Chemistry, aerosols and WACCM

Jean-François Lamarque
NESL/ACD and CGD

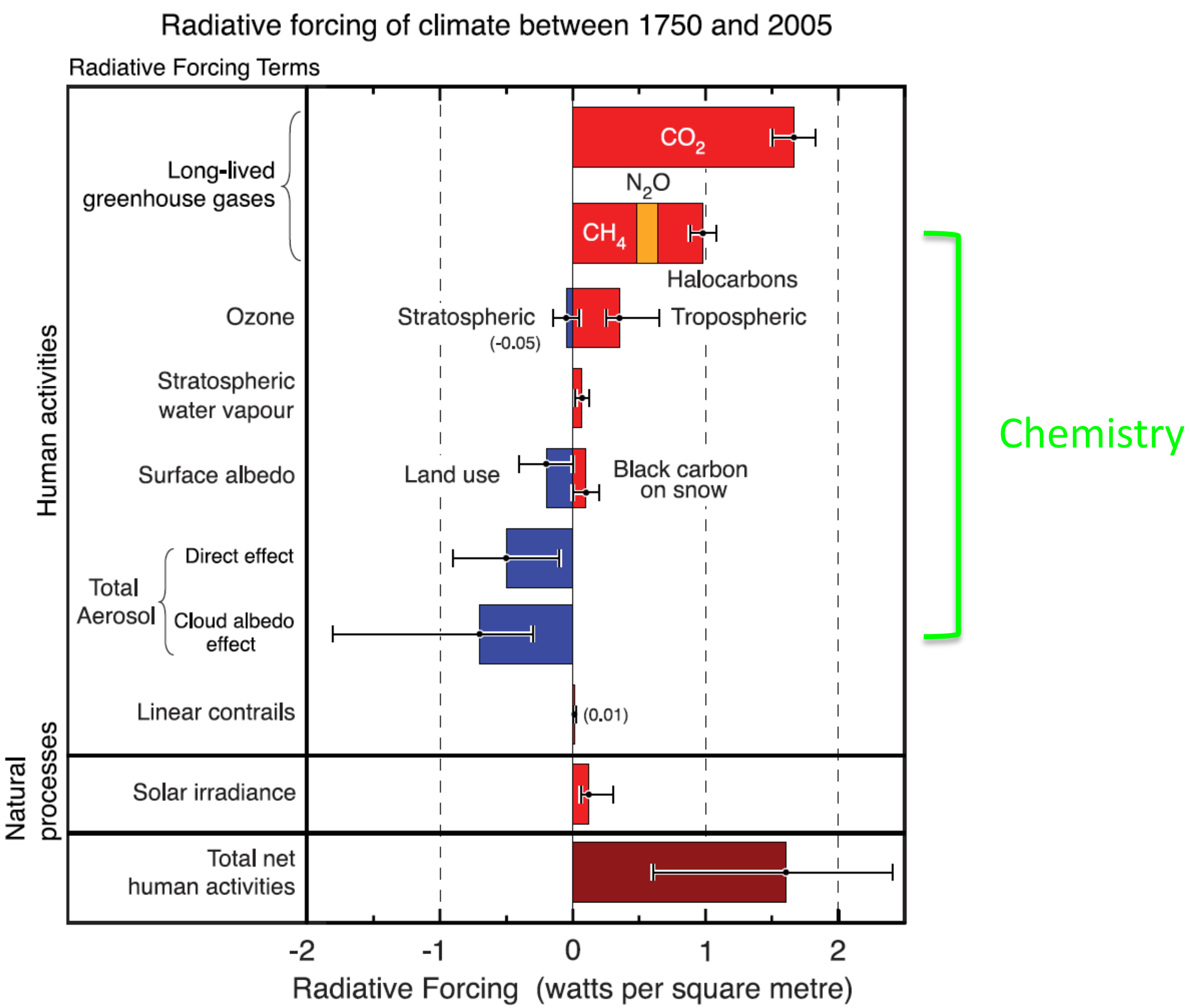
With much input from ChemClimWG and WaccmWG members

Outline

- Chemistry in CESM
  - Motivation
  - Results from several configurations
- Modal aerosols (aka CAM5)
- WACCM

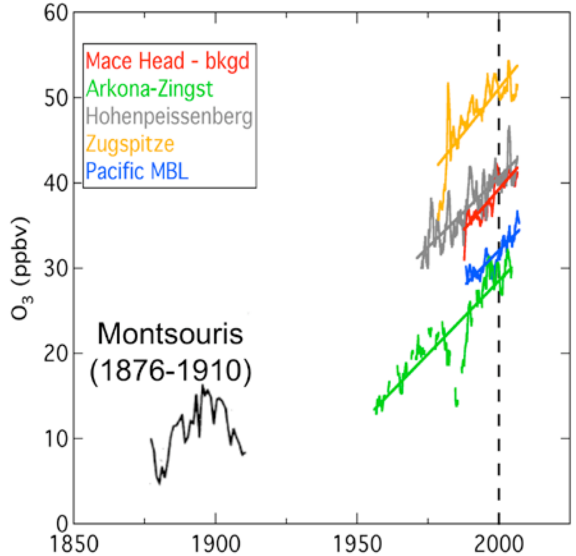
CHEMISTRY IN CESM

Radiative forcing

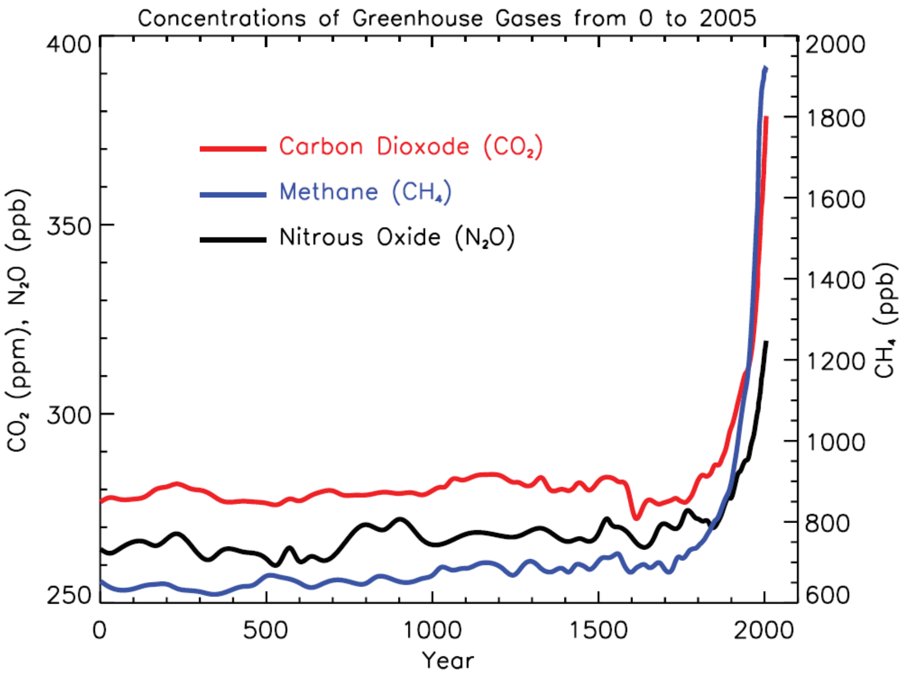


Forster and Ramaswamy. AR4 Chapter 2

Changing composition



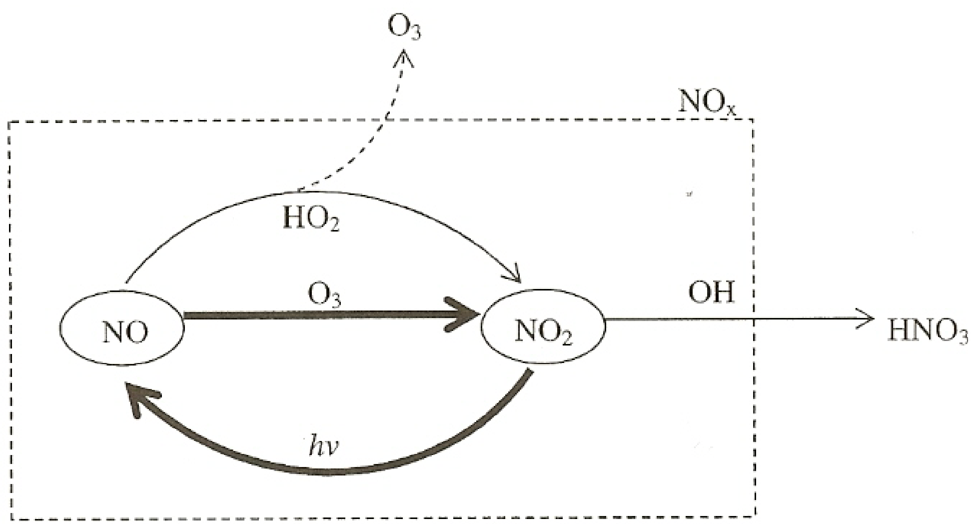
Surface ozone 1850-2000 from obs. Slide from D. Parrish.



