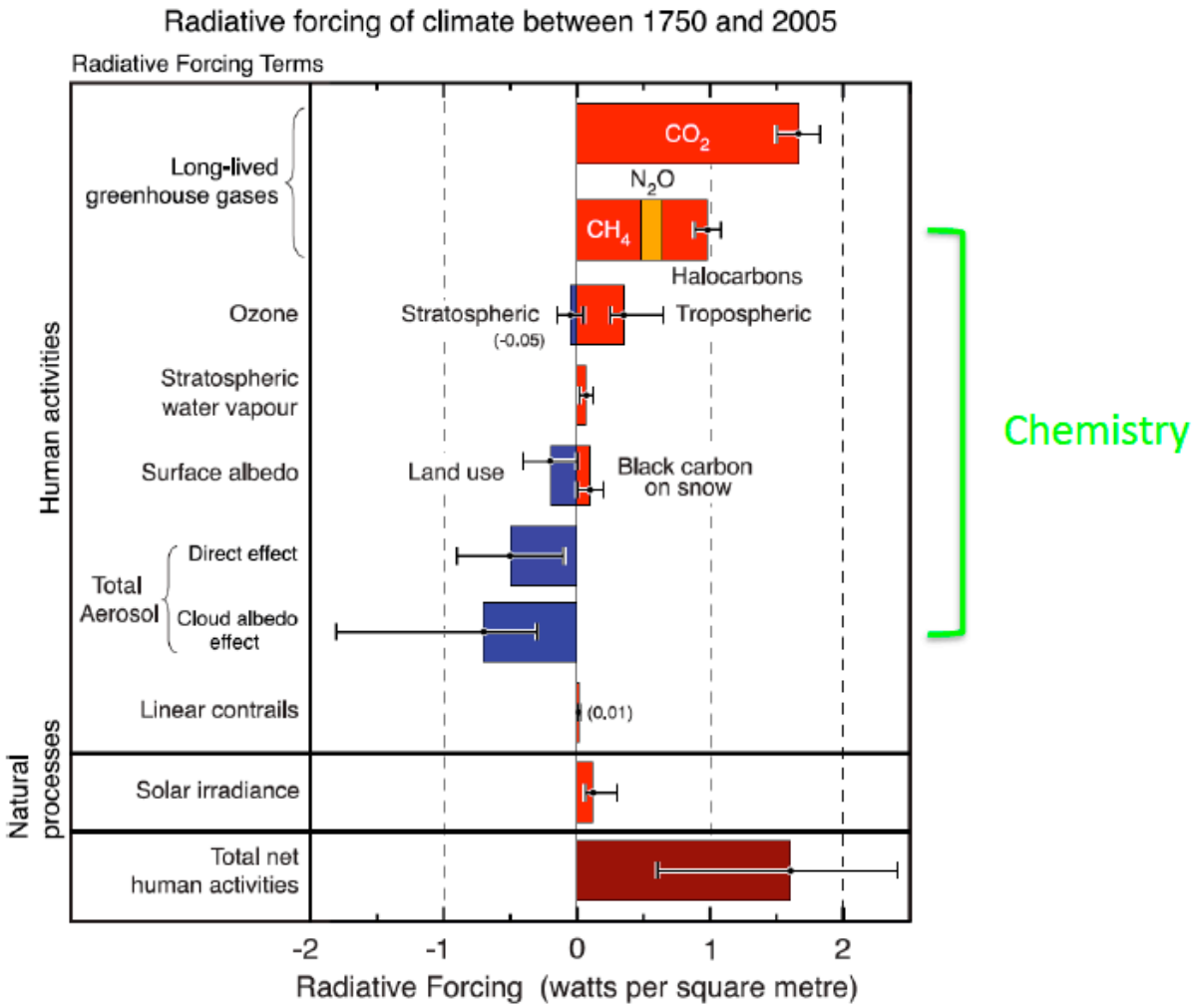
Chemistry-Climate Modeling

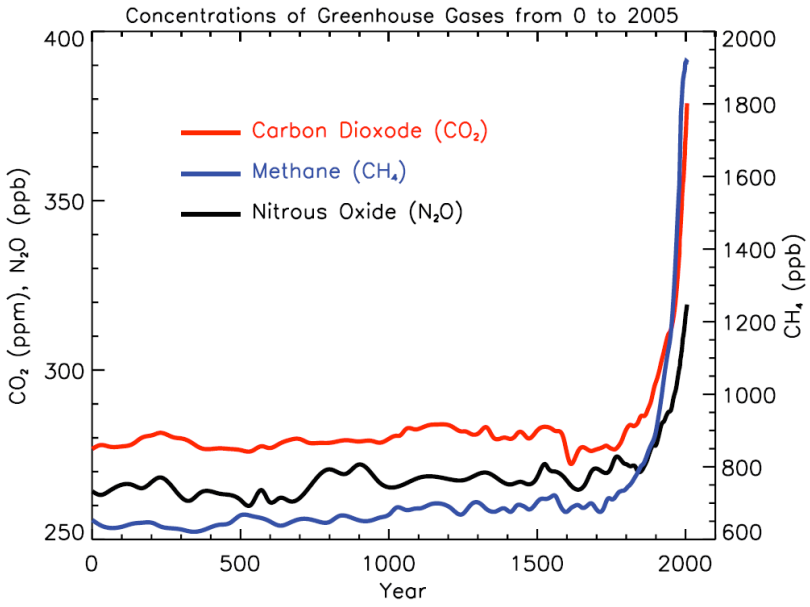
Simone Tilmes
NESL: ACD/CGD

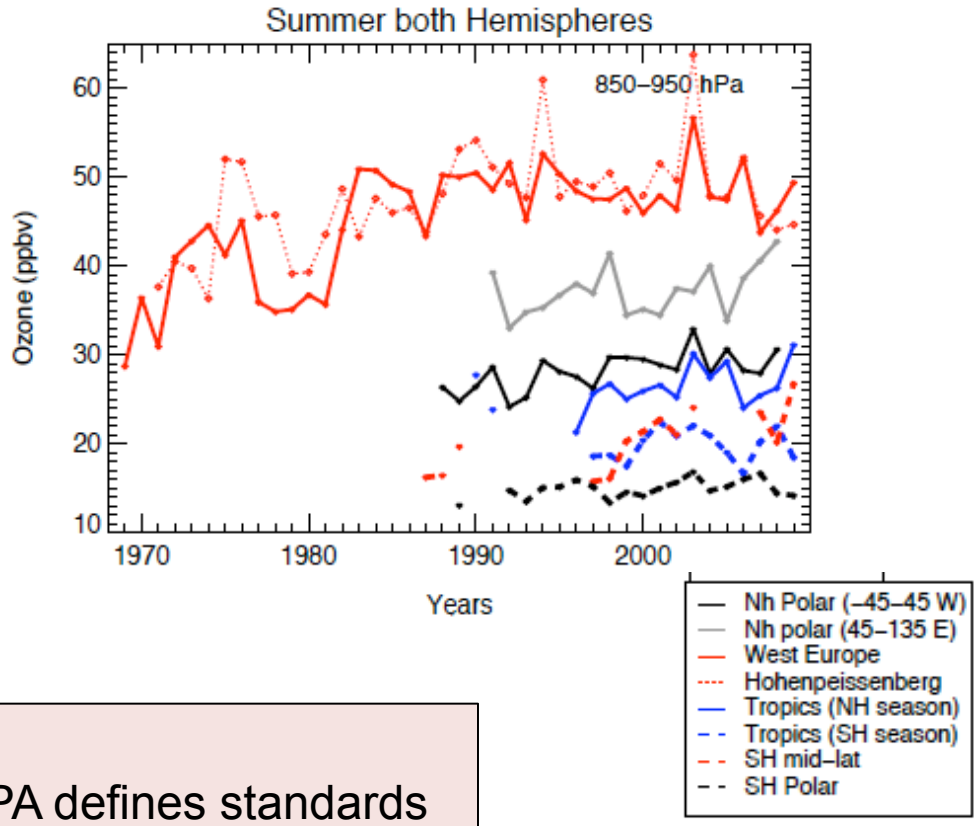
Atmospheric Chemistry and Climate



Forster and Ramaswamy. AR4 Chapter 2

Changing Atmospheric Composition





Implications for Climate
Implications for Air Quality: EPA defines standards for air quality (currently 75 ppb)

