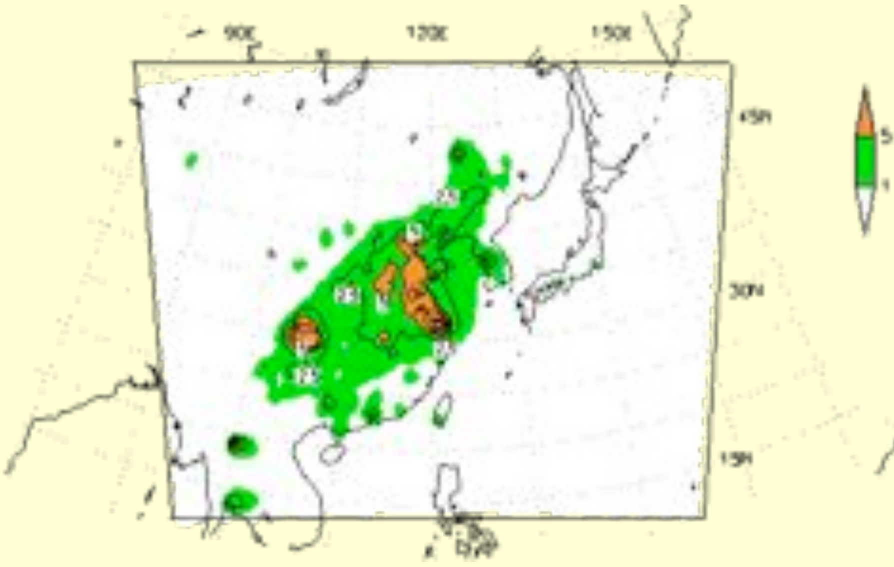
SO2 Burden, DJF, CONT



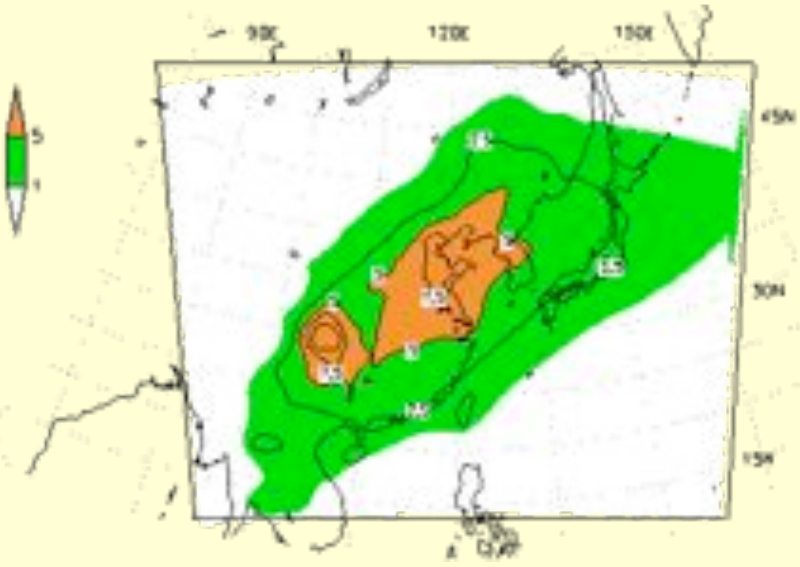
SO4 Burden, DJF, CONT



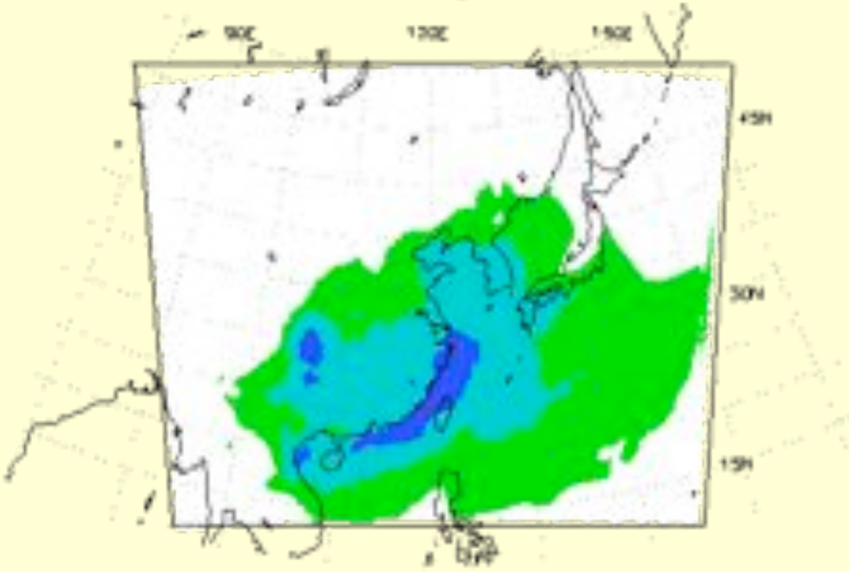
SO2 Burden, JJA, CONT



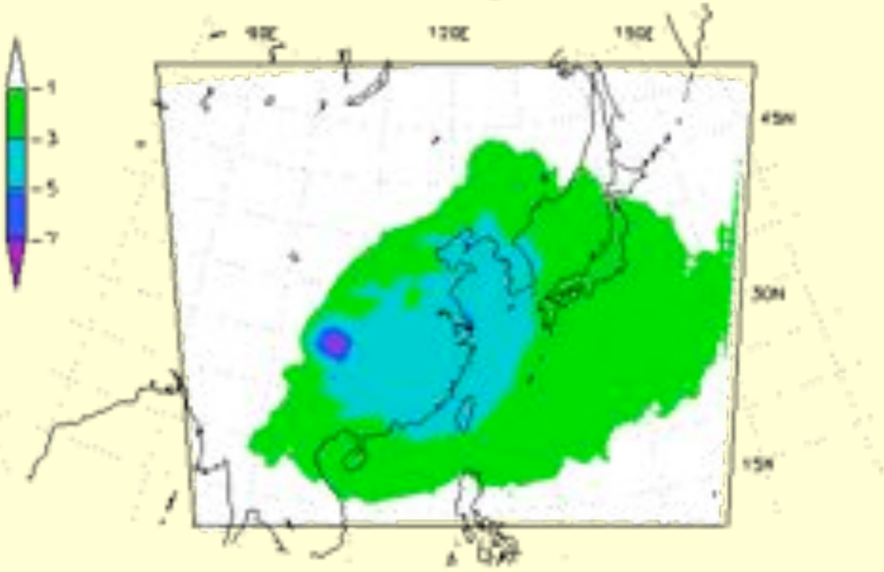
SO4 Burden, JJA, CONT



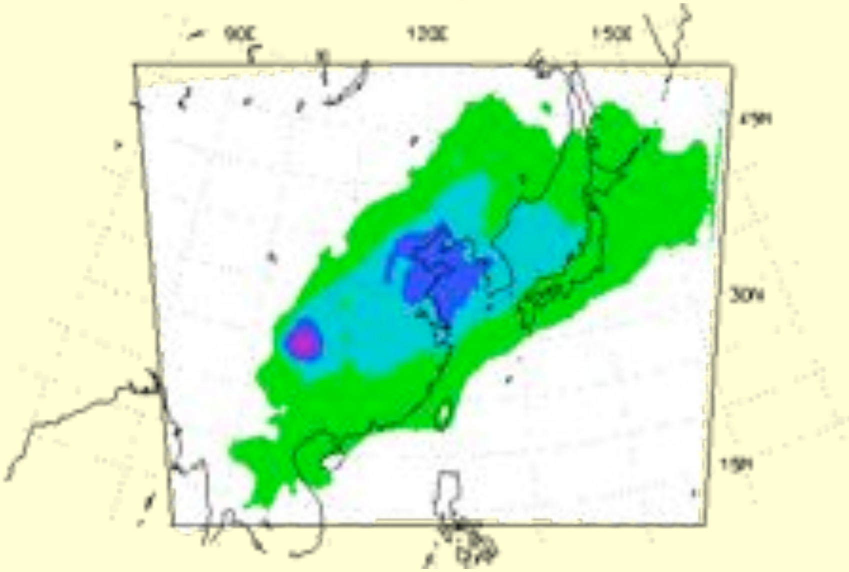
TOA Radiative Forcing, DJF, DIR1-CONT



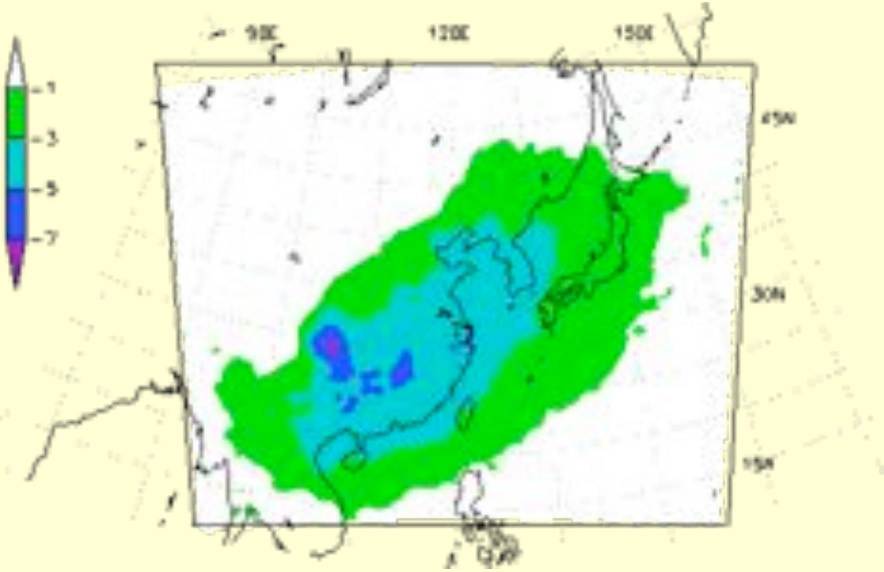
TOA Radiative Forcing, MAM, DIR1-CONT



TOA Radiative Forcing, JJA, DIR1-CONT

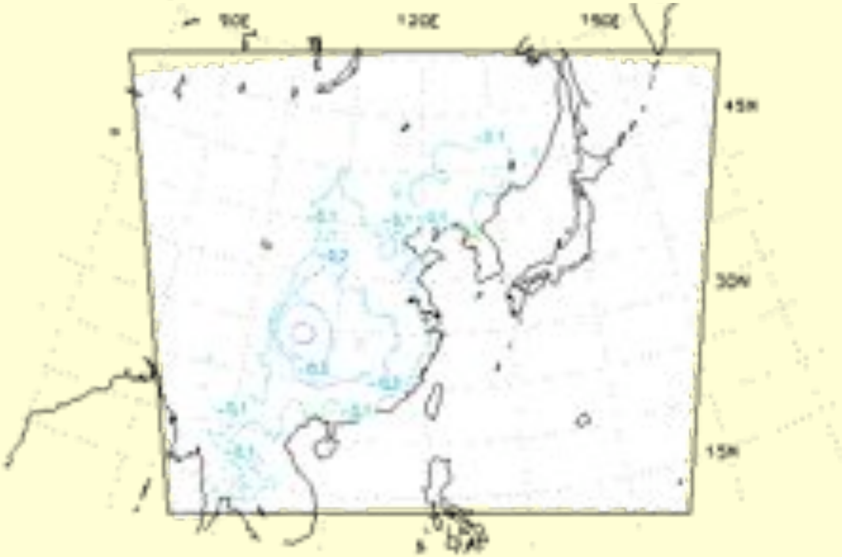