Tropospheric ozone production

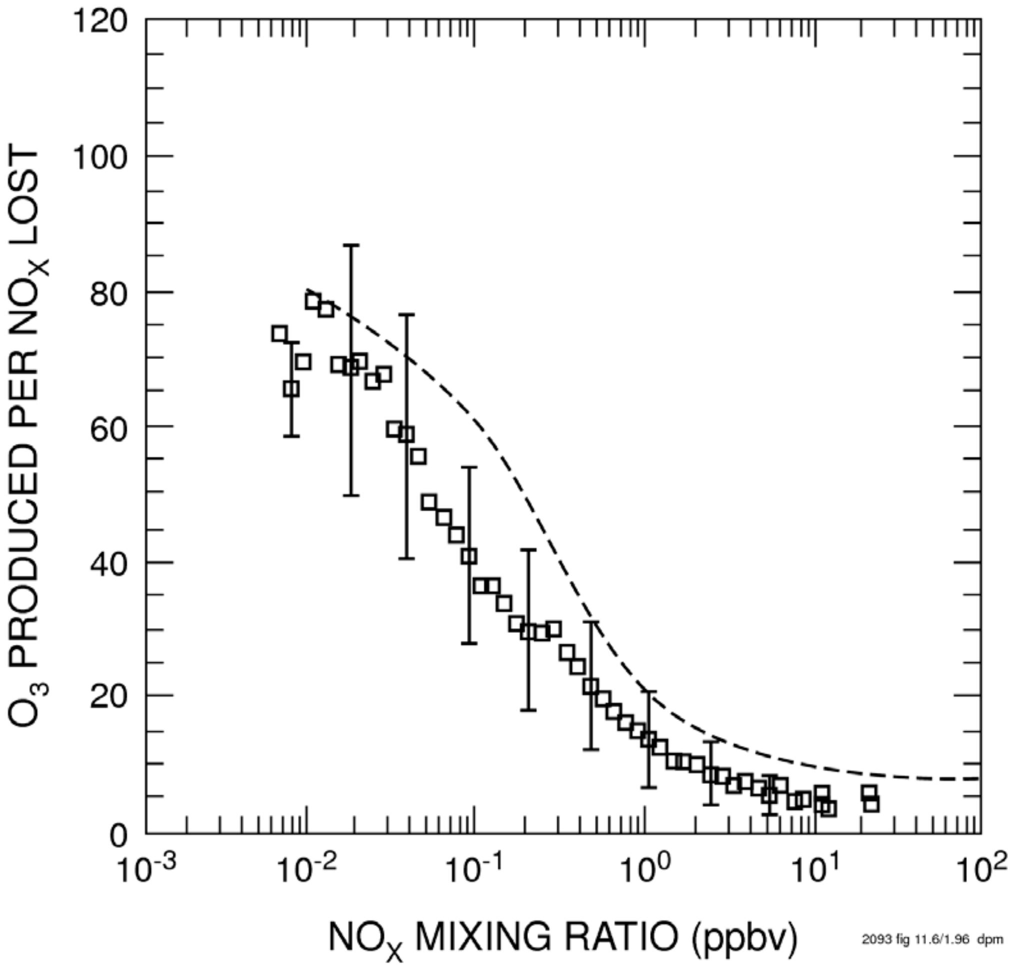
$$CO + OH \xrightarrow{O_2} CO_2 + HO_2$$
$$HO_2 + NO \longrightarrow NO_2 + OH$$
$$NO_2 + h\nu \xrightarrow{O_2} NO + O_3$$
$$\text{Net: } CO + 2O_2 + h\nu \longrightarrow CO_2 + O_3$$