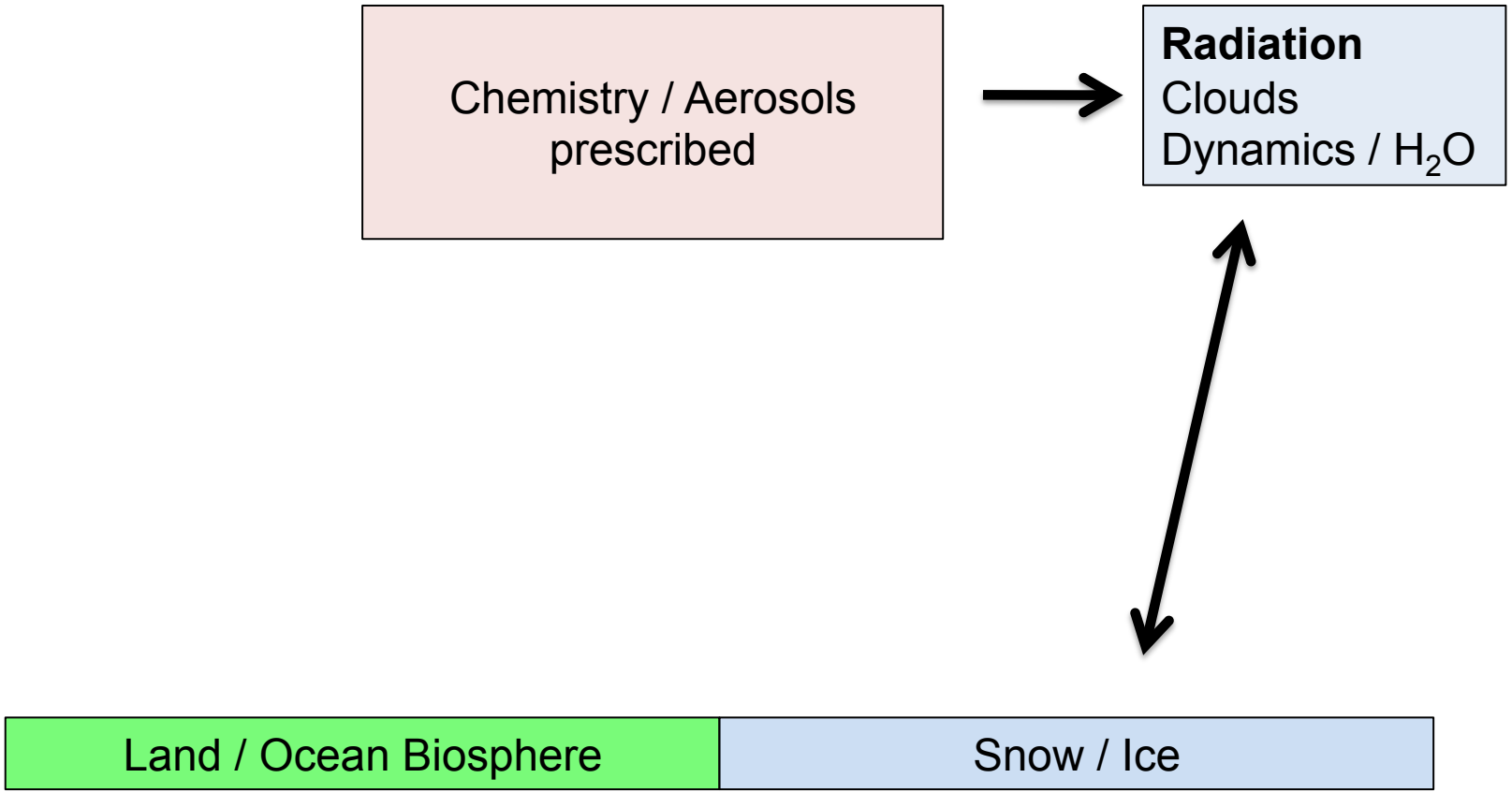
Modeling without Chemistry-Climate interactions CCSM CAM4

- Chemistry and aerosols are prescribed in CAM4: (prescribed monthly fields of CO_2, CH_4, O_3, N_2O, CFCs)

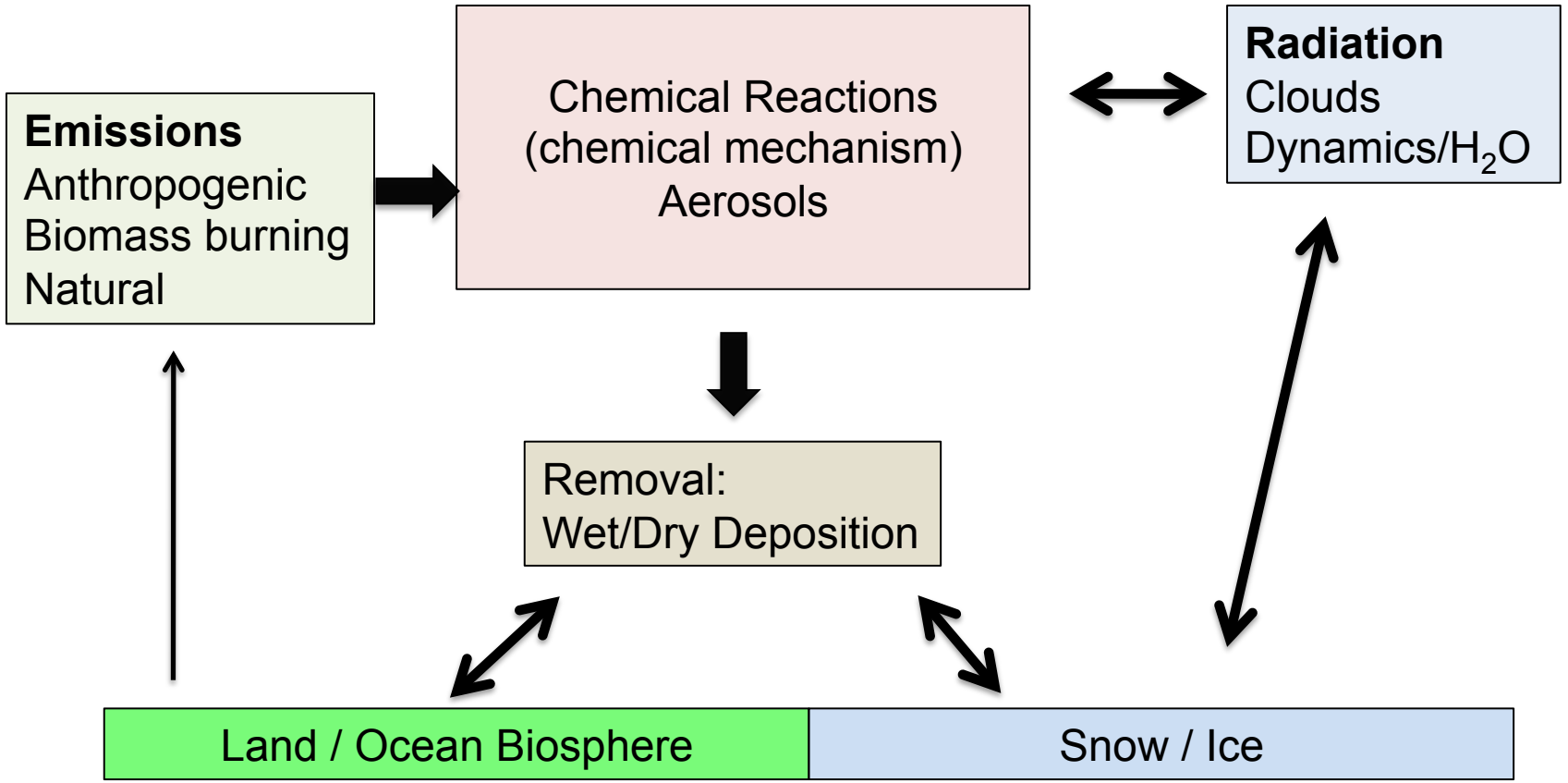
- Aerosols are calculated in CAM5 (Modal Aerosols Model MAM), but not coupled with chemistry