TOA Radiative Forcing, SON, DIR1-CONT

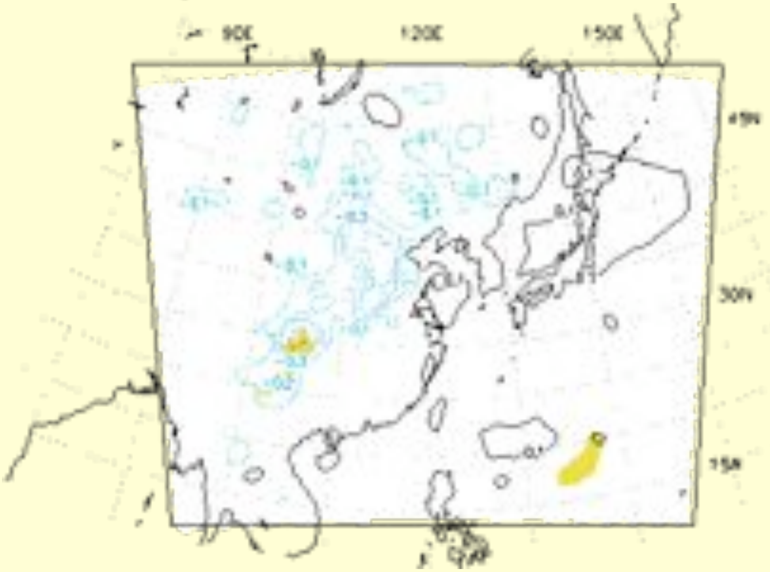


Temperature, DJF, DIR1-CONT

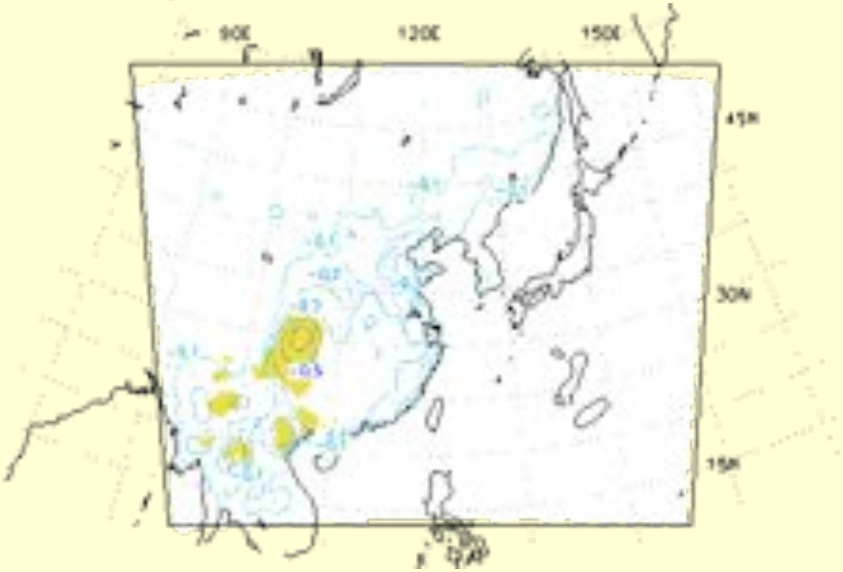
Temperature, MAM, DIR1-CONT



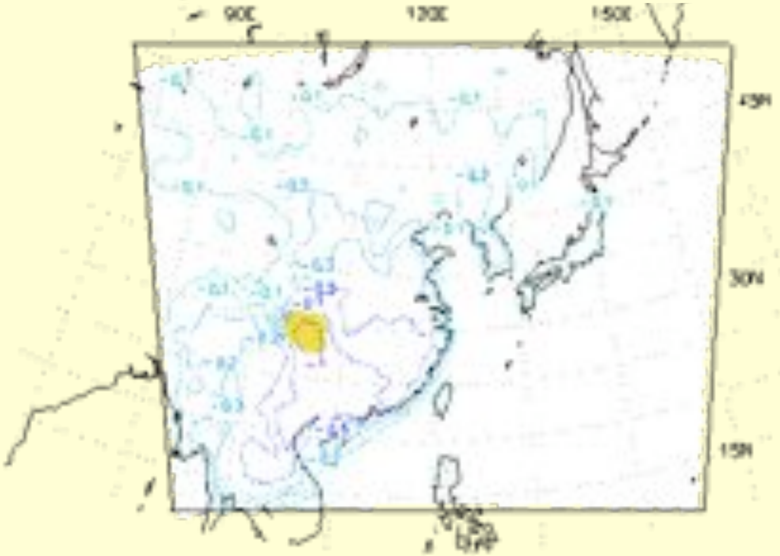
Temperature, JJA, DIR1-CONT



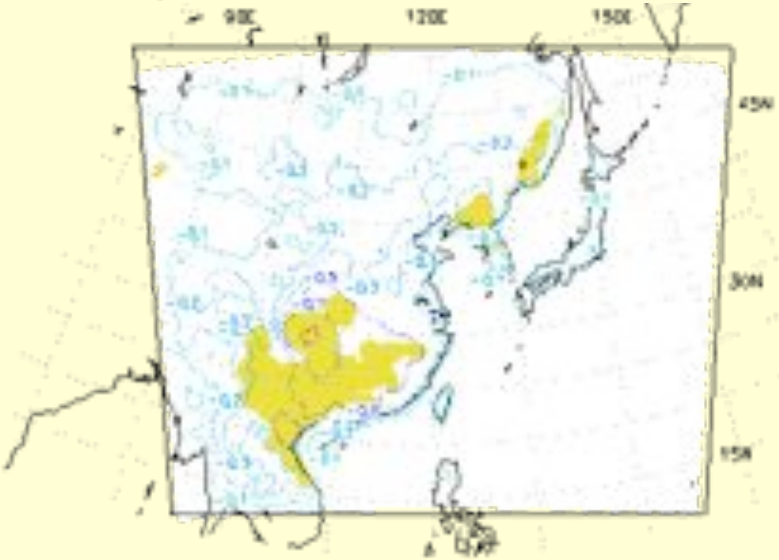
Temperature, SON, DIR1-CONT



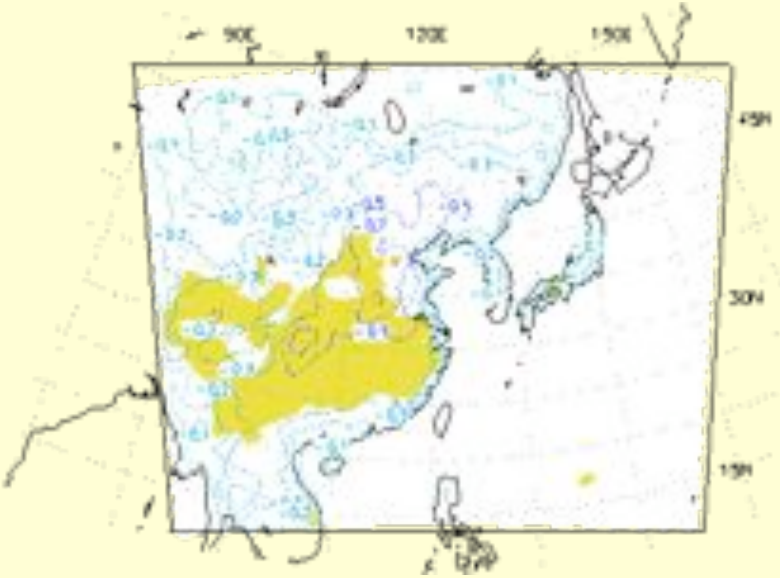
Temperature, DJF, IND1-CONT



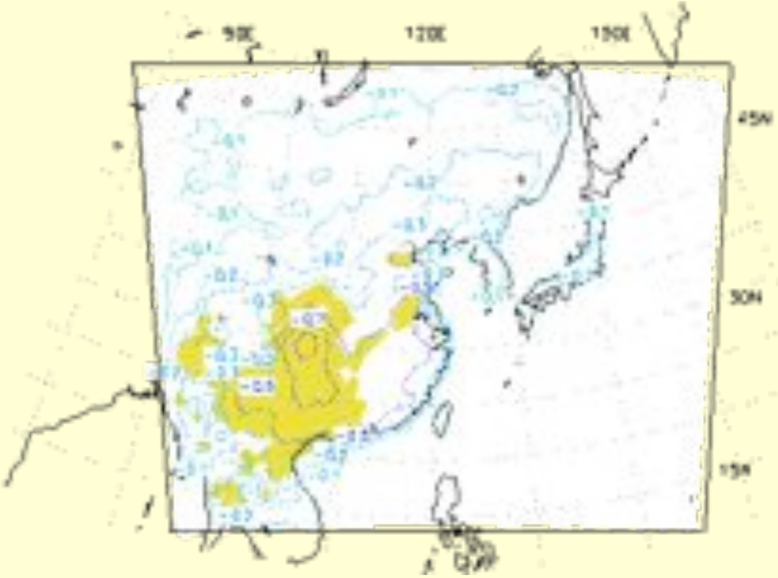
Temperature, MAM, IND1-CONT



Temperature, JJA, IND1-CONT