$NO_x = NO + NO_2$

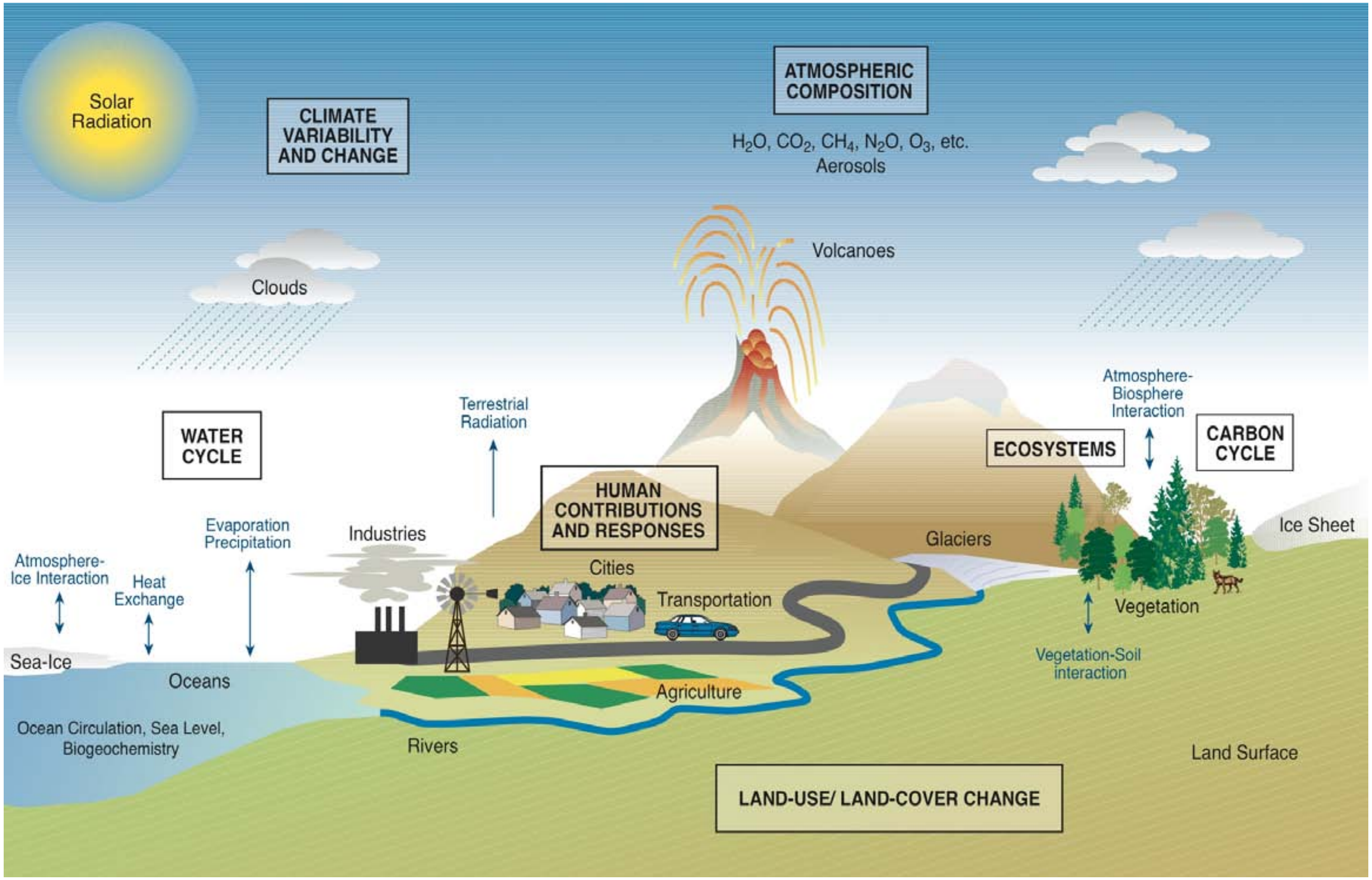


From Seinfeld and Pandis, 2007

Ozone, NOx and VOCs

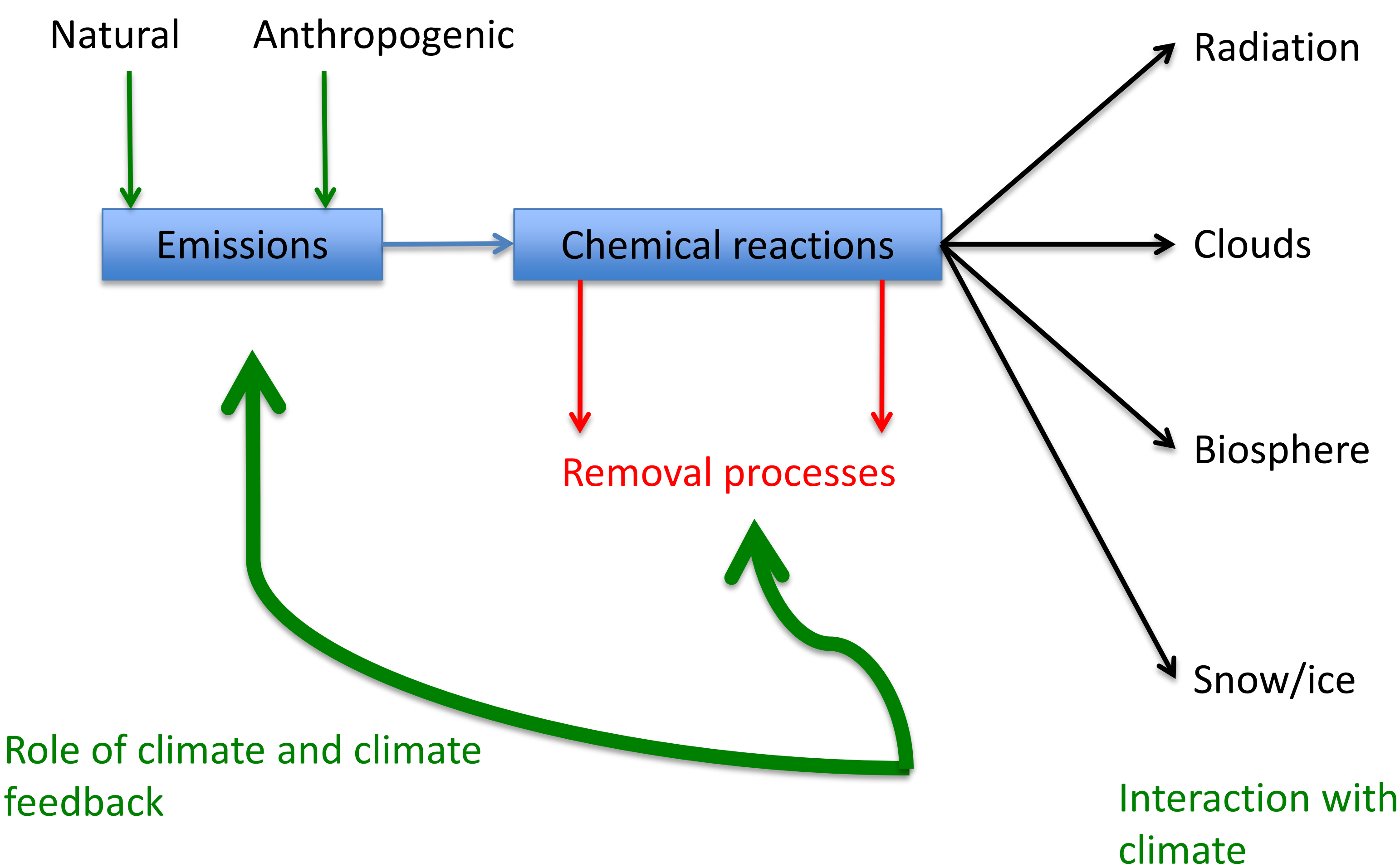


Chemistry in climate world

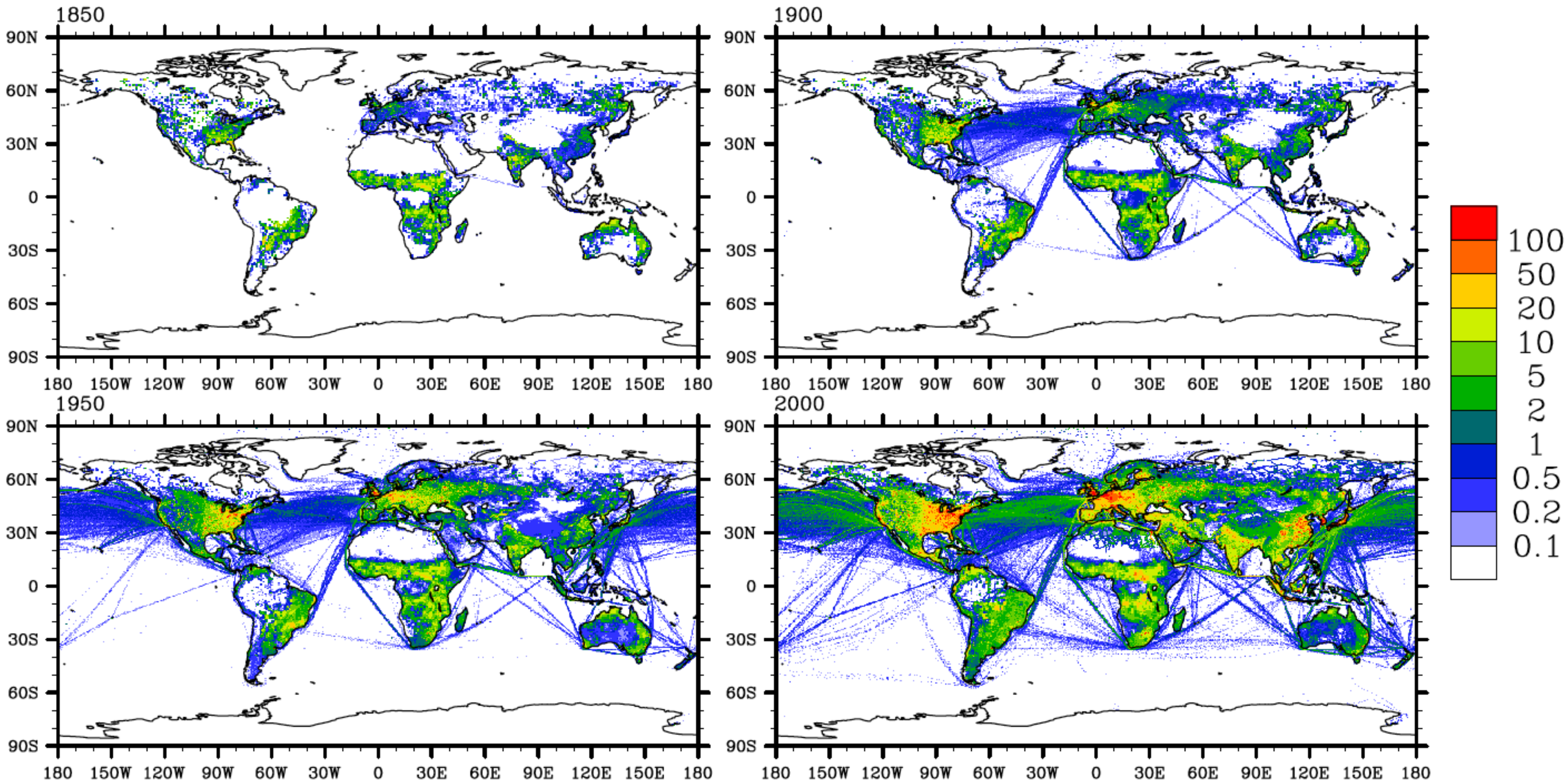


Moss et al., 2010

Chemistry in an Earth System Model



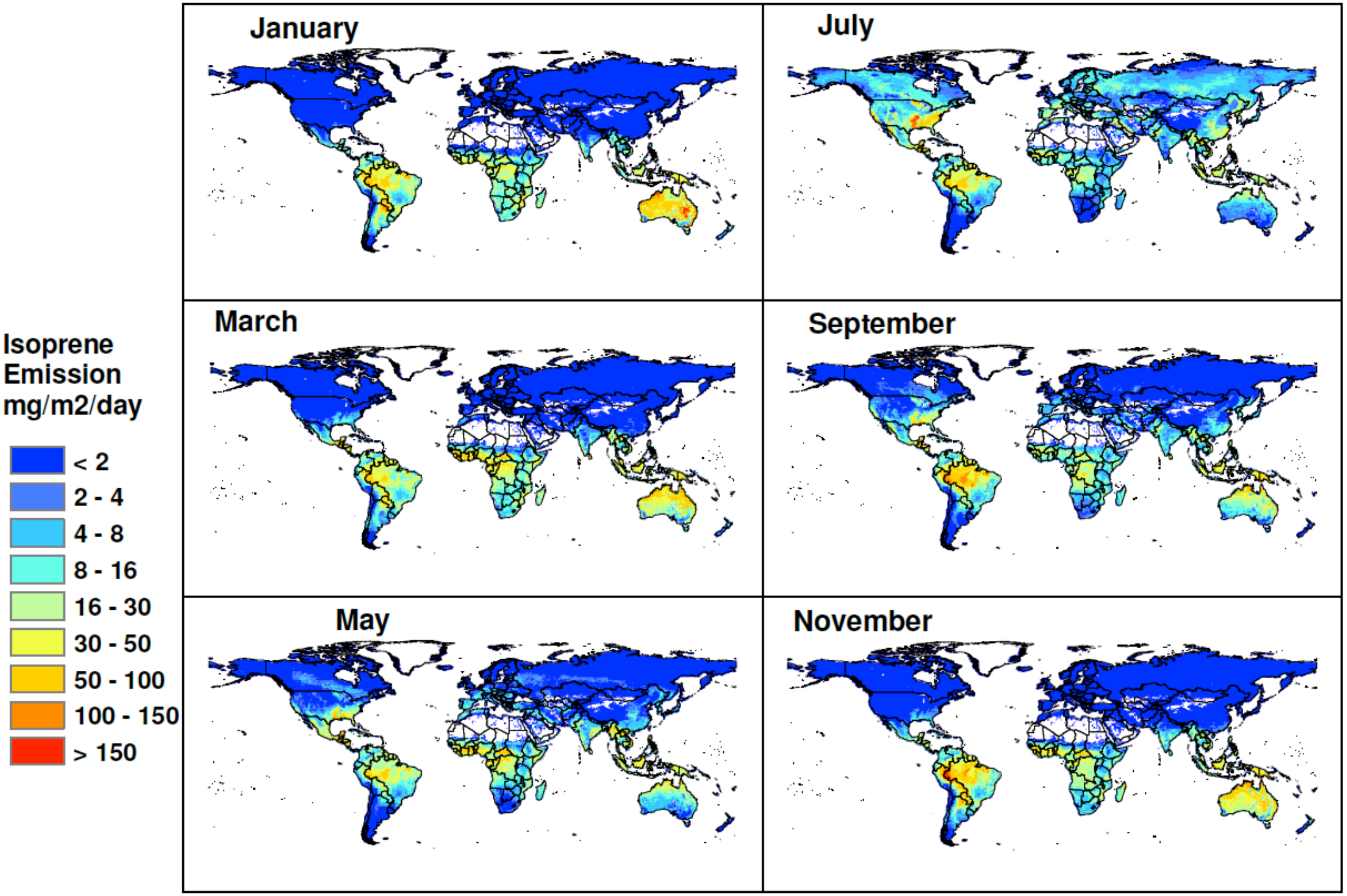
Example: NO_x emissions



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

Lamarque et al., ACP, 2010

Isoprene emissions in CLM



Deposition processes

- Dry deposition: uptake of chemical constituents by plants and soil (handled by CLM), water
- Wet deposition: uptake of chemical constituents in rain or ice (linked to precipitation, both large-scale and convective)