No interaction between Chemistry and Climate

Chemistry in CESM CAM4



Chemistry in CESM CAM4 Chem



Modeling with Chemistry

- Represent Climate gases: (CO_2), CH_4, O_3, H_2O
- Tropospheric/Stratospheric Chemistry: 122 species to cover around 300 main reaction. NO_x ($NO + NO_2$), CO, volatile organic compounds (VOCs), are key species controlling Ozone, OH determines oxidation capacity, CH_4 lifetimes

$$\begin{aligned}
CO + OH &\xrightarrow{O_2} CO_2 + HO_2 \\
HO_2 + NO &\longrightarrow NO_2 + OH \\
NO_2 + h\nu &\xrightarrow{O_2} NO + O_3 \\
\hline
\text{Net: } CO + 2O_2 + h\nu &\longrightarrow CO_2 + O_3
\end{aligned}$$

Modeling with Chemistry

Define Chemical Mechanism: Options in CAM4-Chem

Superfast Chemistry:

12 species, simple chemistry mechanism, CH4 prescribed
LINOZ + Cariolle in stratosphere, fully coupled

Bulk Aerosol Model (BAM):

Includes Black Carbon, Organic Carbon, Sea Salt, Dust
(prescribed monthly fields of CO_2, CH_4, O_3, OH, HO_2, NO_2, N_2O, SO_2/SO_4)

BAM and tropospheric chemistry (trop_mozart):

Tropospheric mechanism, 103 species (MOZART: *Emmons et al., 2010*)
Stratospheric chemistry is prescribed: (O_3, HNO_3, CH_4, CO)
Emissions, Dry/Wet Deposition

Plus stratospheric chemistry (trop-strat mozart):

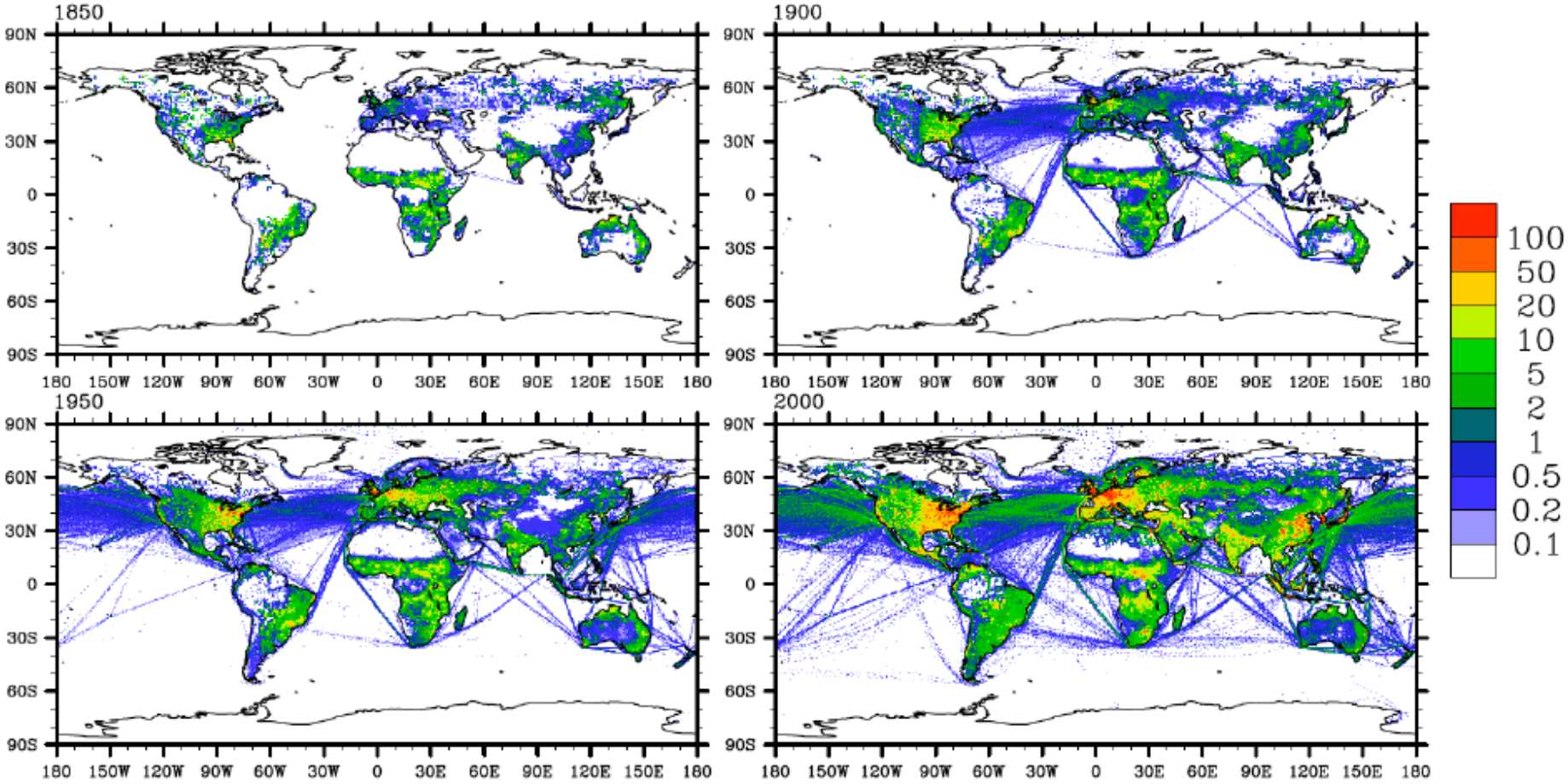
Tropospheric and Stratospheric mechanism (122 species) including
stratospheric heterogeneous reactions, about 300 reactions

CAM-Chem with Tropospheric Chemistry

Lamarque et al., 2012, GMD

Emissions: surface emissions fields, fixed boundary conditions, calculated using vegetation type (biogenic, VOC) , external forcings (aircraft emissions)