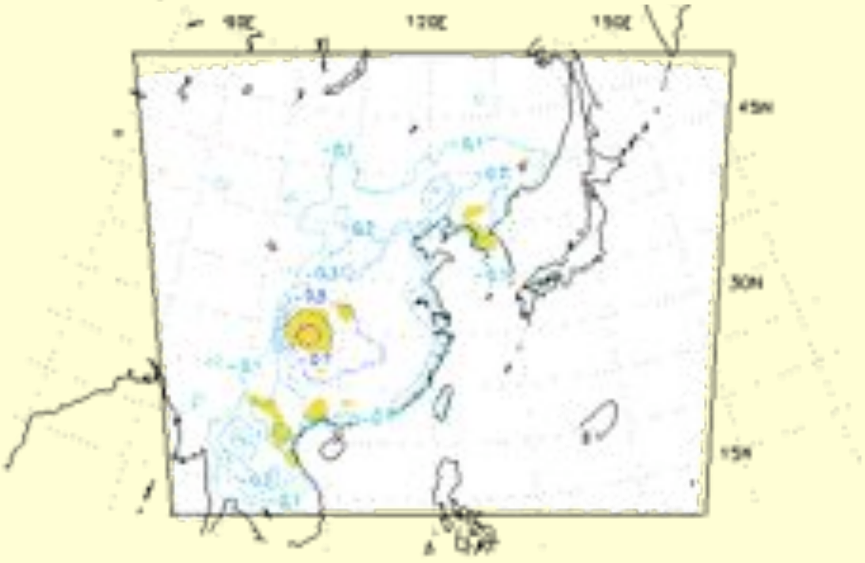


Temperature, SON, IND1-CONT

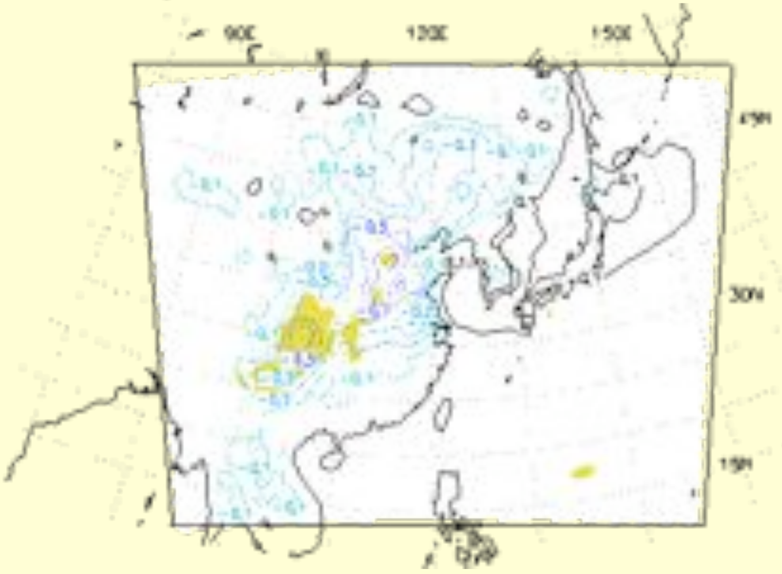


Temperature, DJF, DIR2-CONT

Temperature, MAM, DIR2-CONT

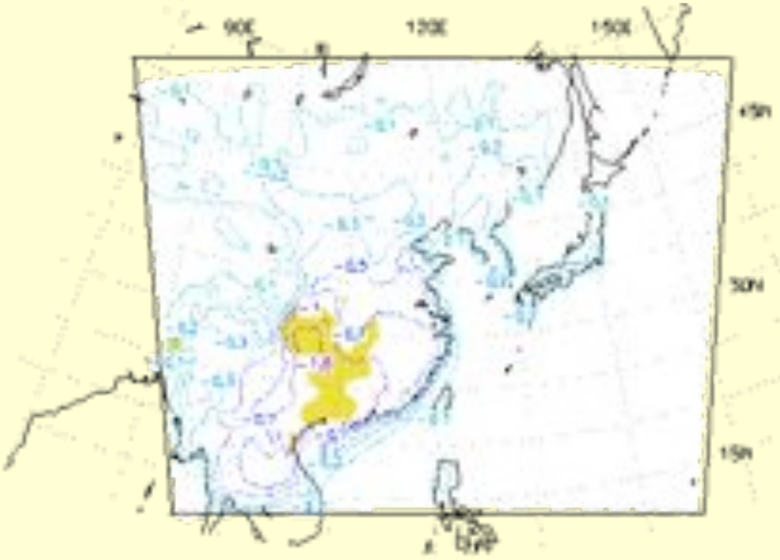


Temperature, JJA, DIR2-CONT

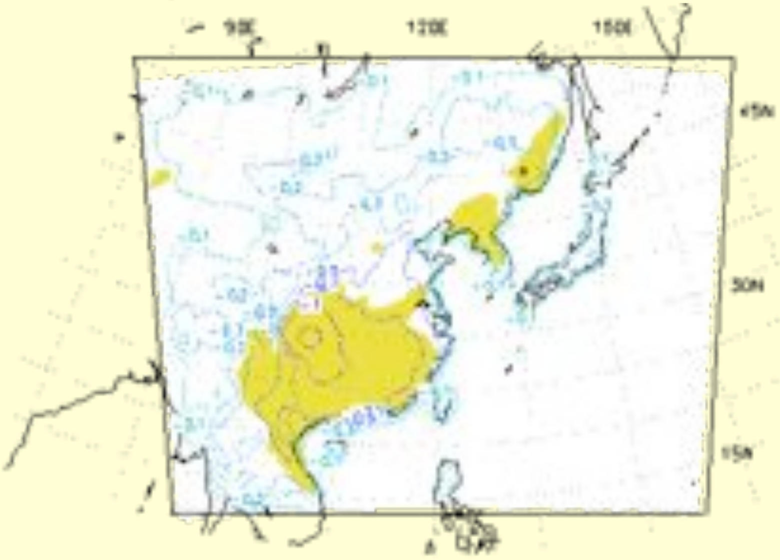


Temperature, SON, DIR2-CONT

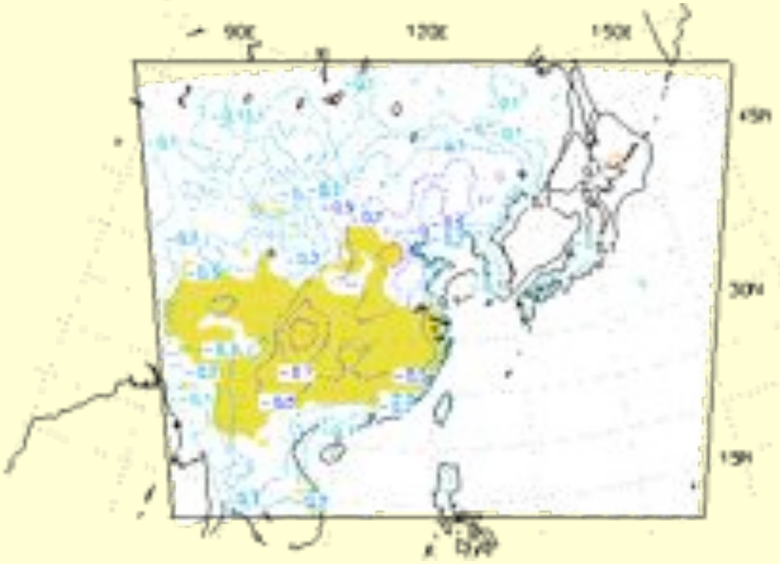
Temperature, DJF, IND2-CONT



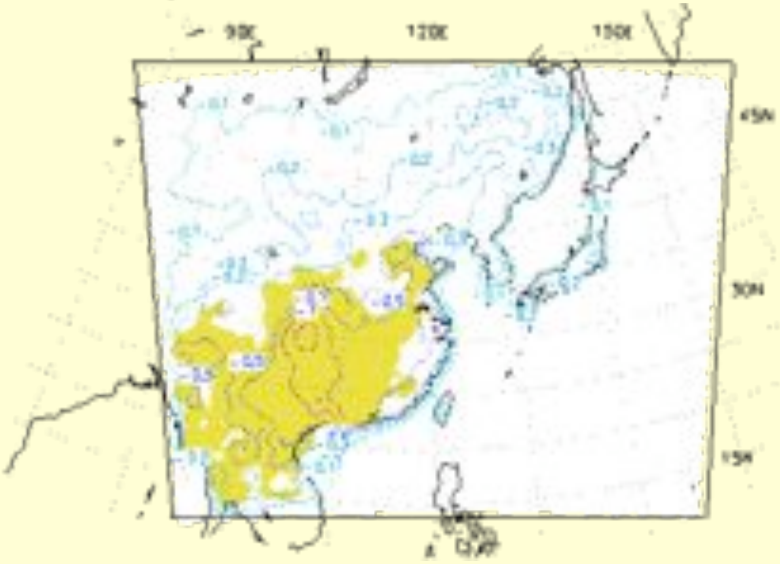
Temperature, MAM, IND2-CONT



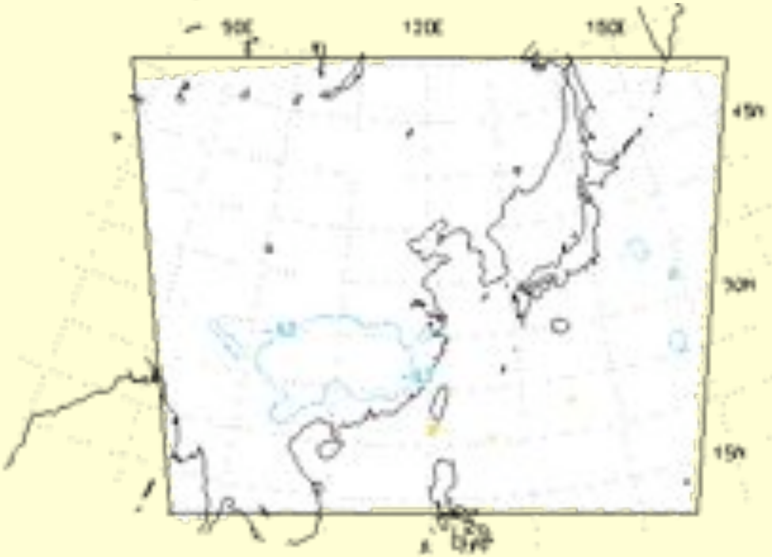
Temperature, JJA, IND2-CONT