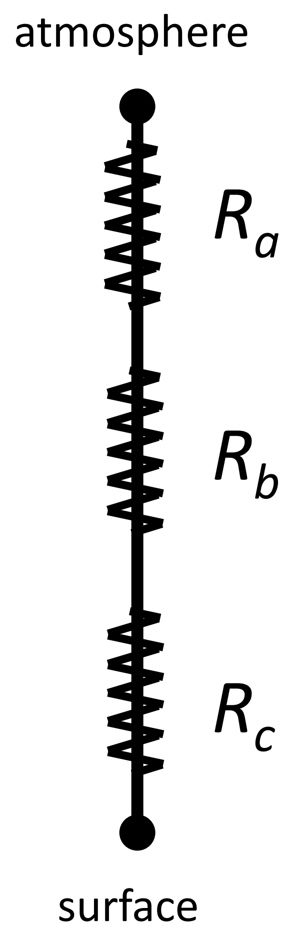
Dry deposition

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

R_a = aerodynamic resistance.
R_b = quasi laminar boundary layer resistance
R_c = canopy resistance

Deposition flux: $$F = -v_d C$$

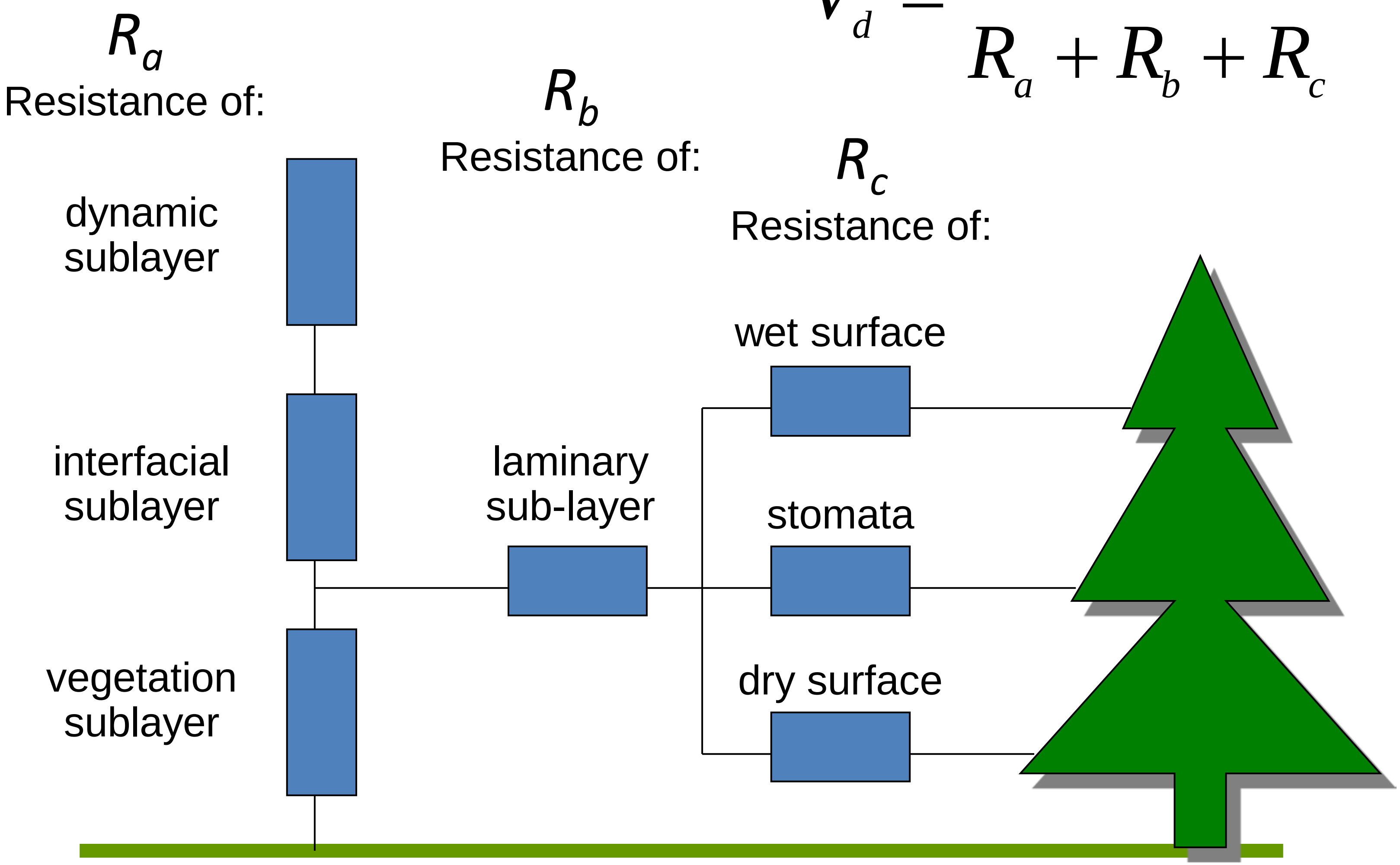
v_d: deposition velocity
C: concentration of species at reference height (~10 m)