Example: NO_x emissions



Lamarque et al., 2010

Anthropogenic + biomass burning + ships: kg(N)/year

CAM-Chem with Tropospheric Chemistry

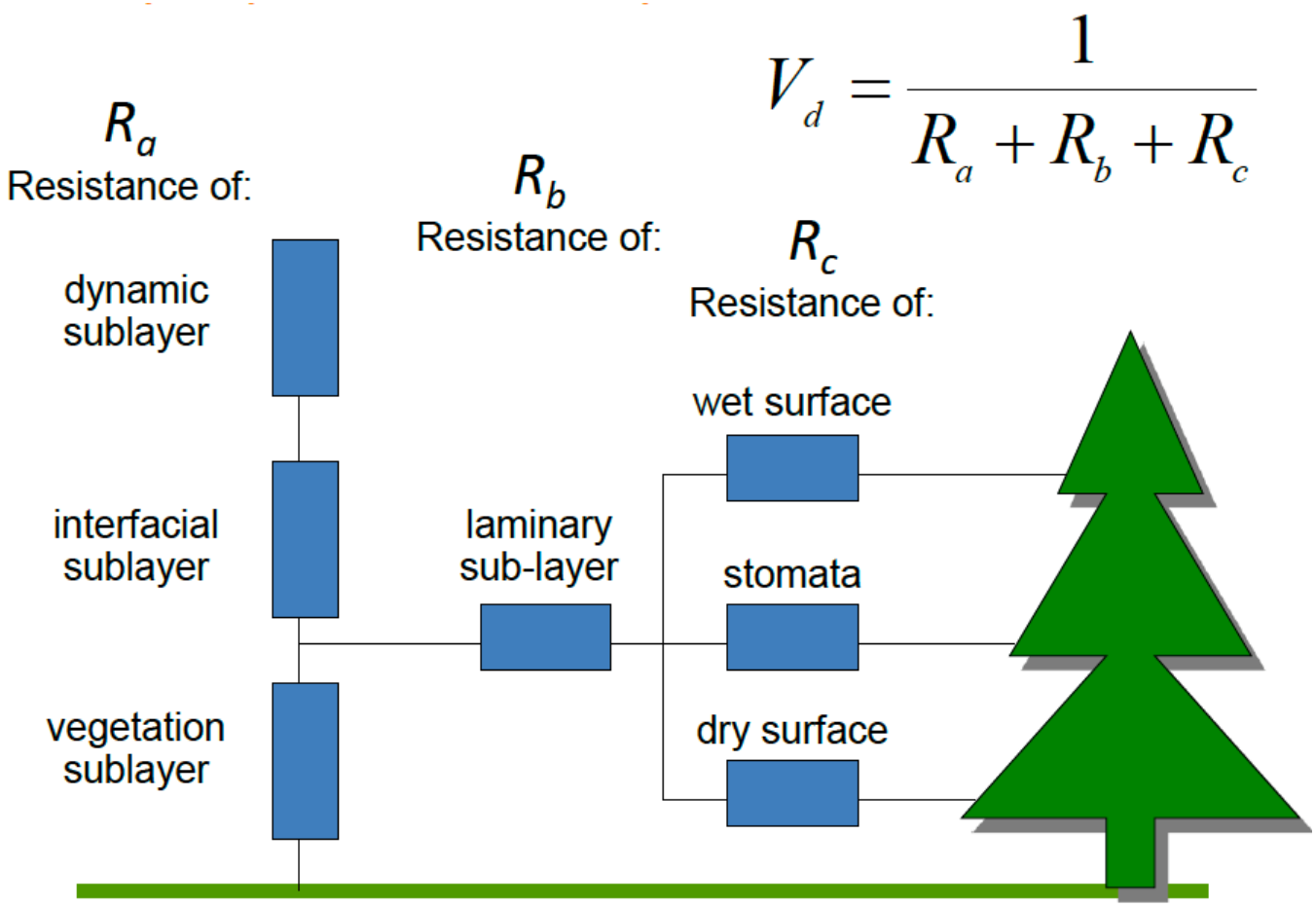
Lamarque et al., 2012, GMD

Emissions: surface emissions fields, fixed boundary conditions, calculated using vegetation type (biogenic, VOC), external forcings (aircraft emissions)

Dry Deposition: uptake of chemical constituents by plants and soil (CLM), depending on land type, roughness of surface, based on resistance approach

Dry Deposition Velocity

$$V_d = \frac{1}{R_a + R_b + R_c}$$



Deposition flux: $F = -v_d C$

C: concentration of species am 10m

CAM-Chem with Tropospheric Chemistry

Lamarque et al., 2012, GMD

Emissions: surface emissions fields, fixed boundary conditions, calculated using vegetation type (biogenic, VOC) , external forcings (aircraft emissions)

Dry Deposition: uptake of chemical constituents by plants and soil (CLM), depending on land type, roughness of surface, based on resistance approach

Wet Deposition: uptake of chemical constituents in rain or ice (linked to precipitation, both large-scale and convective).

- Removal is modeled as a simple first-order loss process

$$X_{\text{iscav}} = X_i \times F \times (1 - \exp(-\lambda \ \Delta t))$$

- X_{iscav} is the species mass (in kg) of Xi scavenged in time
- F is the fraction of the grid box from which tracer is being removed, and λ is the loss rate.

CAM-Chem with Online/Offline Meteorology

Fully coupled model:

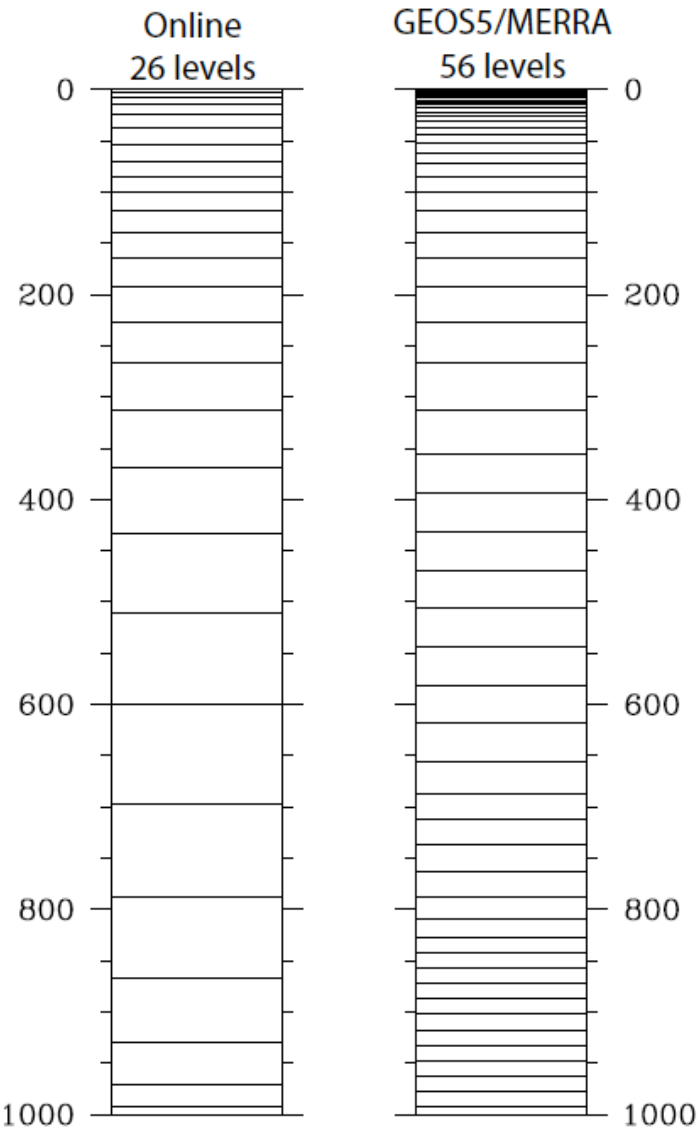
Chemistry interacts with radiation, atmosphere, land, ocean