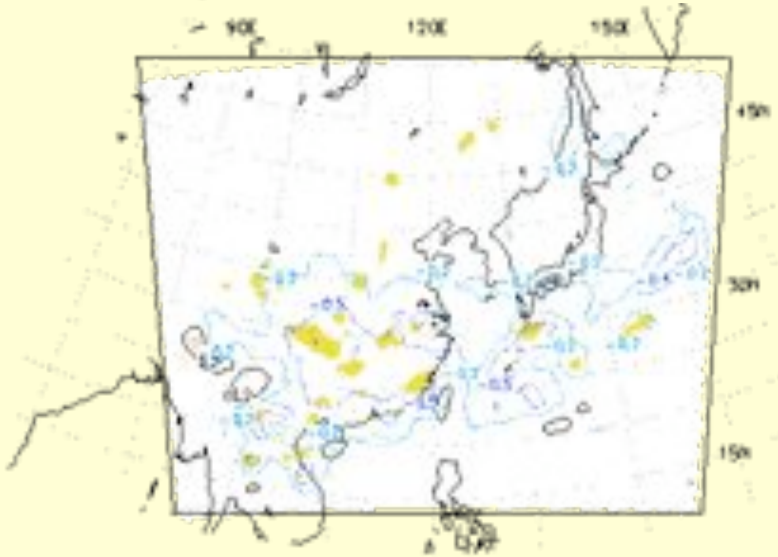
Temperature, SON, IND2-CONT



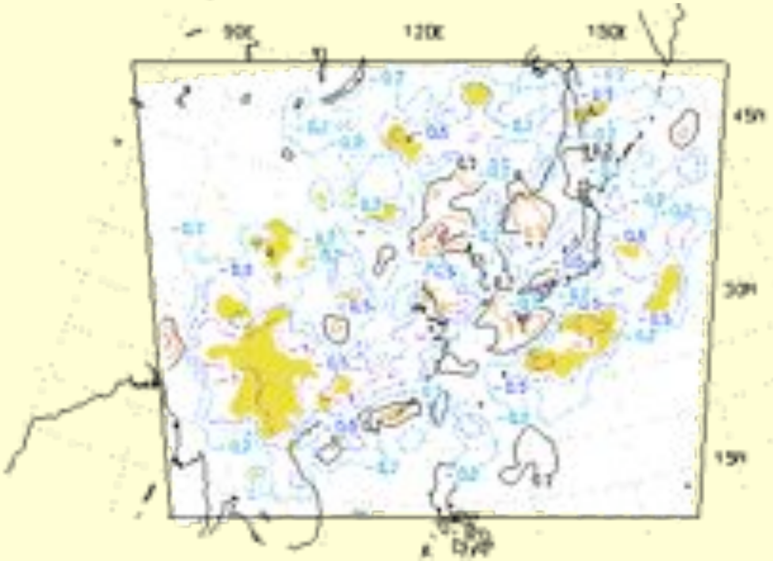
Precipitation, DJF, IND1-CONT



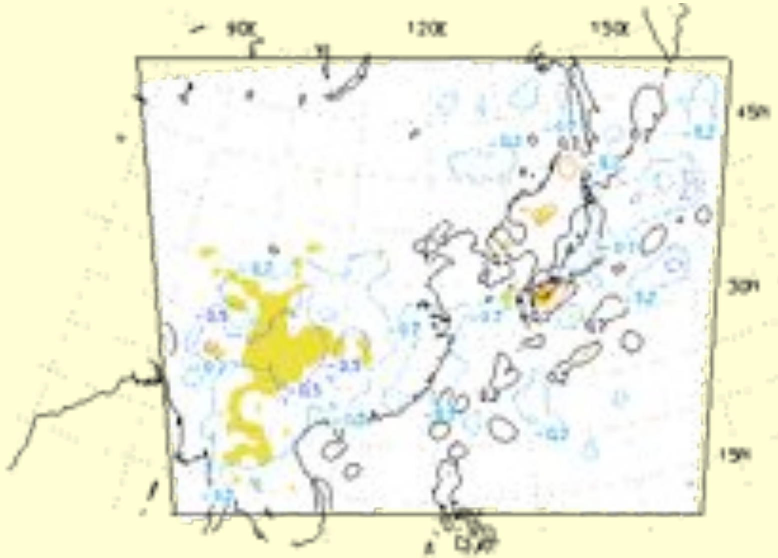
Precipitation, MAM,IND1-CONT



Precipitation, JJA, IND1-CONT



Precipitation, SON, IND1-CONT

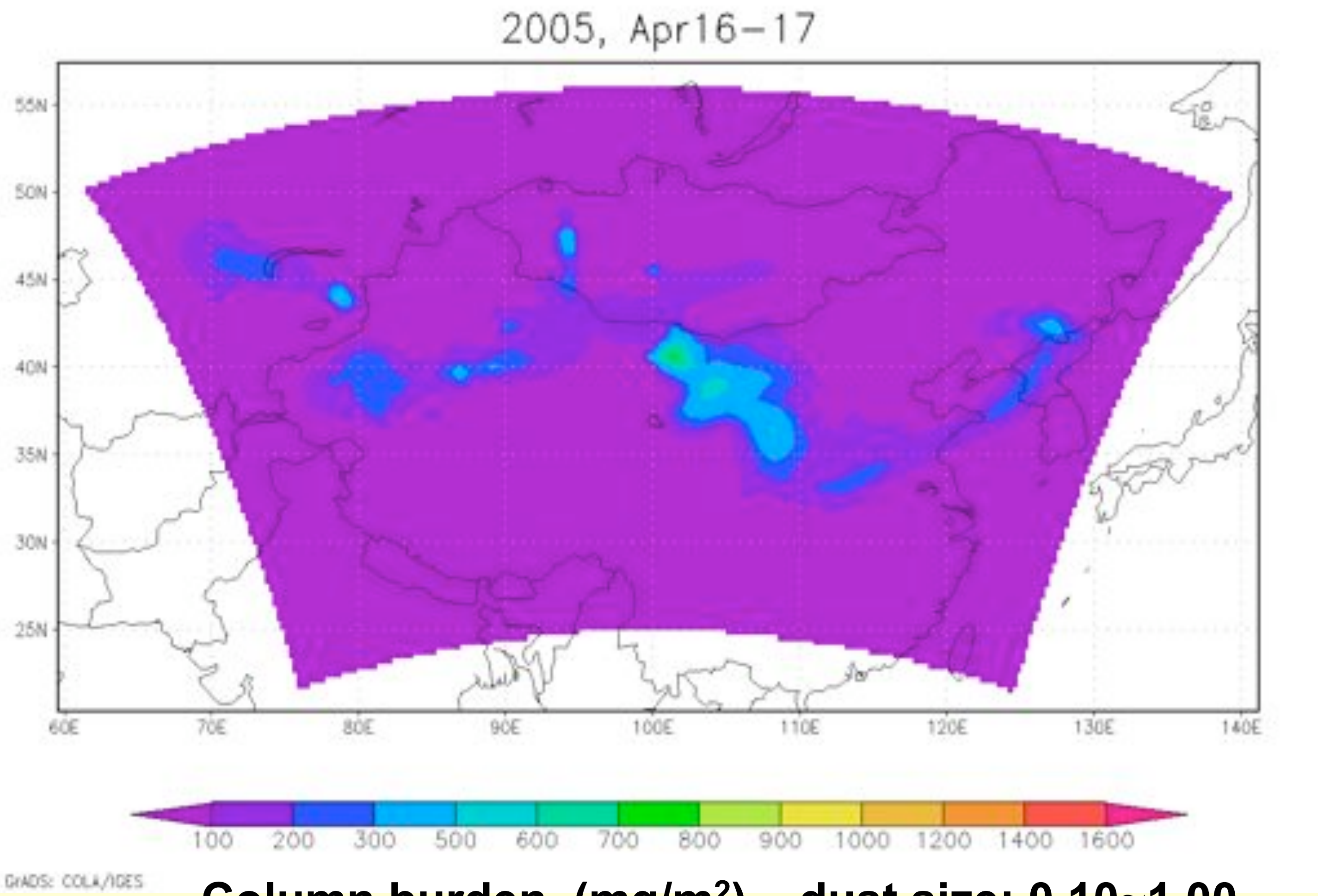


Conclusions

- 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

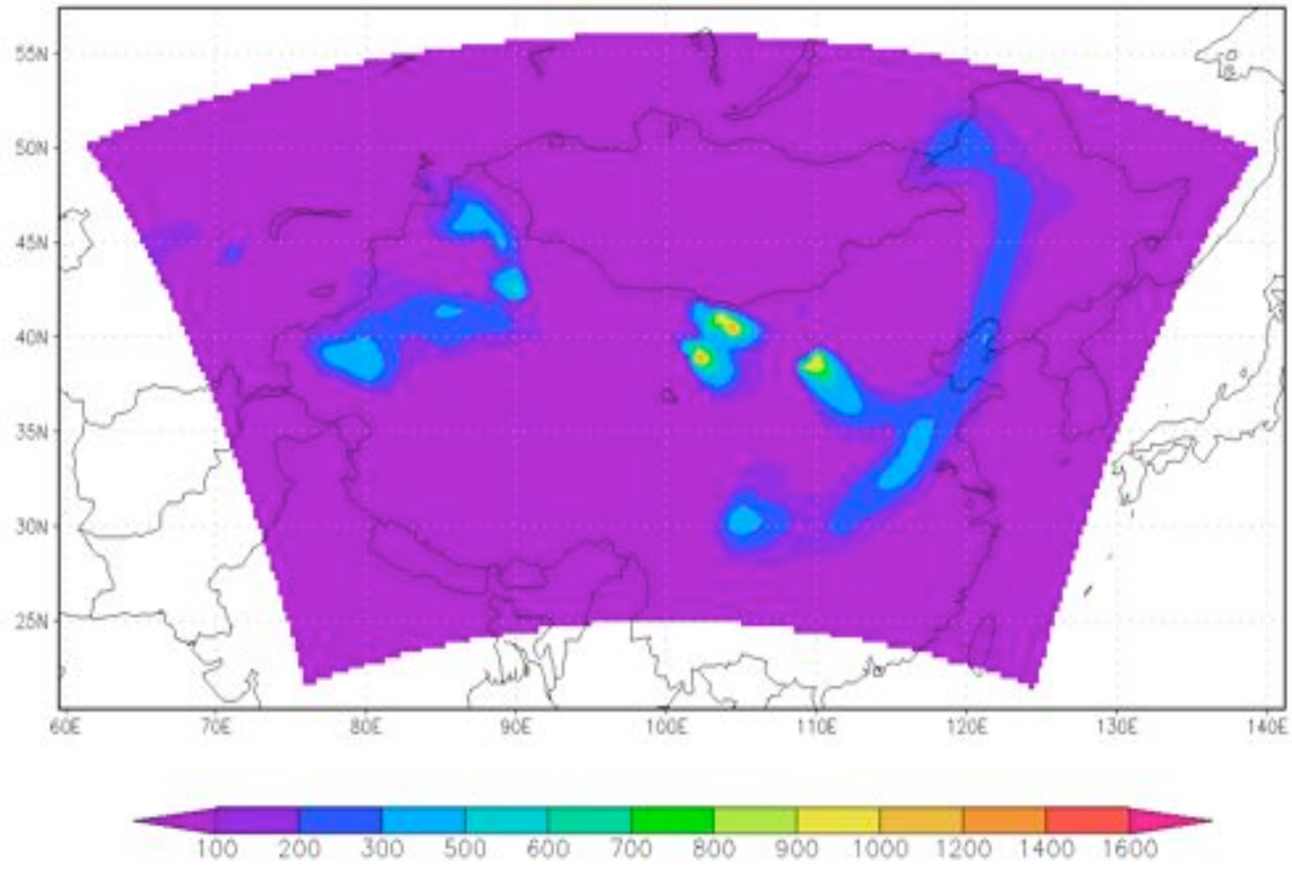
Dust simulation over East Asia

(Preliminary results; 1 hour interval output)