Seinfeld & Pandis, 1998

Dry deposition velocity

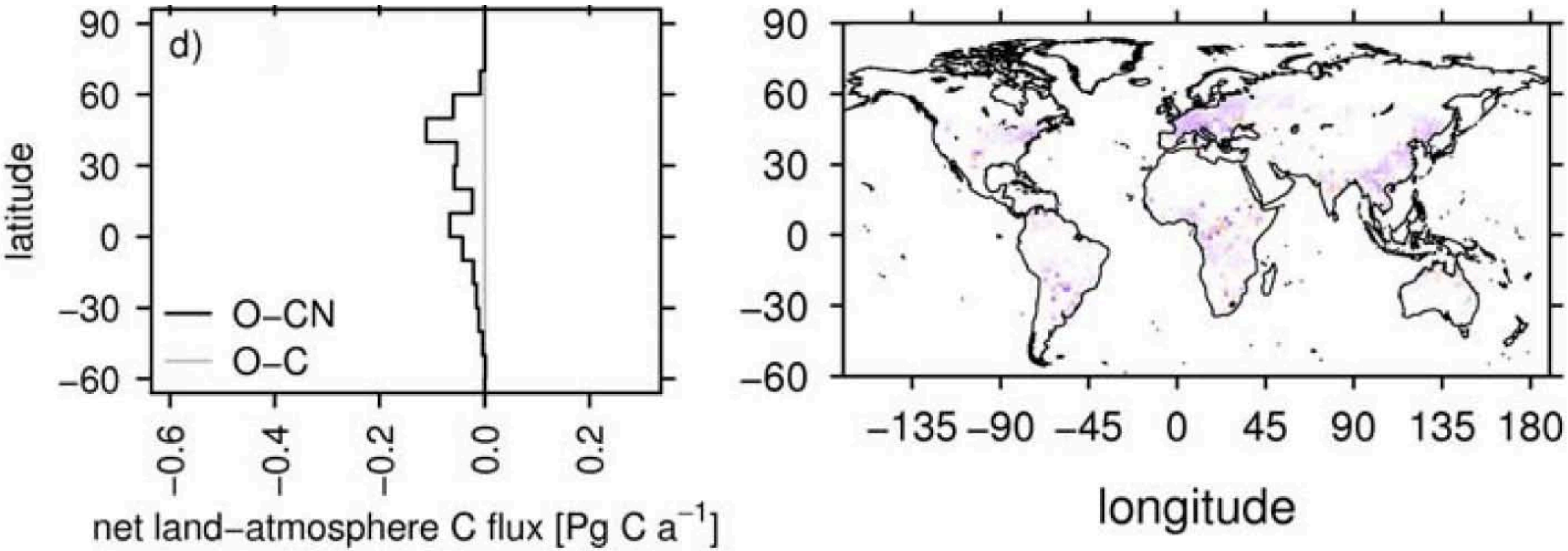
$$V_d = \frac{1}{R_a + R_b + R_c}$$



Deposition processes

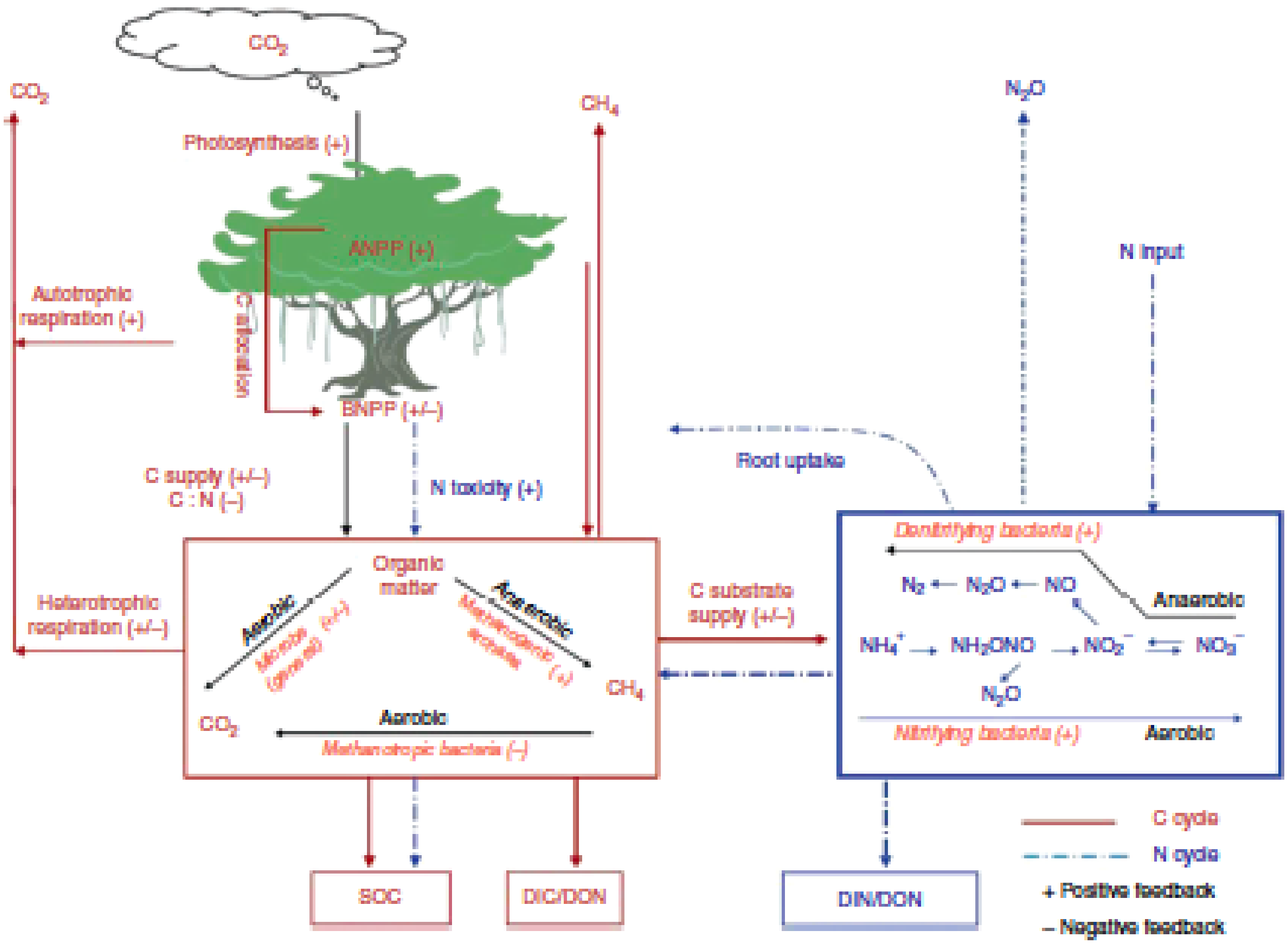
- Dry deposition: uptake of chemical constituents by plants and soil (handled by CLM), water
- Wet deposition: uptake of chemical constituents in rain or ice (linked to precipitation, both large-scale and convective)

Impact of N deposition on C uptake



Zaehne et al., 2010

Impact of nitrogen deposition

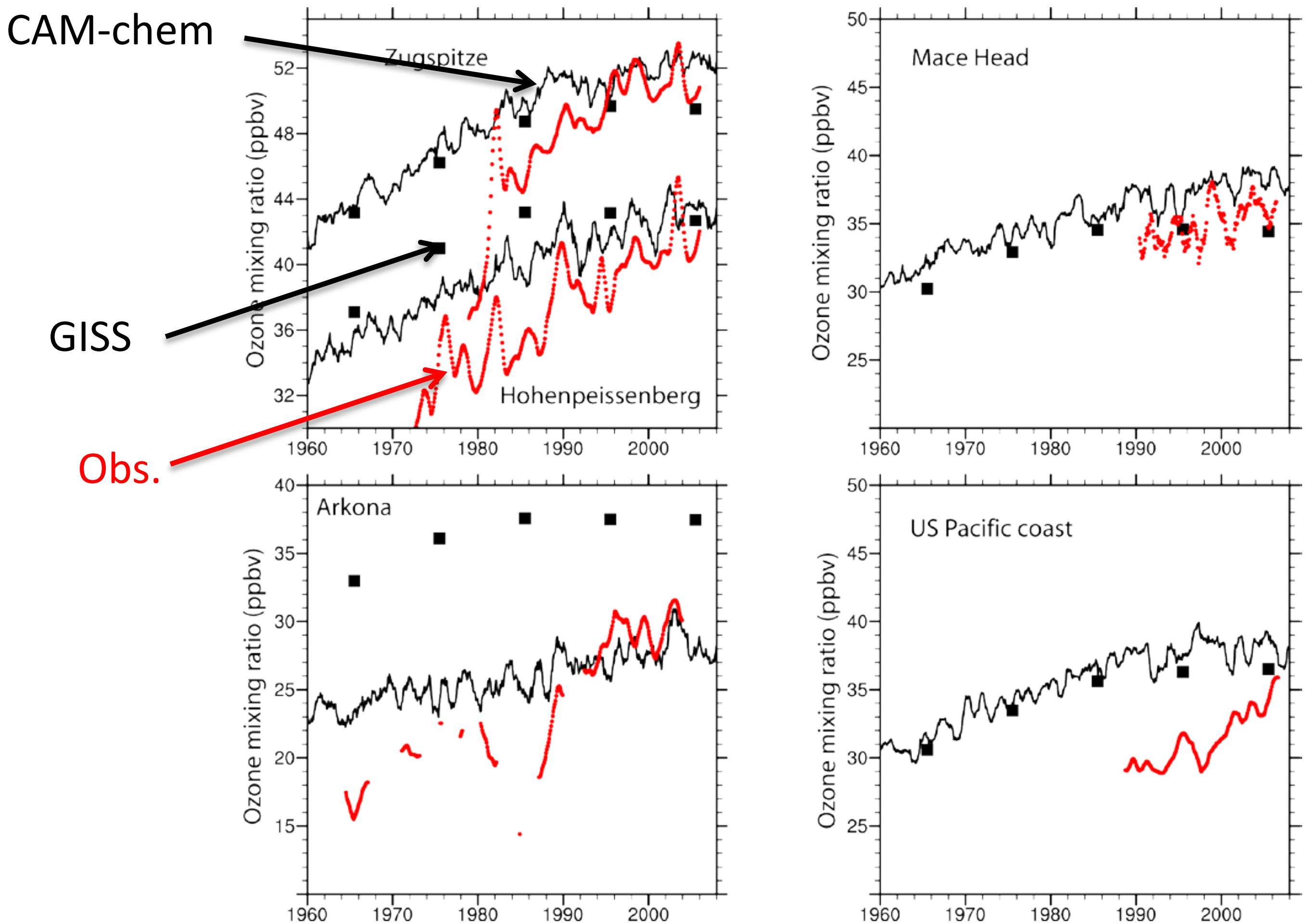


European Nitrogen Assessment,2011

CAM with chemistry

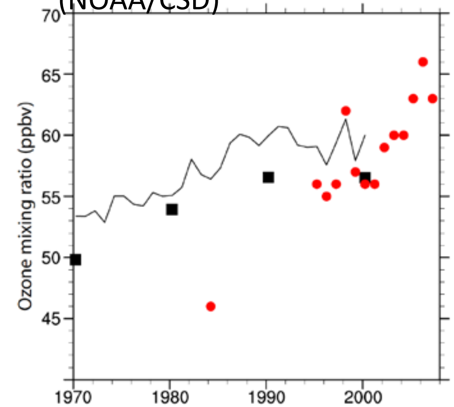
- Surface to 40 km, 1.9°x2.5°, 1850-2100
- Atmosphere-land only (SSTs from CCSM3 simulation)
- 81 species (version evaluated in CCMval-2)
  - Reduced NMHC chemistry + isoprene
  - Stratospheric chemistry (including PSCs)
  - Bulk aerosols (incl. SOA)
- Emissions for short-lived species (natural emission are constant!)
- Concentrations for long-lived species