Specified Sea/Ice distribution

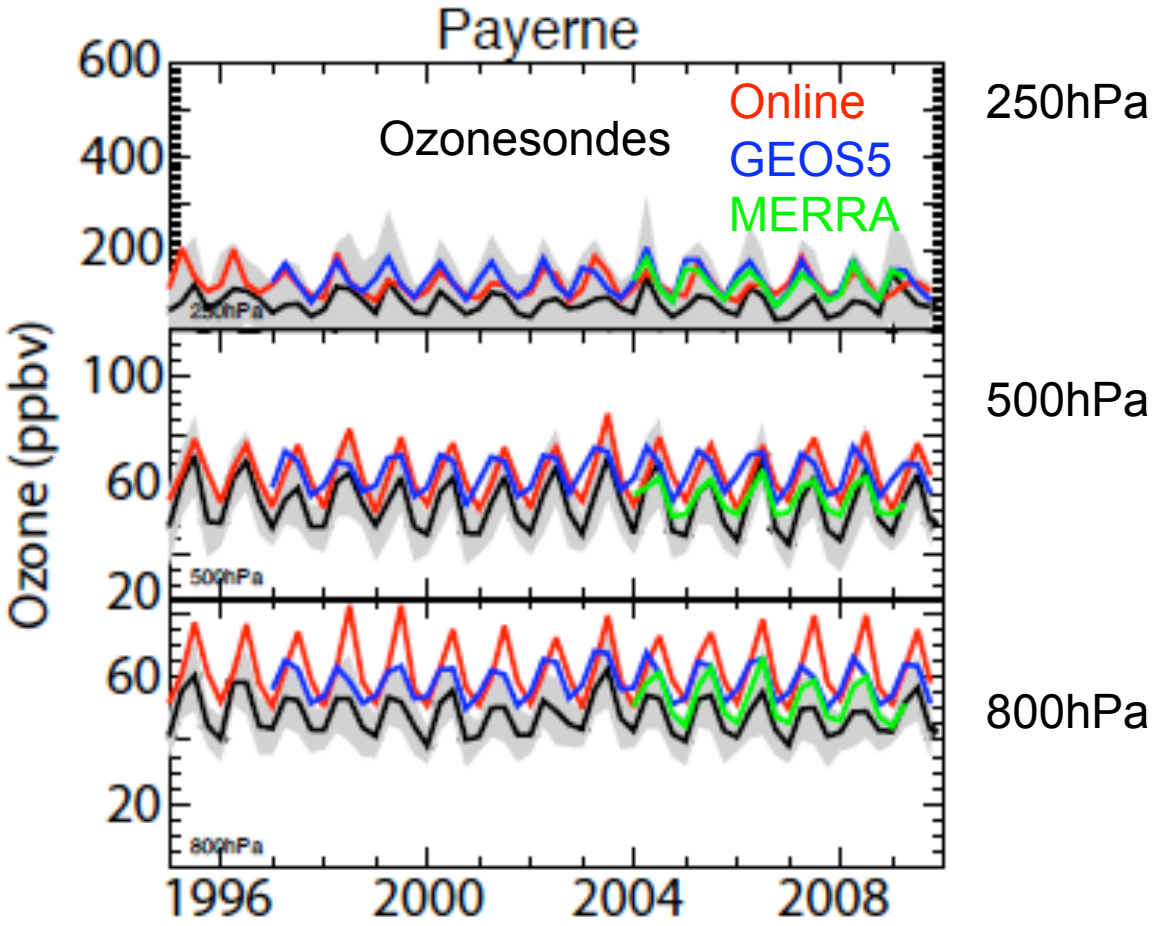
Specified Dynamics (offline) model:

Meteorological Data are prescribed or nudge (%) for defined altitudes

Nudging: the amount and altitudes of nudging cam be defined



CAM-Chem with Online/Offline Meteorology



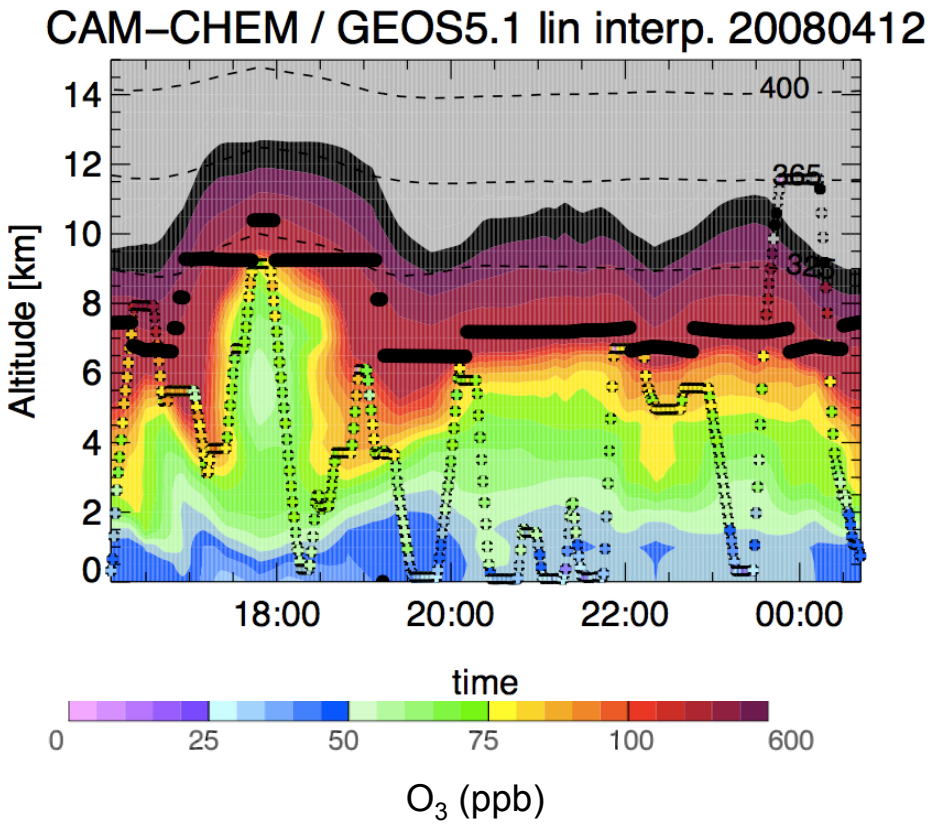
250hPa

500hPa

800hPa

Lamarque et al., 2012

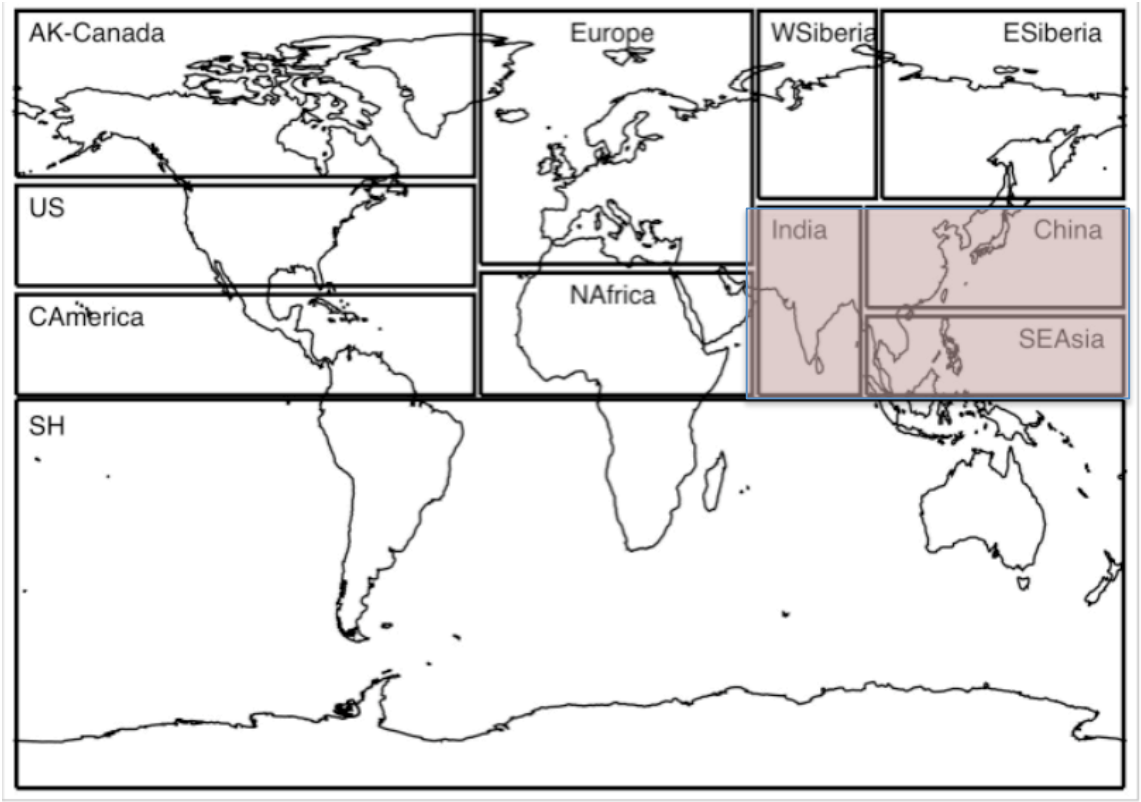
CAM-Chem with Offline Meteorology



Comparisons to Aircraft campaigns:
Model output on the flight path for direct comparison

O_3, CO, BC tags with Offline Meteorology

Emmons et al., 2012, GMDD



South Asia

The Model for Ozone and Related chemical Tracers (MOZART4)

Resolution: T85 (1.4°x1.4°)

Meteorology: NCEP/GFS

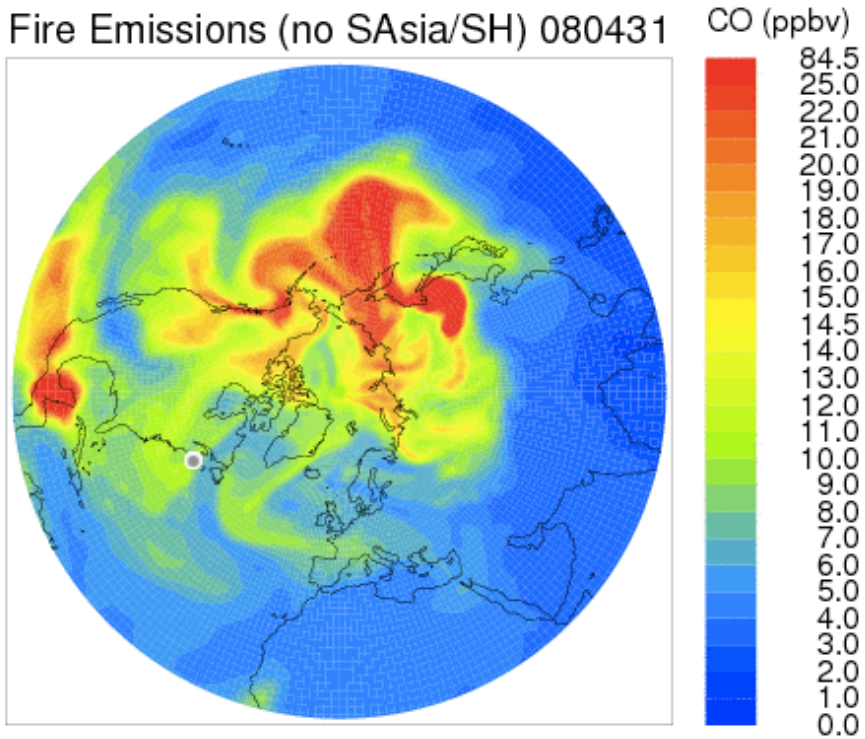
Emissions: Streets ARCTAS emissions + daily fires (C.Wiedinmyer)

Vertical Injection of Fire Emission between 0-6 km

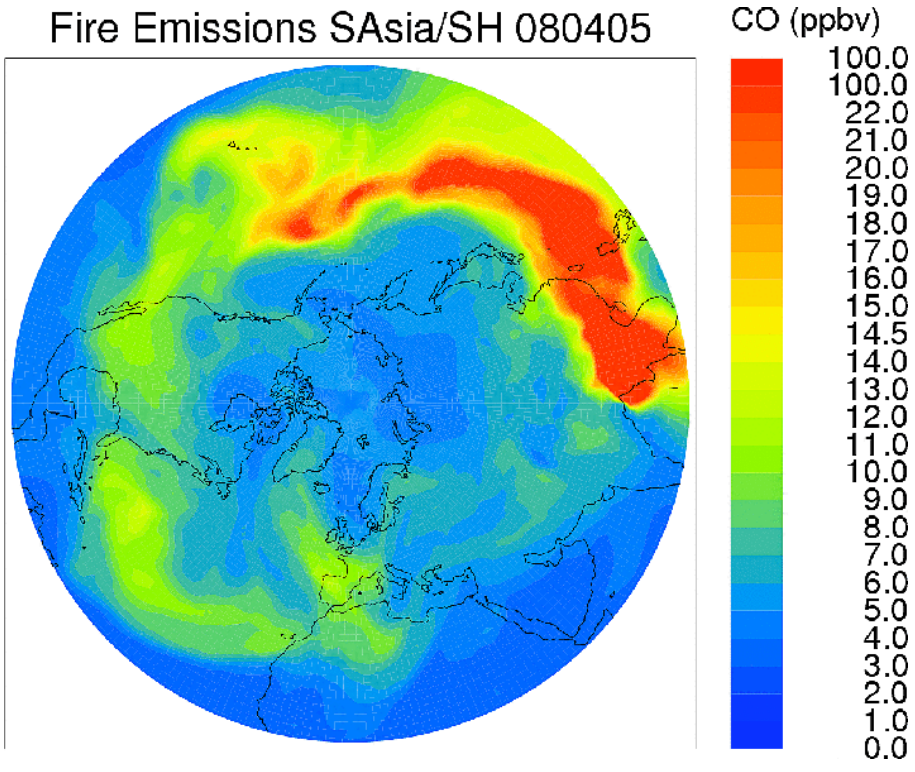
Importance of Fire Emissions

April

without South Asia and SH



South Asia and SH only



CO averaged column between surf. and 200 hPa

Aerosols

Direct Effects:

- Radiation (scattering/absorbing)

Indirect Effects:

- Changes in cloud properties (consistency, reflectivity), precipitation

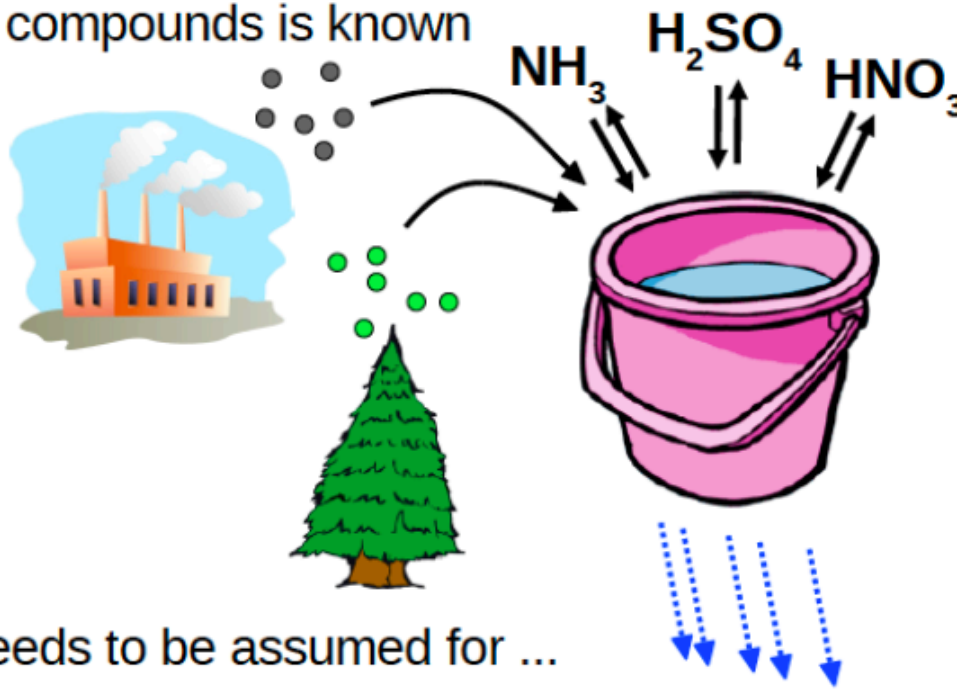
Controlled by: Emissions, Nucleation processes, Deposition

Aerosols in CESM:

- Bulk Aerosols Model (BAM)
- Modal aerosol Model (MAM)

Bulk aerosol scheme

- Only total mass of aerosol compounds is known
- No information on
  - Particle number
  - Aerosol size distribution

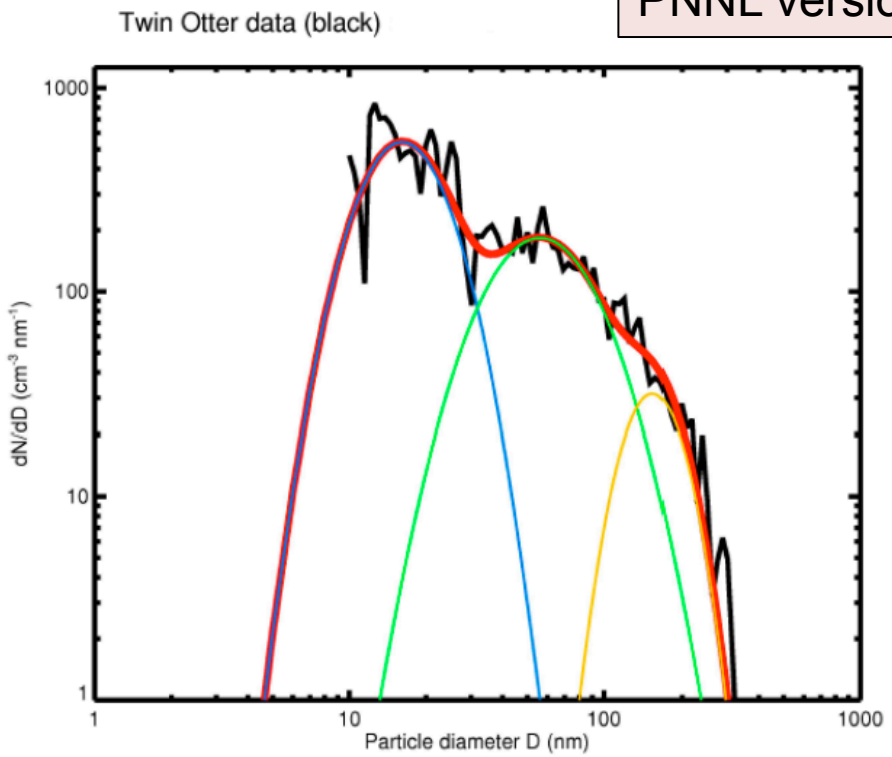


- Aerosol size distribution needs to be assumed for ...
  - radiative transfer
  - response of cloud properties to aerosol number
- Can't do aerosol nucleation
- **Numerically efficient**
- **Useful when focus is on complex gas phase / aerosol chemistry**

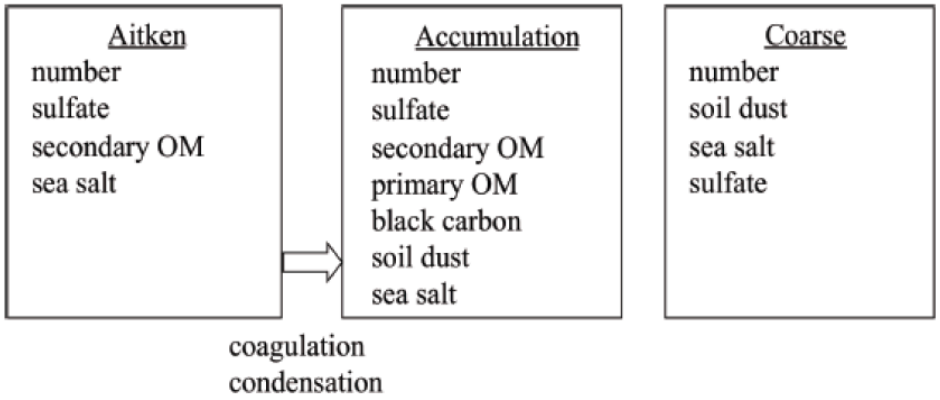
From J. Kazil, CIRES

Modal Aerosol Model (MAM3)

CESM CAM5
Aerosol size distribution using 3 modes
PNNL version exists with 7 Modes.