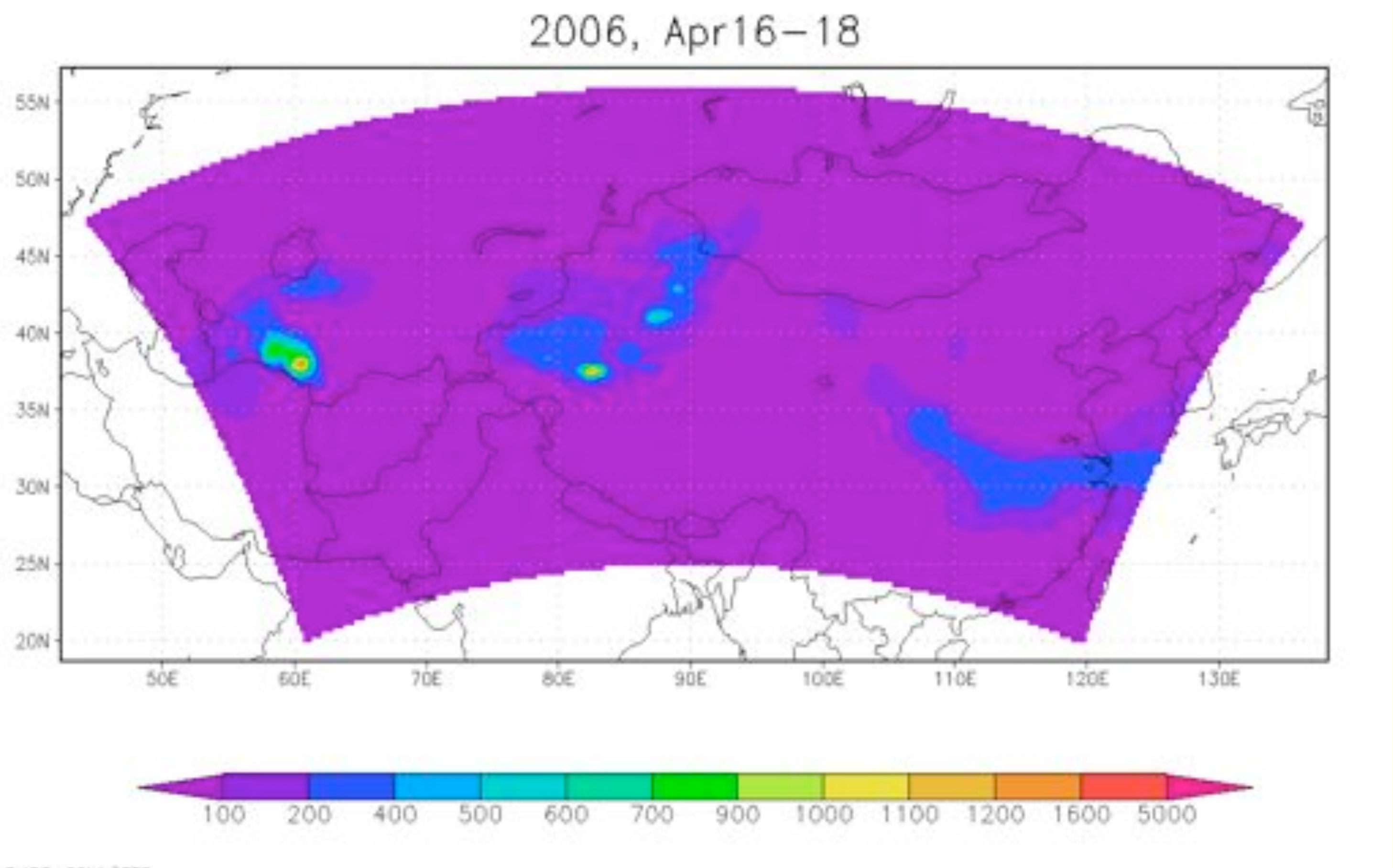


Column burden (mg/m^2) dust size: 0.10~1.00

2005, Apr18-19

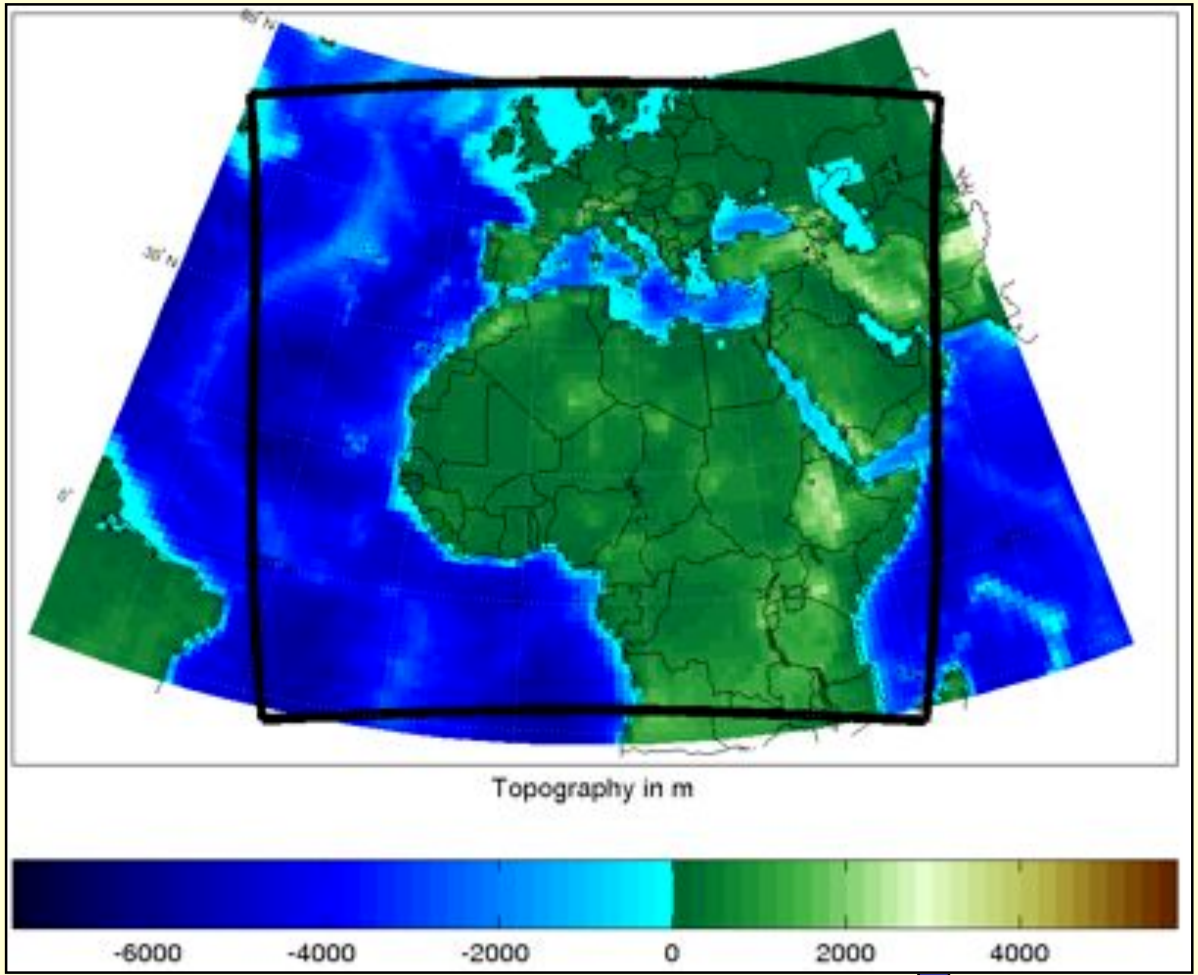


GrADS: COLA/IGES

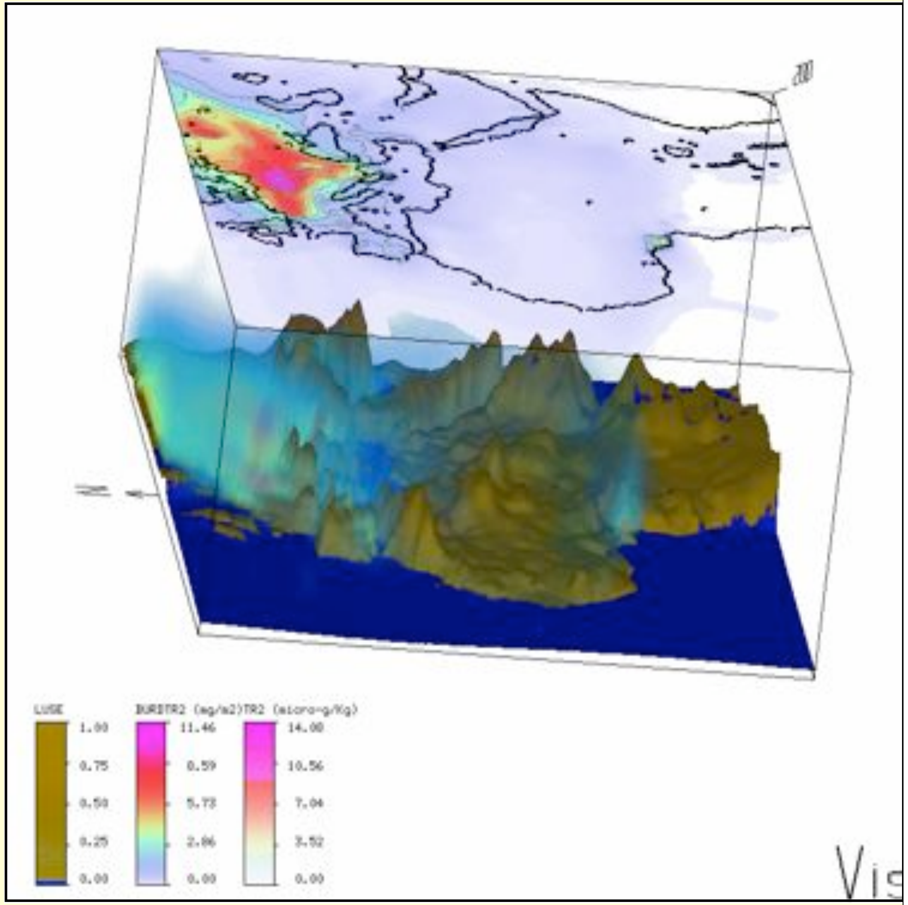


Dry deposition of dust over 330,000 t in Beijing

The case of the Europe/Africa region



Example I: SO2 and SO4 burden, DJF 2000



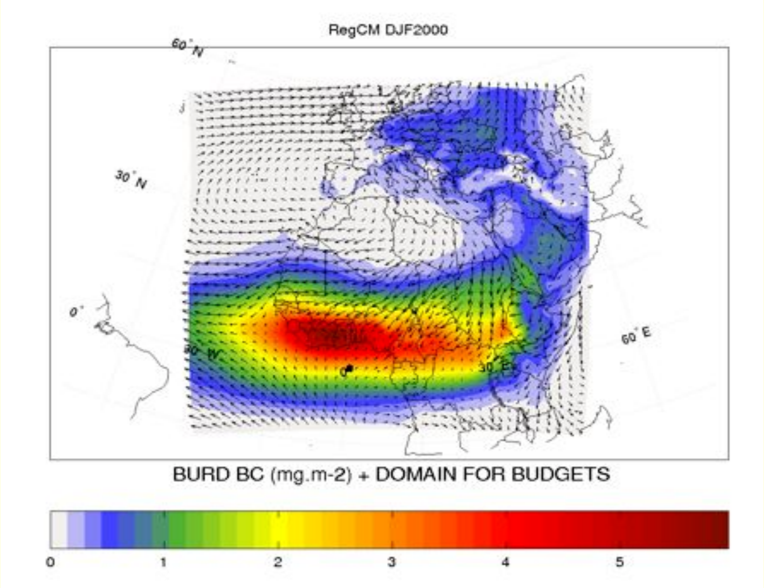
Shading = SO4

Isocontour = SO2

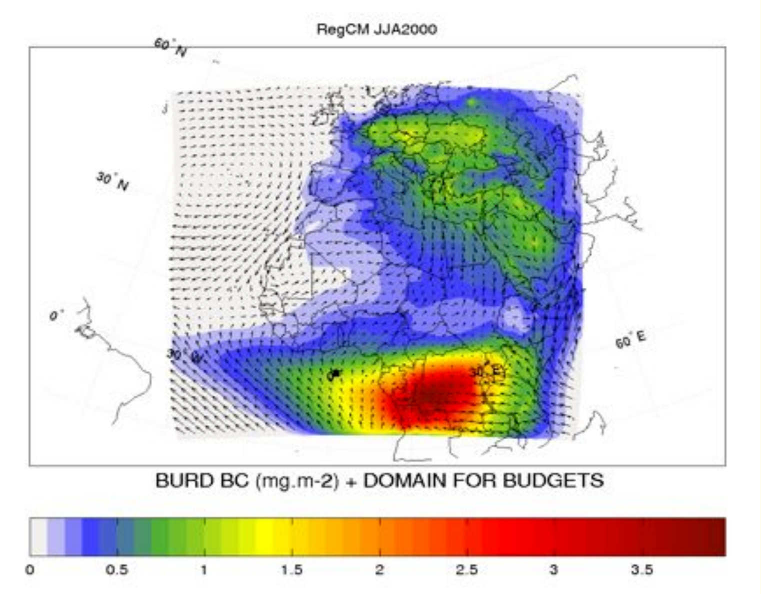
Average SO_4^{2-} concentration field ($\mu g.m^{-3}$) and column burden

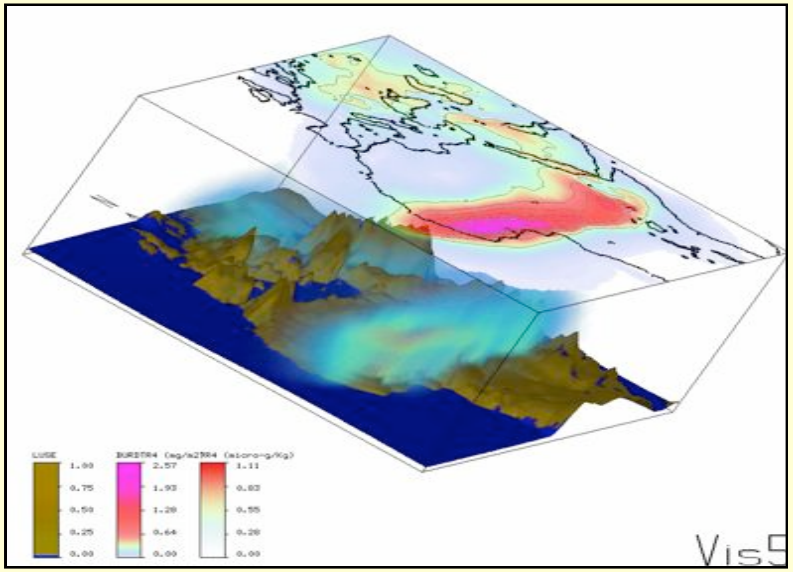
Example II: BC burden

DJF 2000

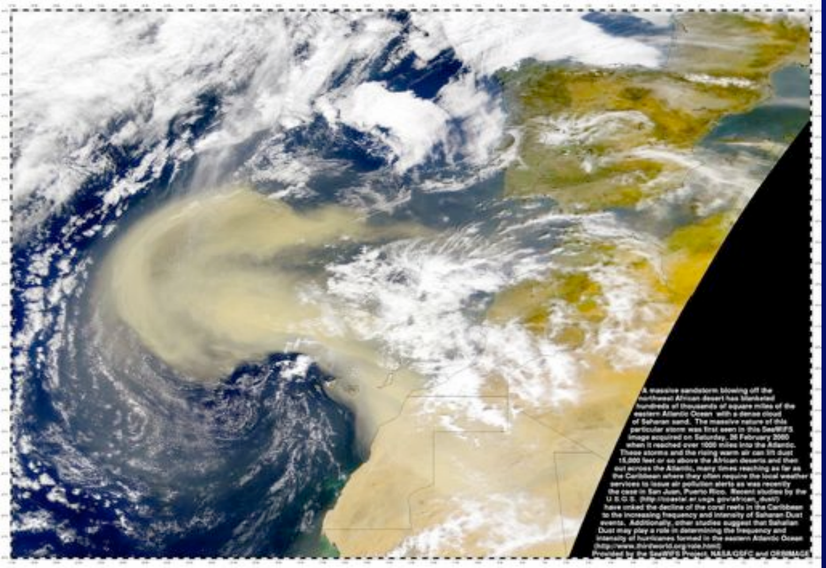


JJA 2000





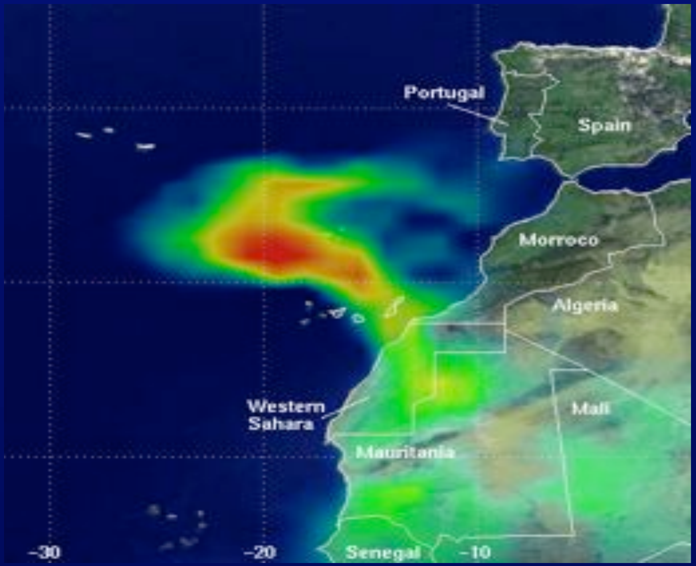
Preliminary case study: Dust storm of 20-28 February 2000



A massive sandstorm blowing off the northwest African desert has blanketed hundreds of thousands of square miles of the eastern Atlantic Ocean with a dense cloud of Saharan sand. The massive nature of this