Trends: surface ozone



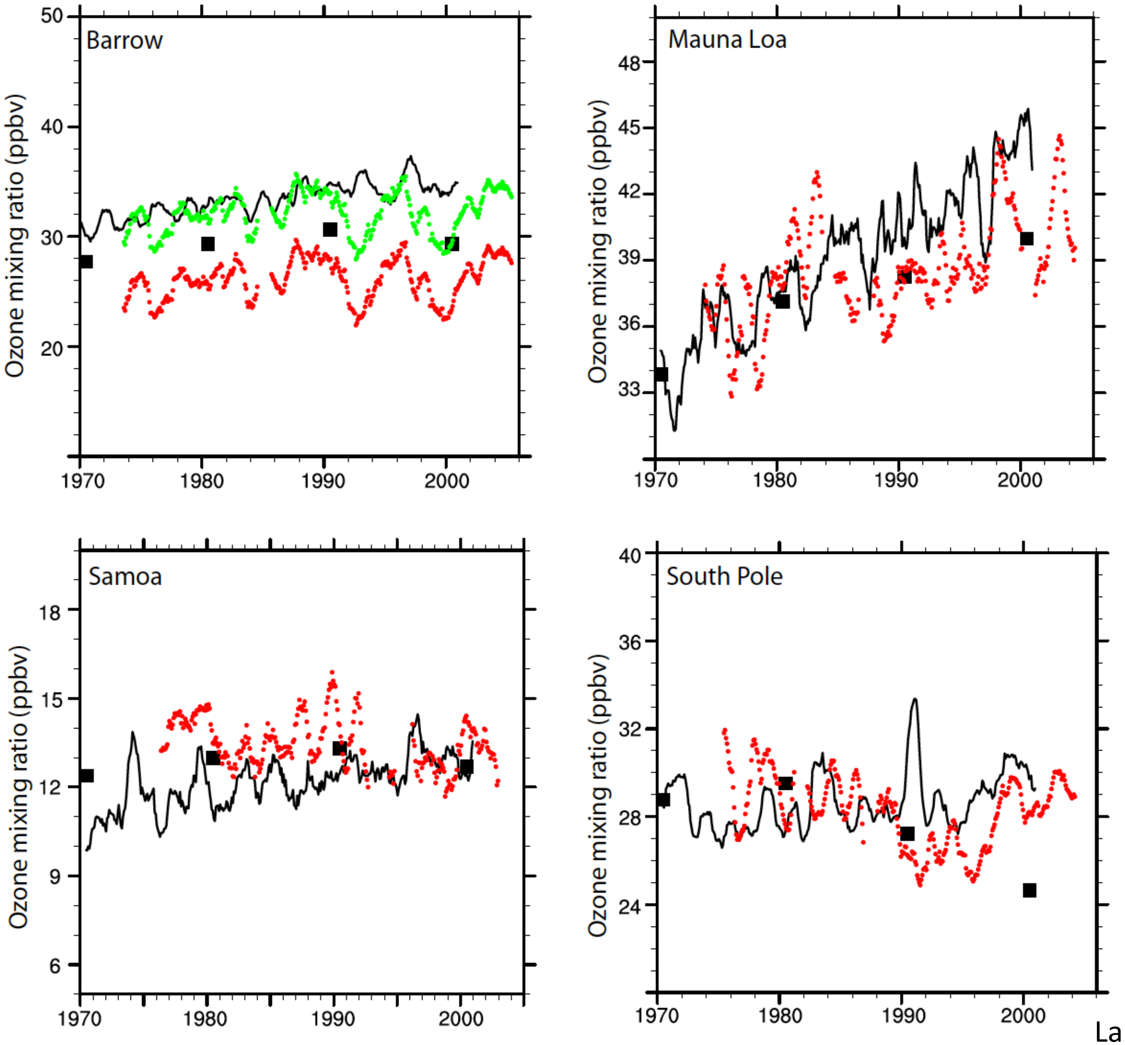
Obs. provided by D. Parrish (NOAA/CSD)

Obs. provided by O. Cooper (NOAA/CSD)



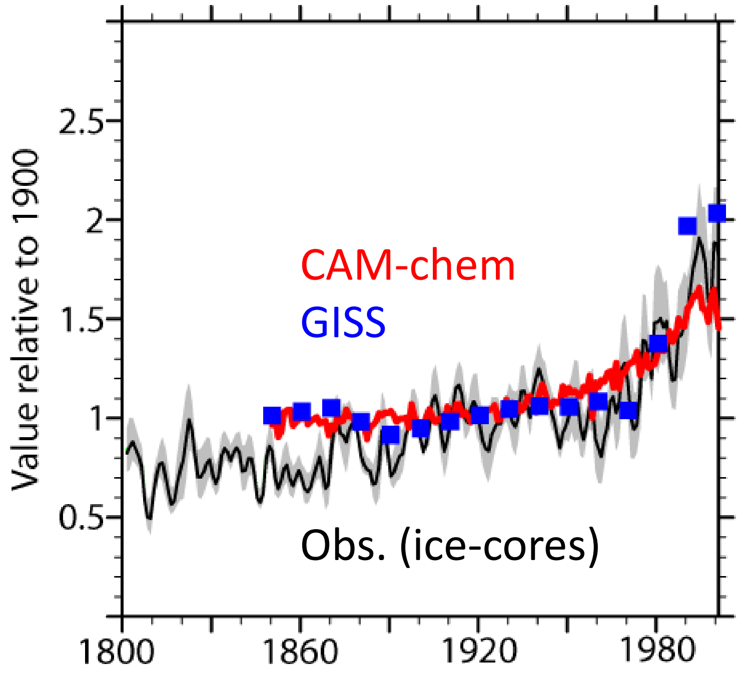
Application: historical surface ozone

Obs. provided by D. Parrish (NOAA/CSD)