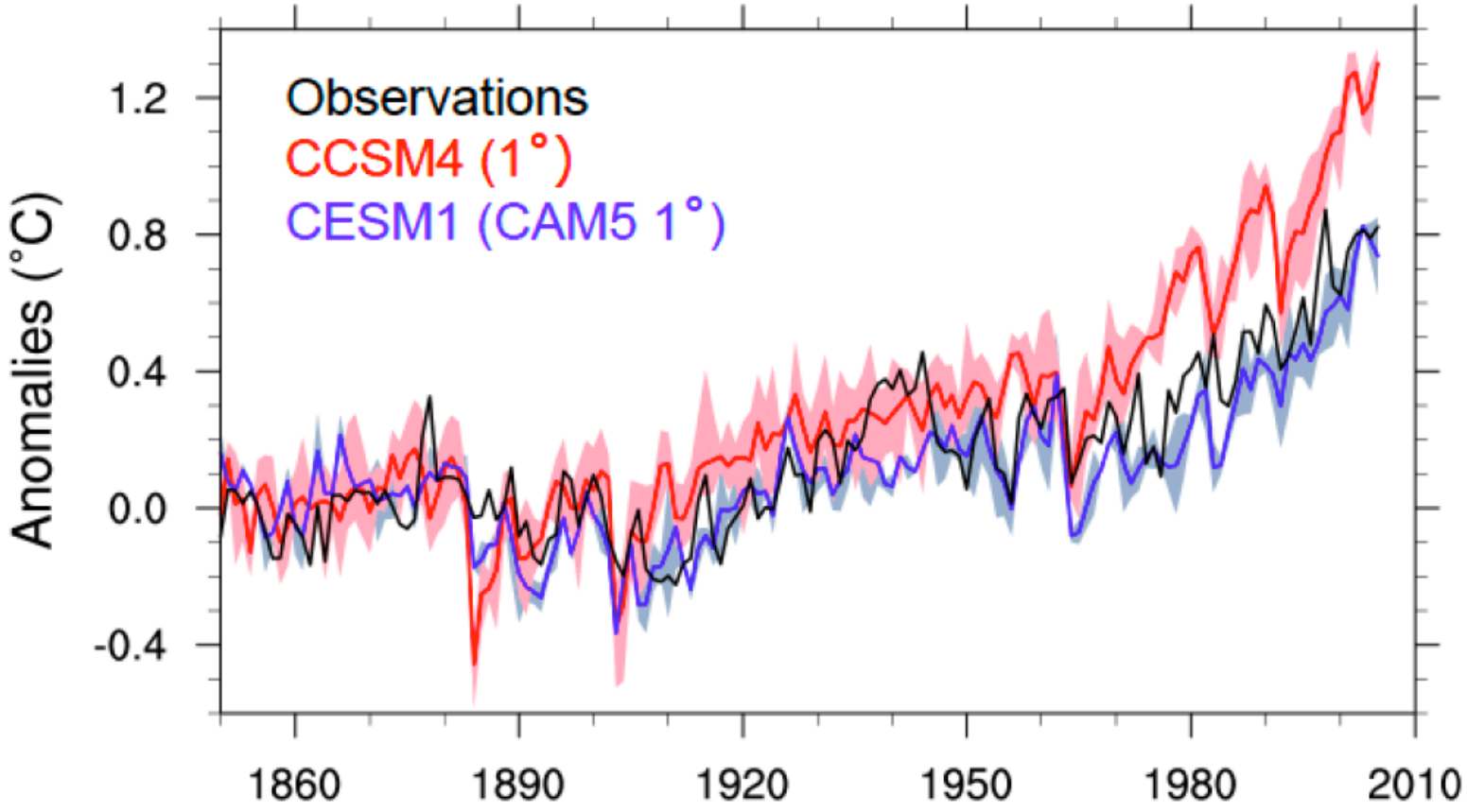


From J. Kazil, CIRES



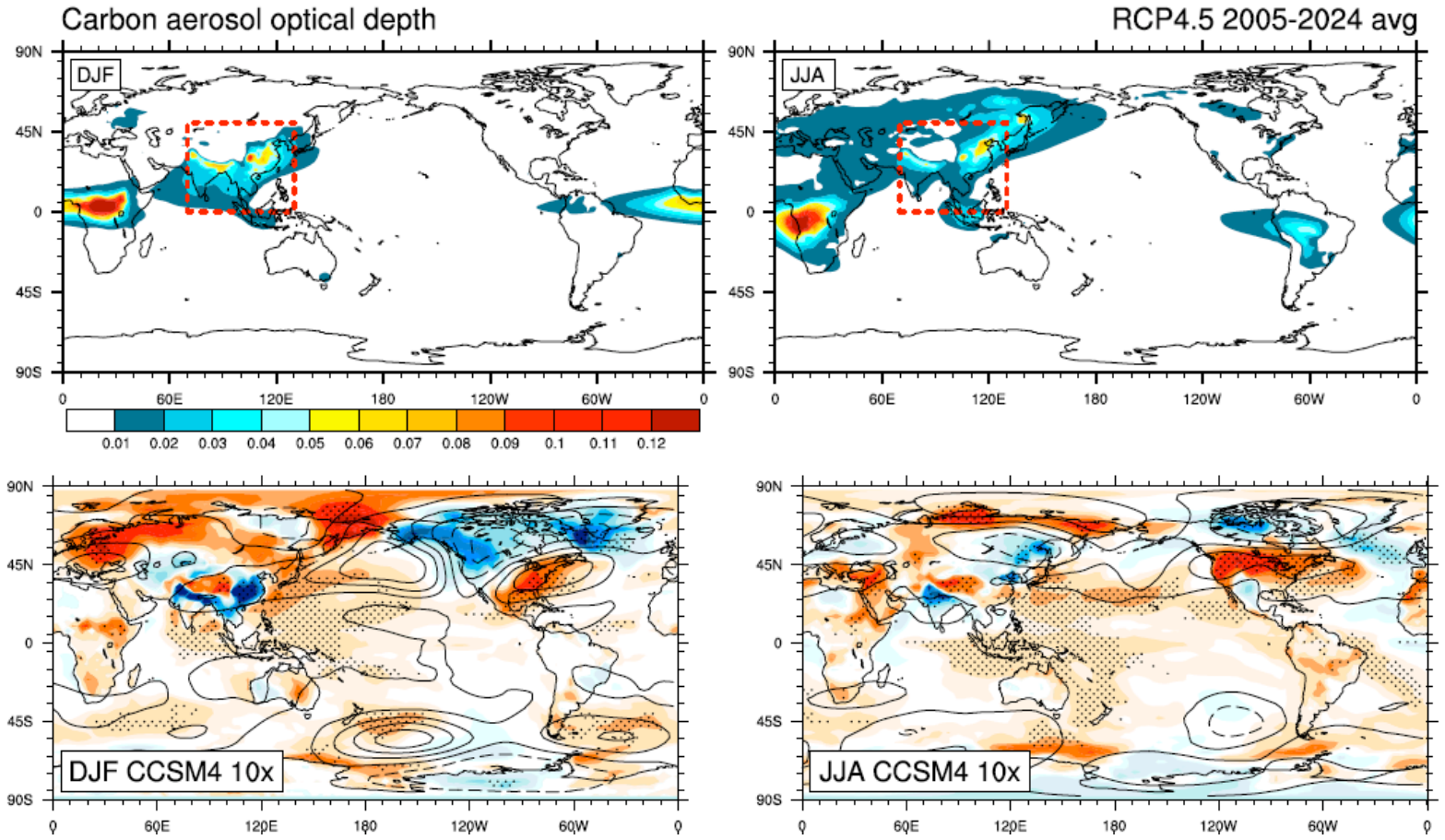
Liu et al., 2011

Modal Aerosol Model (in CESM)



Single forcing Experiment

Teng et al., 2012



10x increase of organic and black carbon over South-East Asia -> temperature response in the US

Modal Aerosol Model (in CESM)

MAM available with CAM5 physics
Adds ~ 25 species and simple chemistry (“fixed” oxidants)

Work in progress:
CAM5Chem: Chemistry is couple to MAM3
Better description of SOA