particular storm was first seen in this SeaWiFS image acquired on Saturday, 26 February 2000 when it reached over 1000 miles into the Atlantic. These storms and the rising warm air can lift dust 15,000 feet or so above the African deserts and then out across the Atlantic, many times reaching as far as the Caribbean where they often require the local weather services to issue air pollution alerts as was recently the case in San Juan, Puerto Rico. Recent studies by the U.S.G.S. (http://coastal.er.usgs.gov/african_dust/) have linked the decline of the coral reefs in the Caribbean to the increasing frequency and intensity of Saharan Dust events. Additionally, other studies suggest that Sahelian Dust may play a role in determining the frequency and intensity of hurricanes formed in the eastern Atlantic Ocean (http://www.thirdworld.org/role.html)

Provided by the SeaWiFS Project, NASA/GSFC and ORBIMAGE

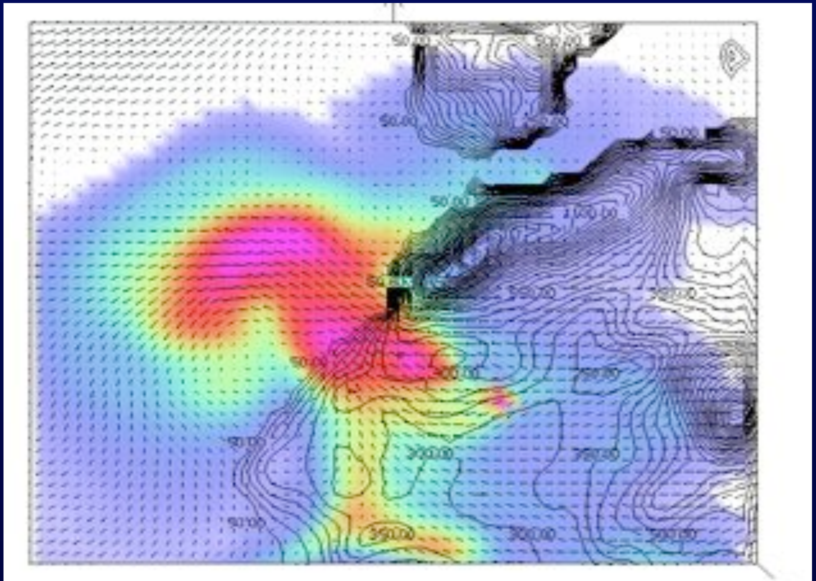
SeaWIFS (NGSFC)