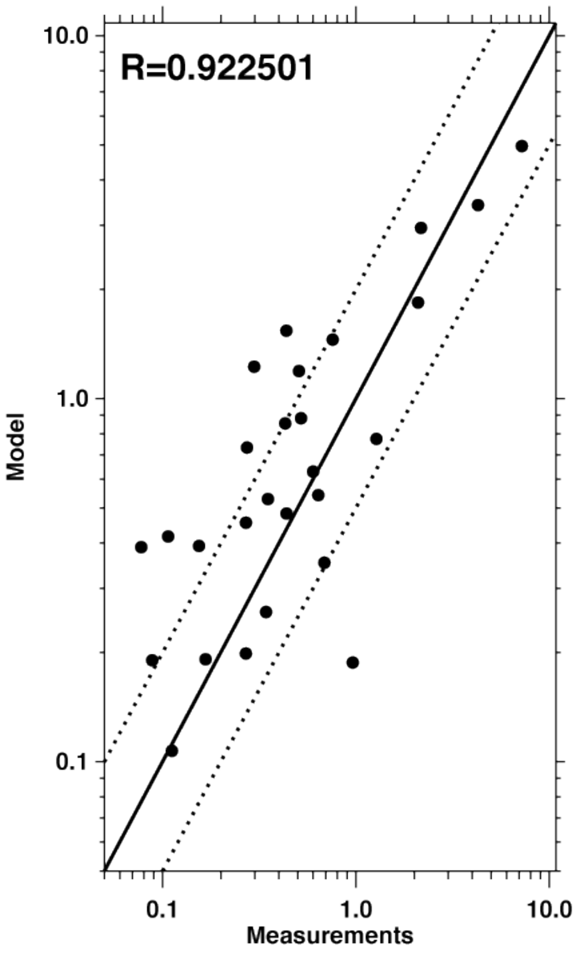
Lamarque et al., ACP, 2010

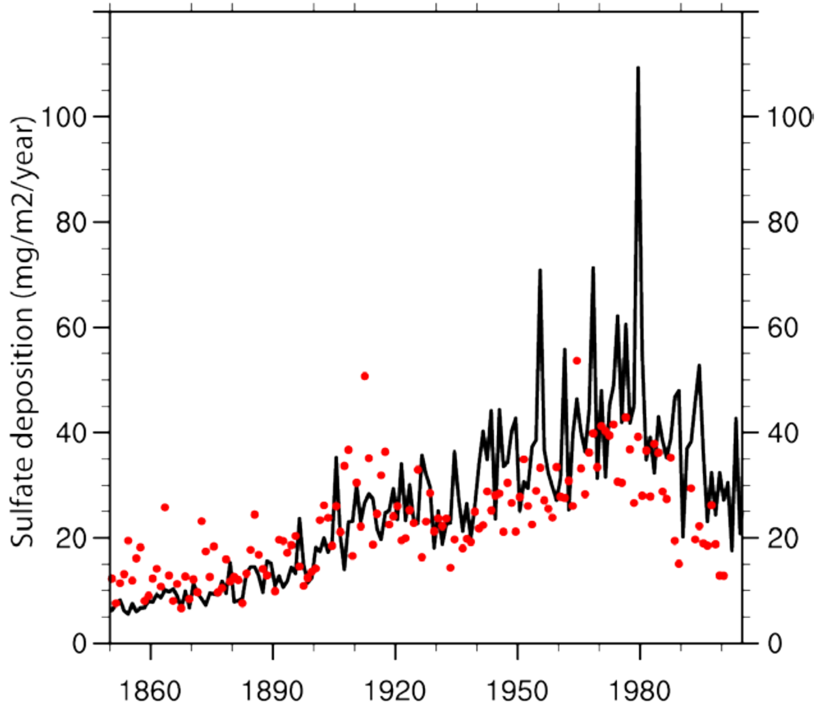
Antarctic H_2O_2



Lamarque et al., GRL, 2011

Sulfate aerosols

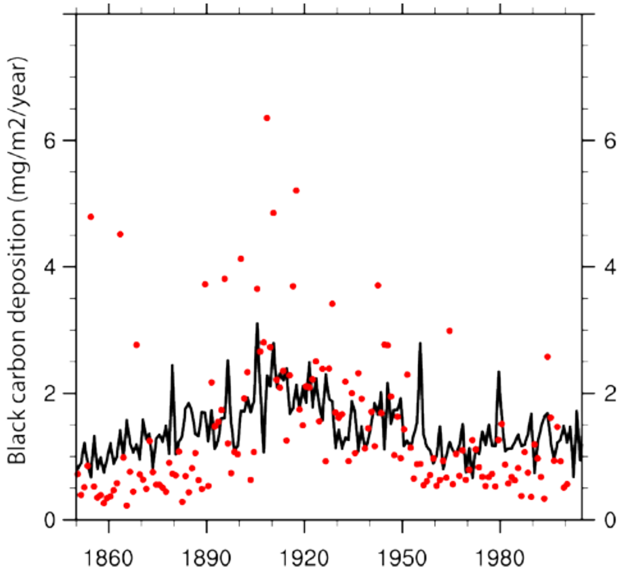




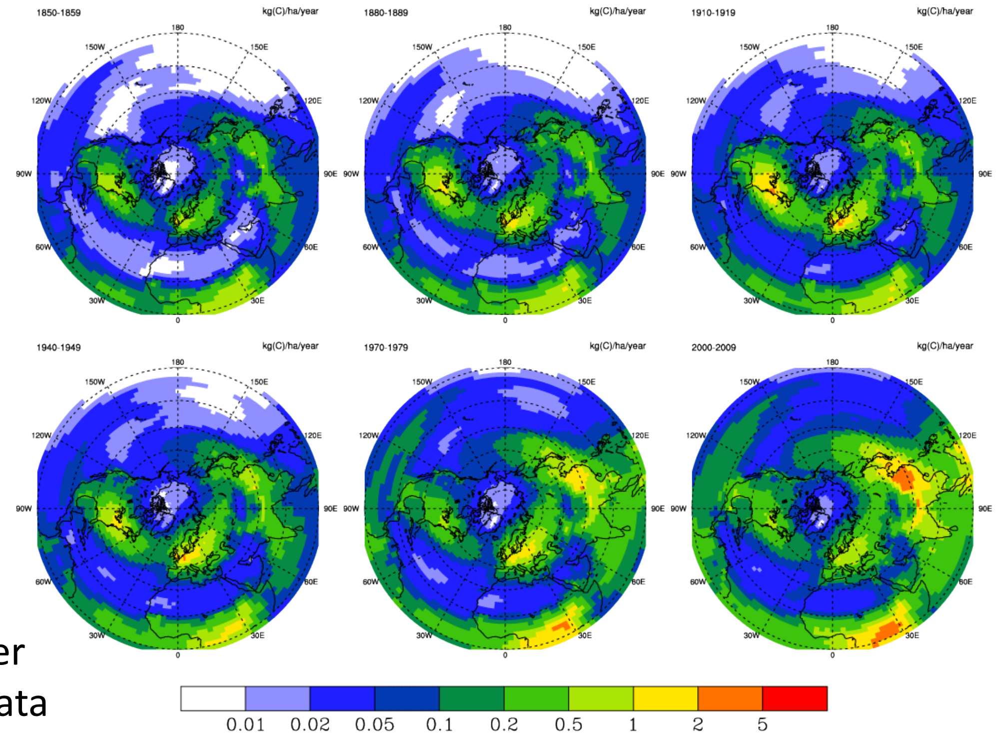
Deposition rate (annual average) over Greenland (D4 site) of sulfate vs. year. Data from J. McConnell (DRI).

Lamarque et al., ACP, 2010

Black carbon

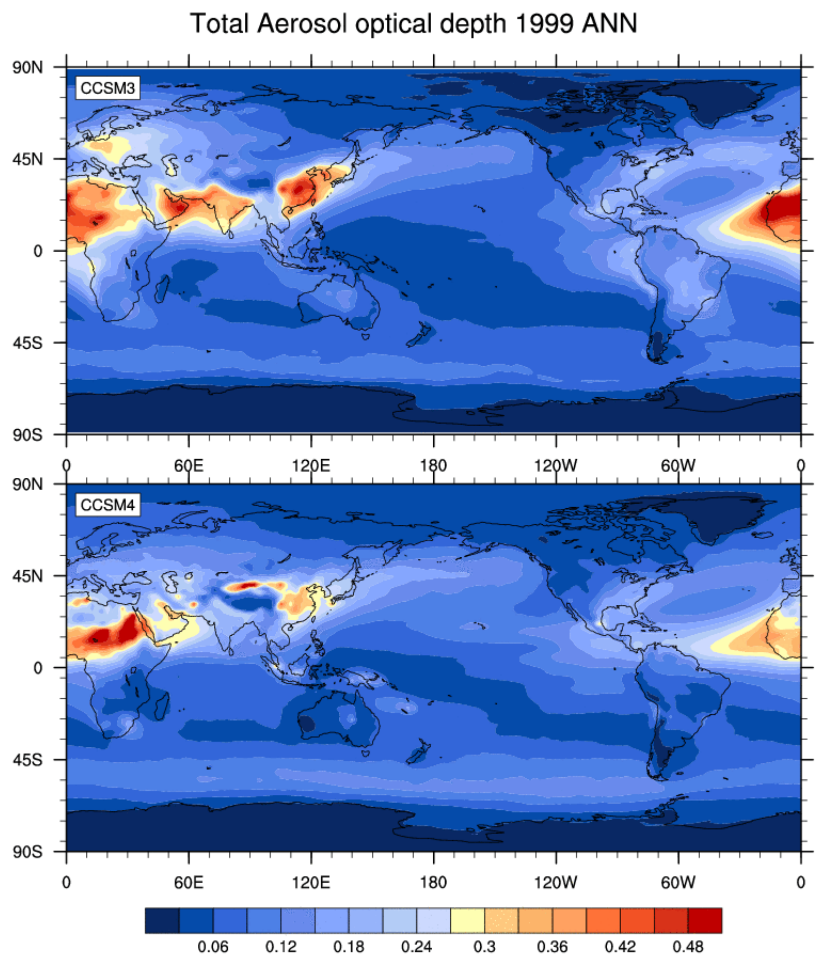


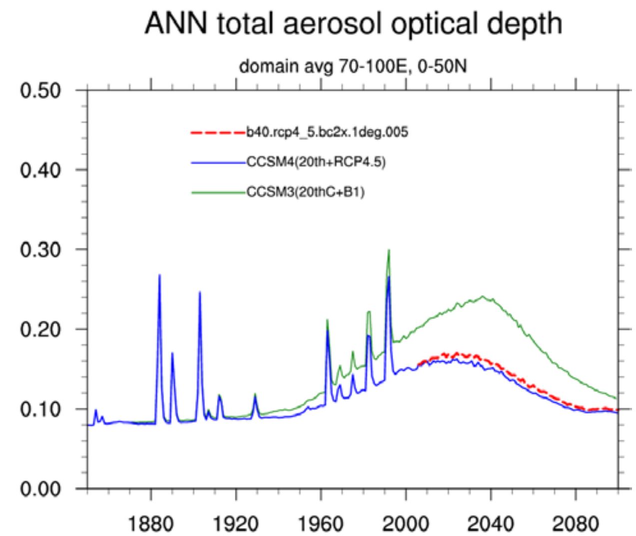
Deposition rate (annual average) over Greenland (D4 site) of BC vs. year. Data from J. McConnell (DRI).