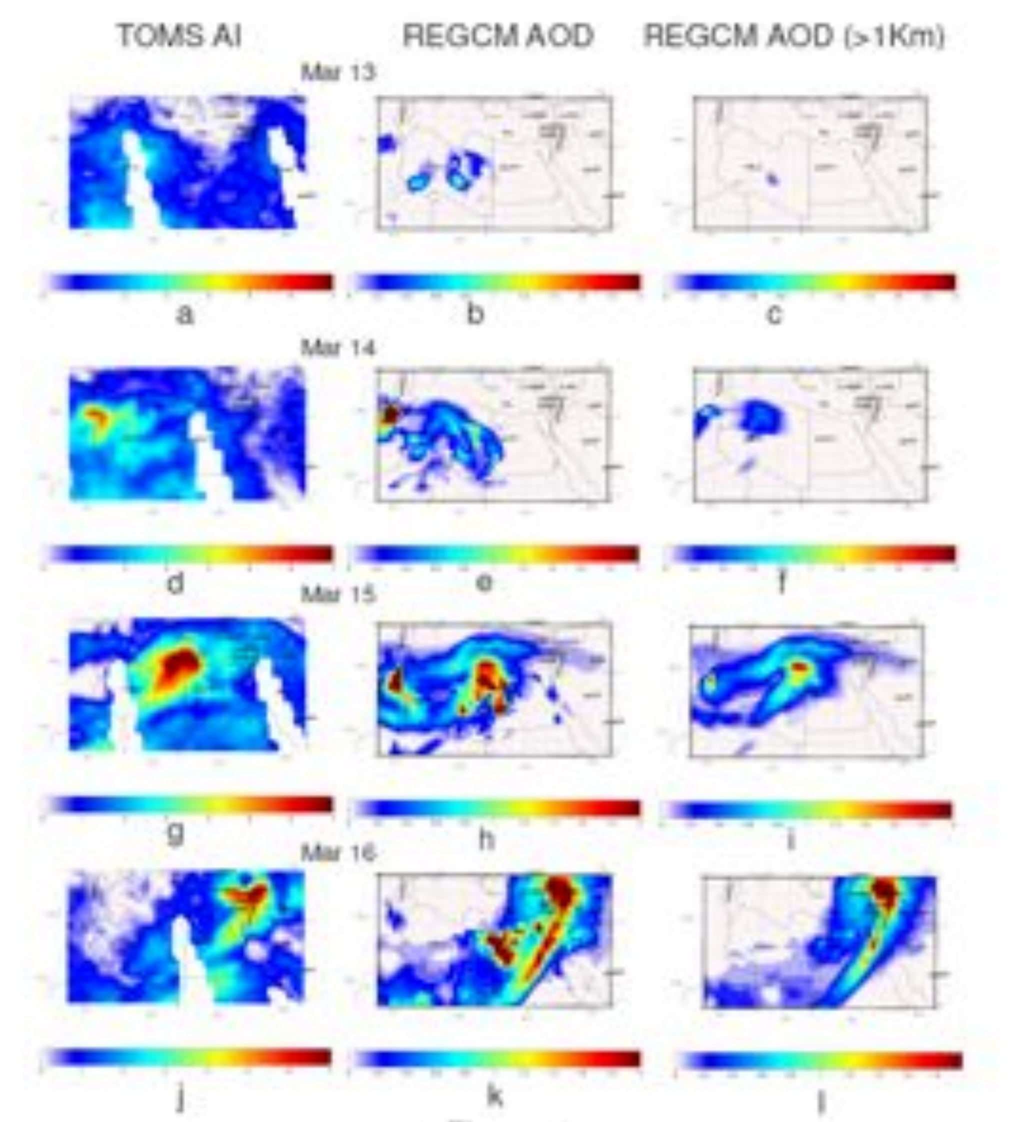
TOMS (aerosol index)

RegCM

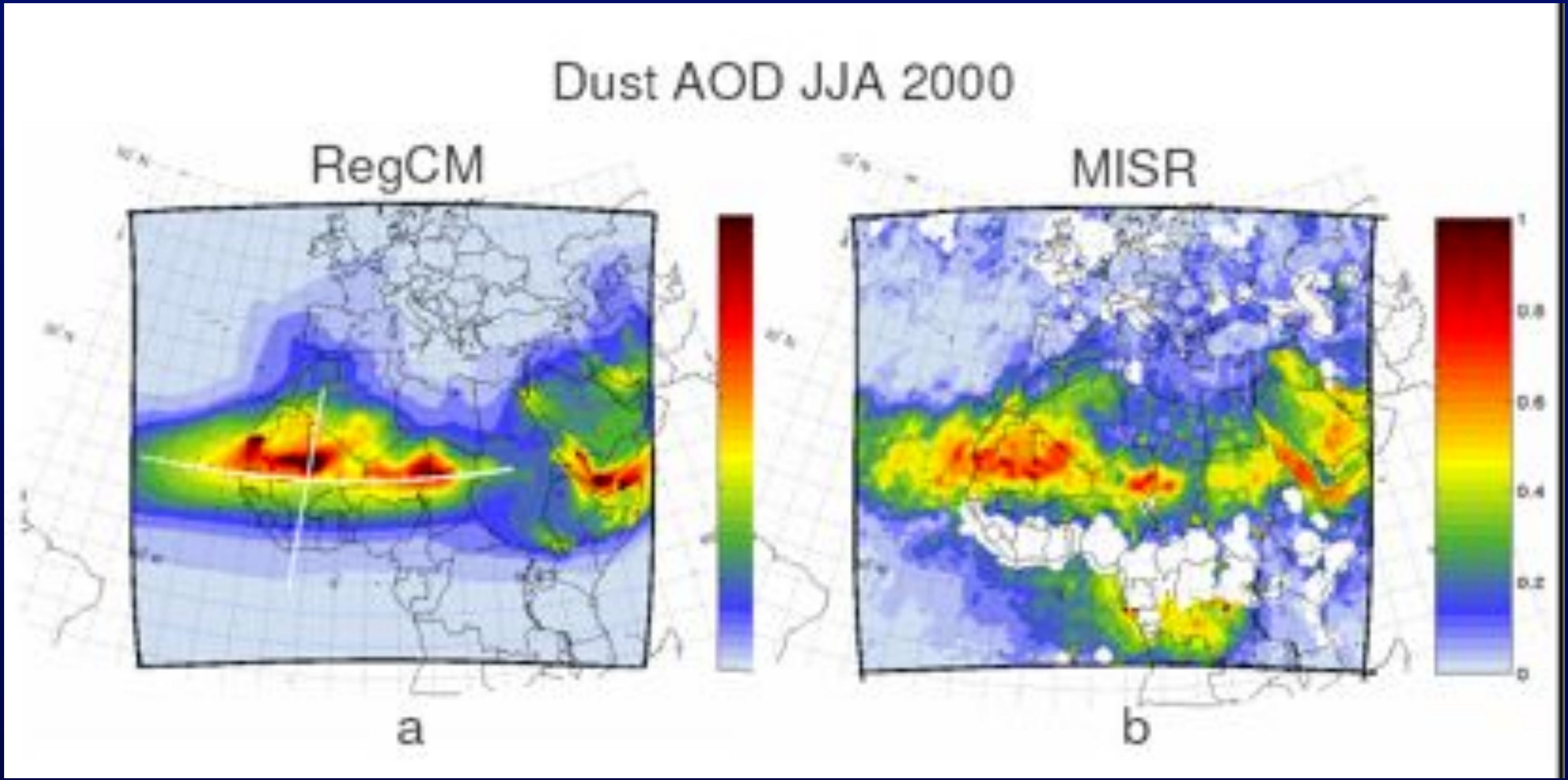
(0.1-10 µm dust burden)



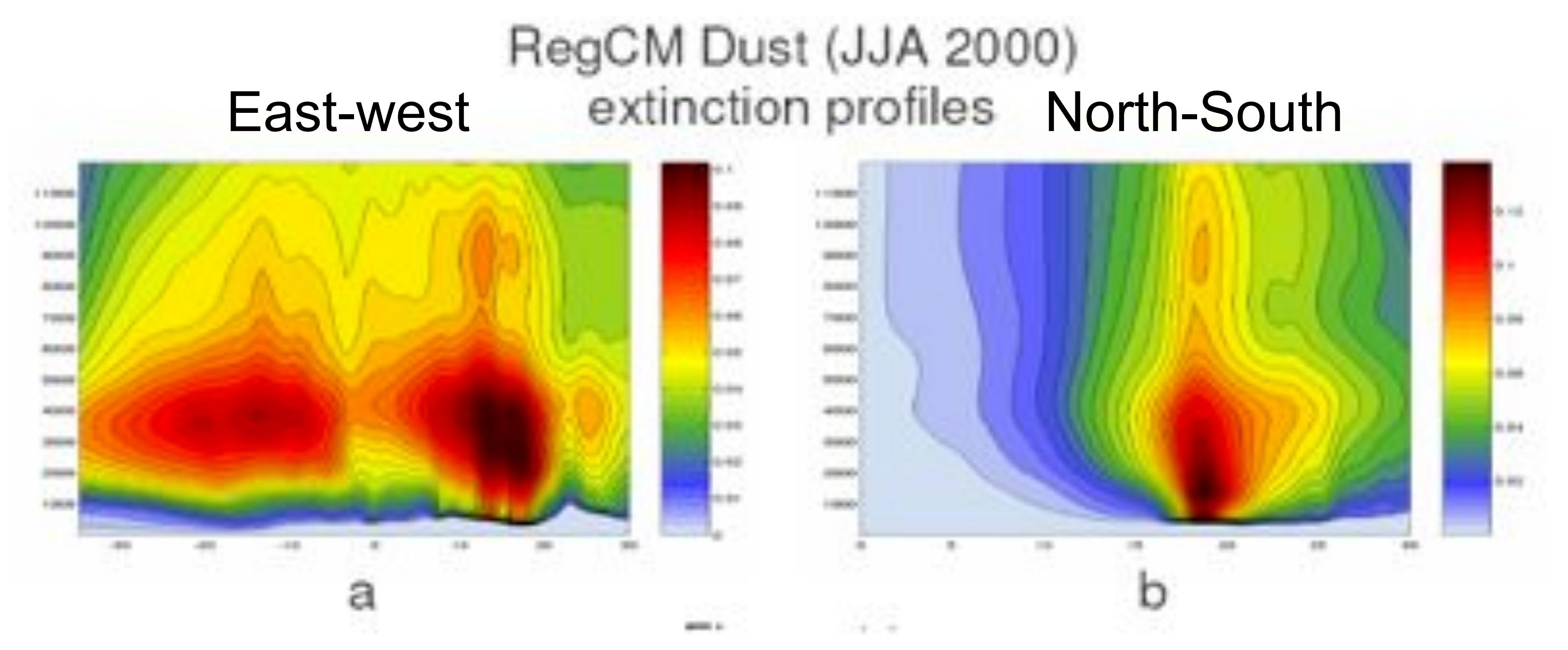
Simulation of northern Sahara dust outbreak (March13-16, 2002)



Long term dust simulation, JJA 2000
Total AOD

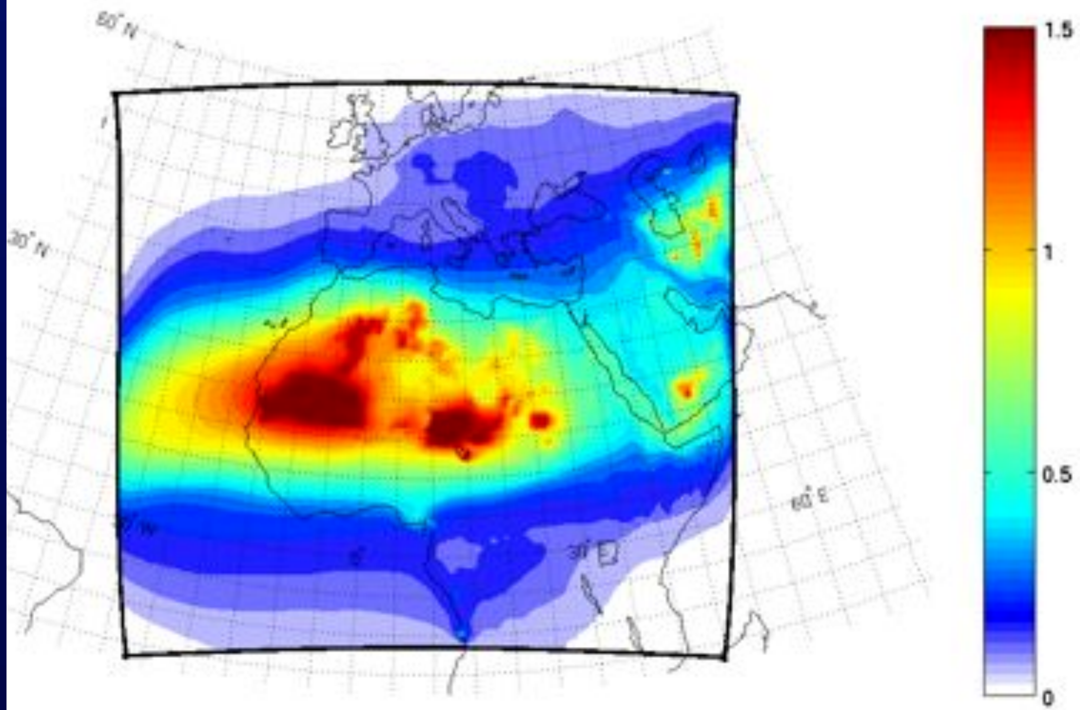


Long term dust simulation, JJA 2000
Cross sections



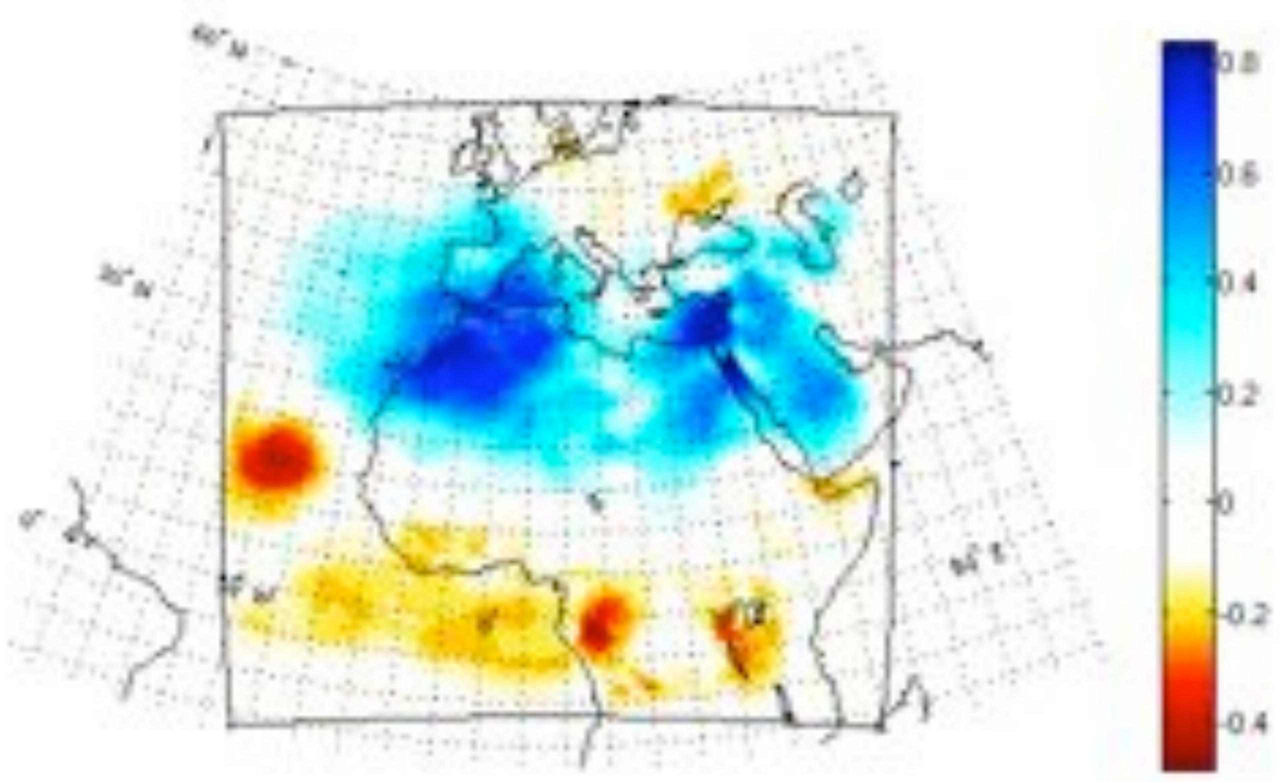
Effects of aerosols and dust on the African monsoon

Total AOD,JJA, 1998-2002



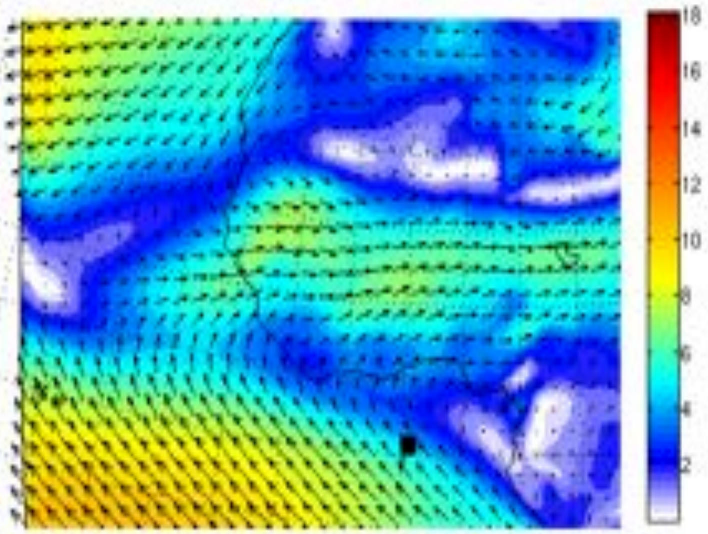
Effects of aerosols and dust on the African monsoon

Surface temperature, control - aerosol

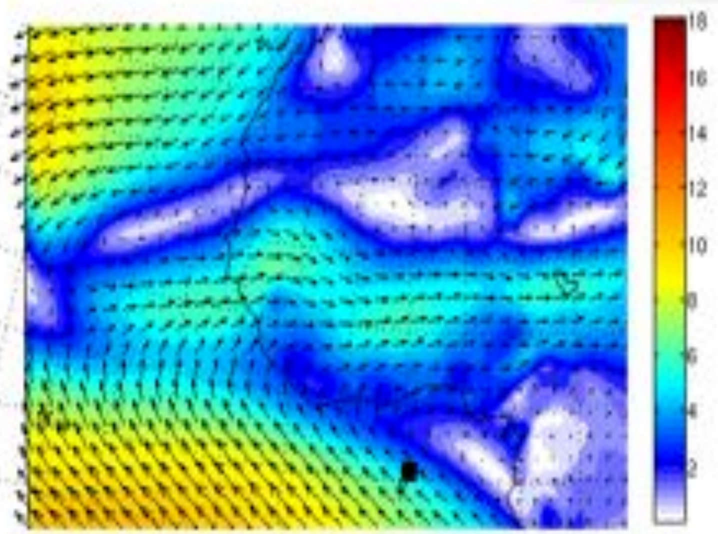


Effects of aerosols and dust on the African monsoon

700 mb wind, control

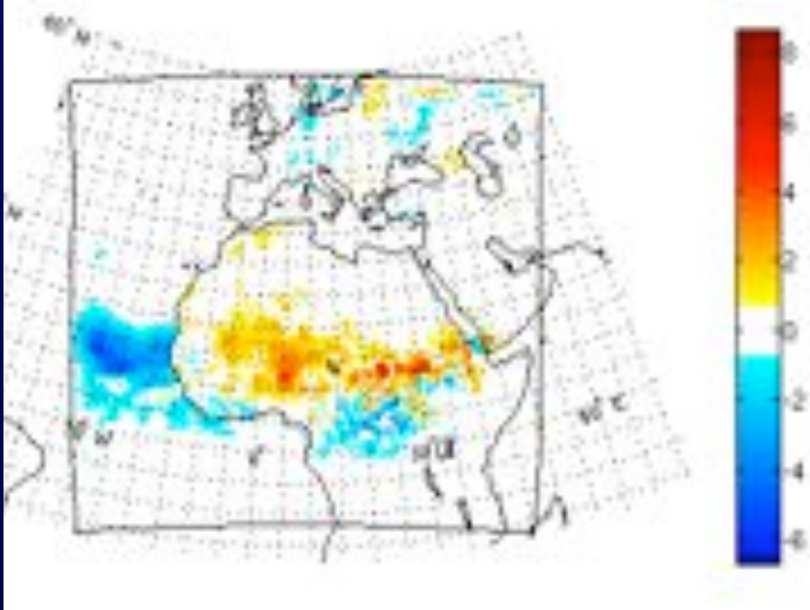


700 mb wind, aerosol

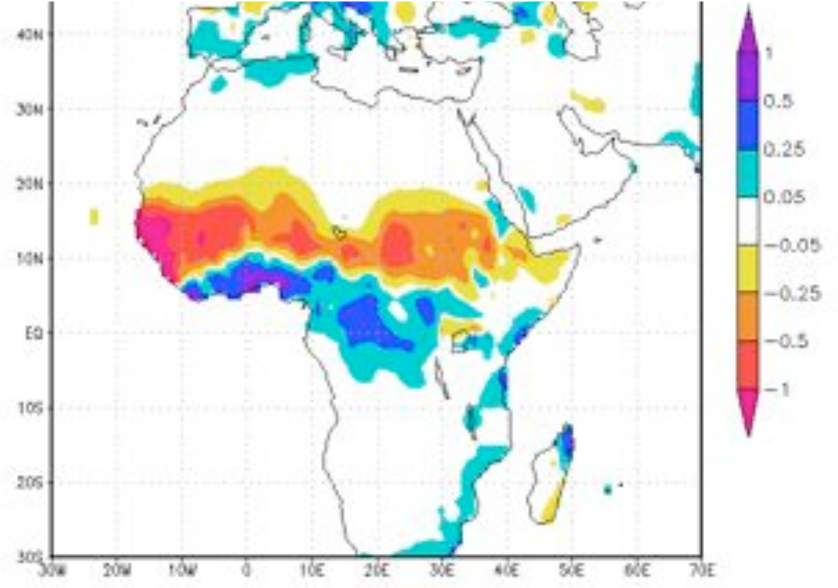


Effects of aerosols and dust on the African monsoon

Precipitation control - aerosol



Precipitation, CRU (1961-1990) – (1901-1980)



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)