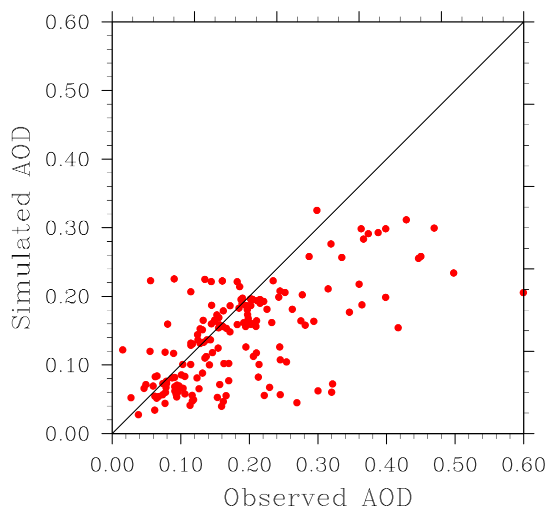


Lamarque et al., ACP, 2010

Comparison with CCSM3







Figures courtesy of Haiyan Teng

Lamarque et al., ACP, 2010

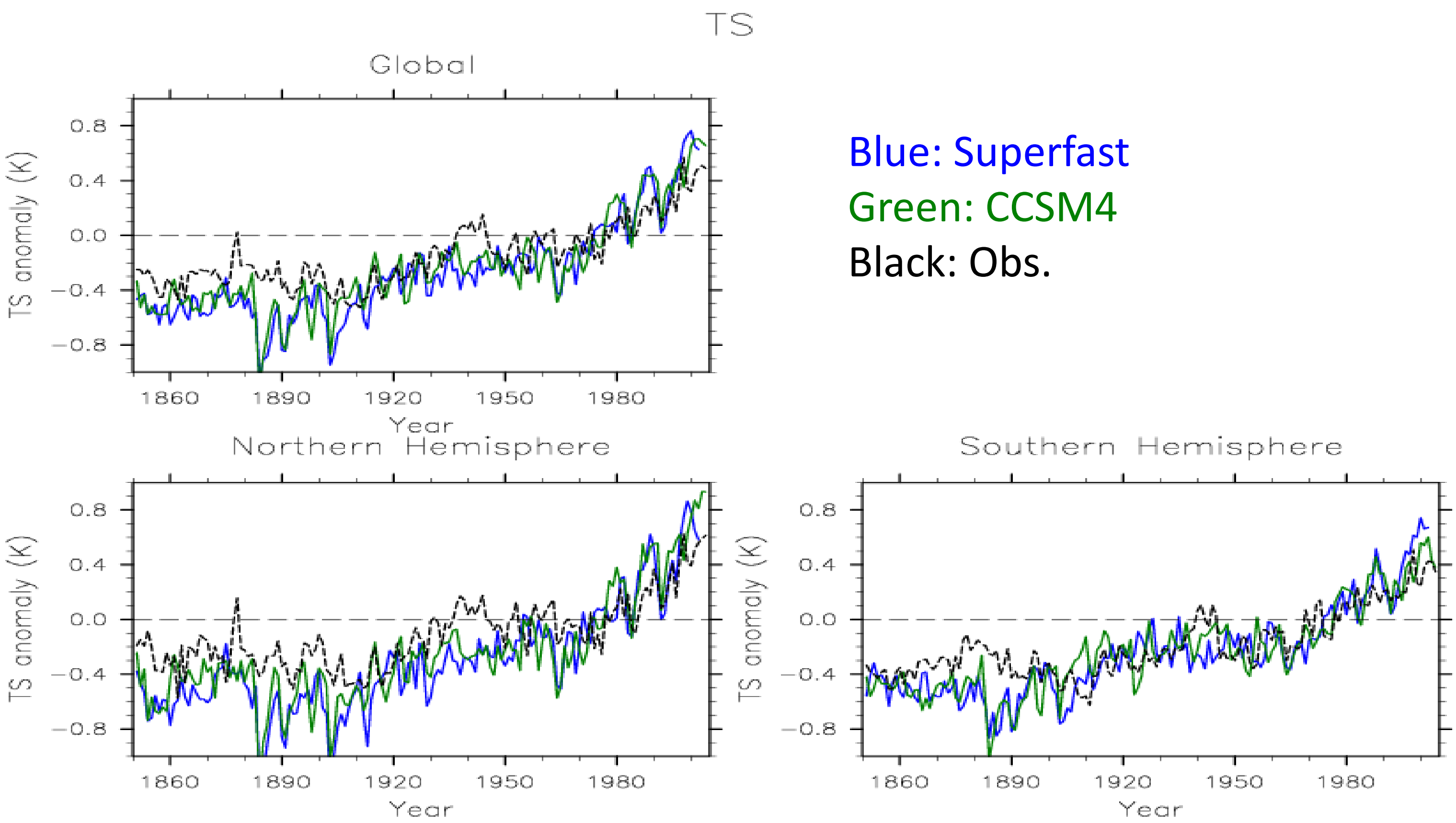
Available compsets

Compsets	Model (phys)/ radiation	Chemistry	Components / Meteorology
B_2000_TROP_MOZART (BMOZ) F_2000_TROP_MOZART (FMOZ)	CAM4, active CAM4, passive	trop_mozart trop_mozart	All active Prescr. ocn/ice, CLM dry dep
F_SD_CAMCHEM (FSDCHM) F_SD_BAM (FSDBAM)	CAM4, passive	trop_mozart trop_bam	Prescr. ocn/ice, clm dry dep, offline: GEOS5 (56lev)
F_TROP_STRAT_CHEM	CAM4, passive	trop/ strat_mozart	Prescr. ocn/ice, clm dry dep
B_2000_CN_CHEM (B2000CNCHM) B_1850_CN_CHEM (B1850CNCHM) F_1850_CN_CHEM (F1850CNCHM) B_1850-2000_CN_CHEM (B20TRCNCHM)	CAM4, active	super_fast_llnl	MEGAN VOC emis CLM dry dep, land nitrogen cycle

CESM superfast

- CCSM4 0.9x1.25
- Super-fast chemistry in troposphere
- LINOZ + Cariolle in stratosphere
- CH_4 prescribed everywhere from CAM3.5
- Fully coupled
- 1850 control (250 years)
- 3 20th century simulations

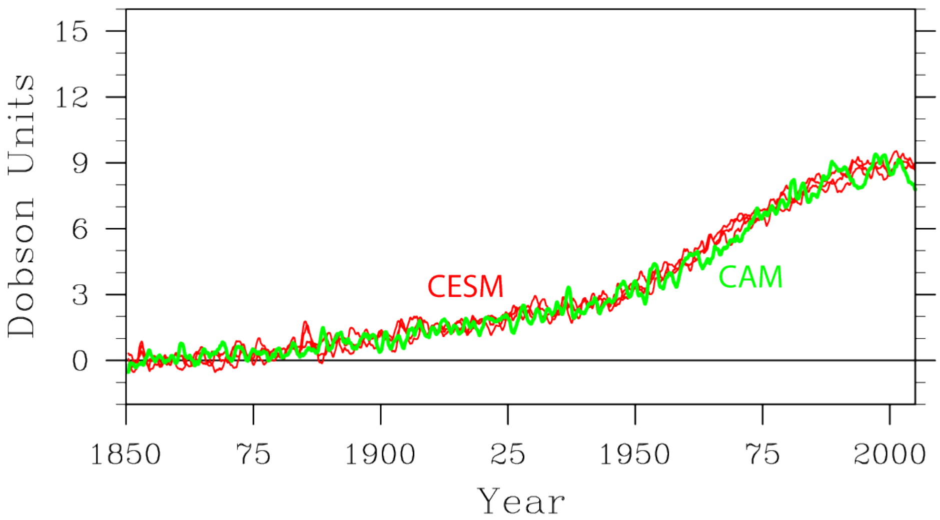
SST from CCSM4 w/ superfast chemistry



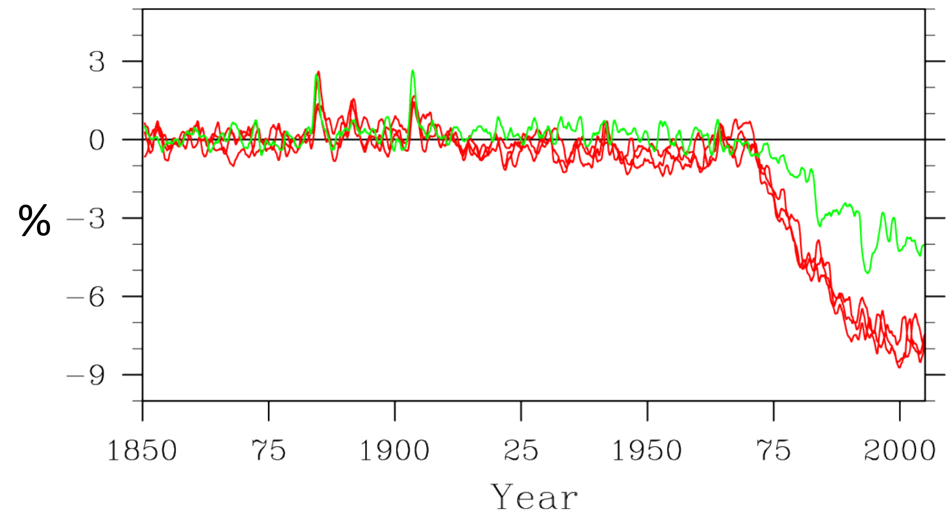
Blue: Superfast
Green: CCSM4
Black: Obs.

Ozone: historical change

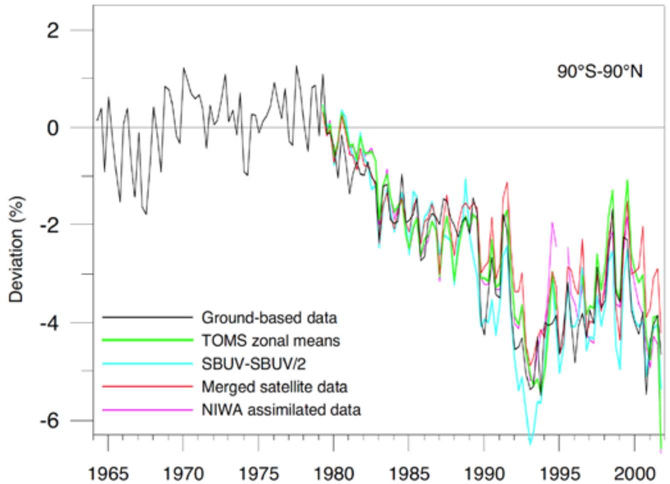
Tropospheric (200 hPa-surface)



Stratospheric (Top-200 hPa)



From WMO, 2002

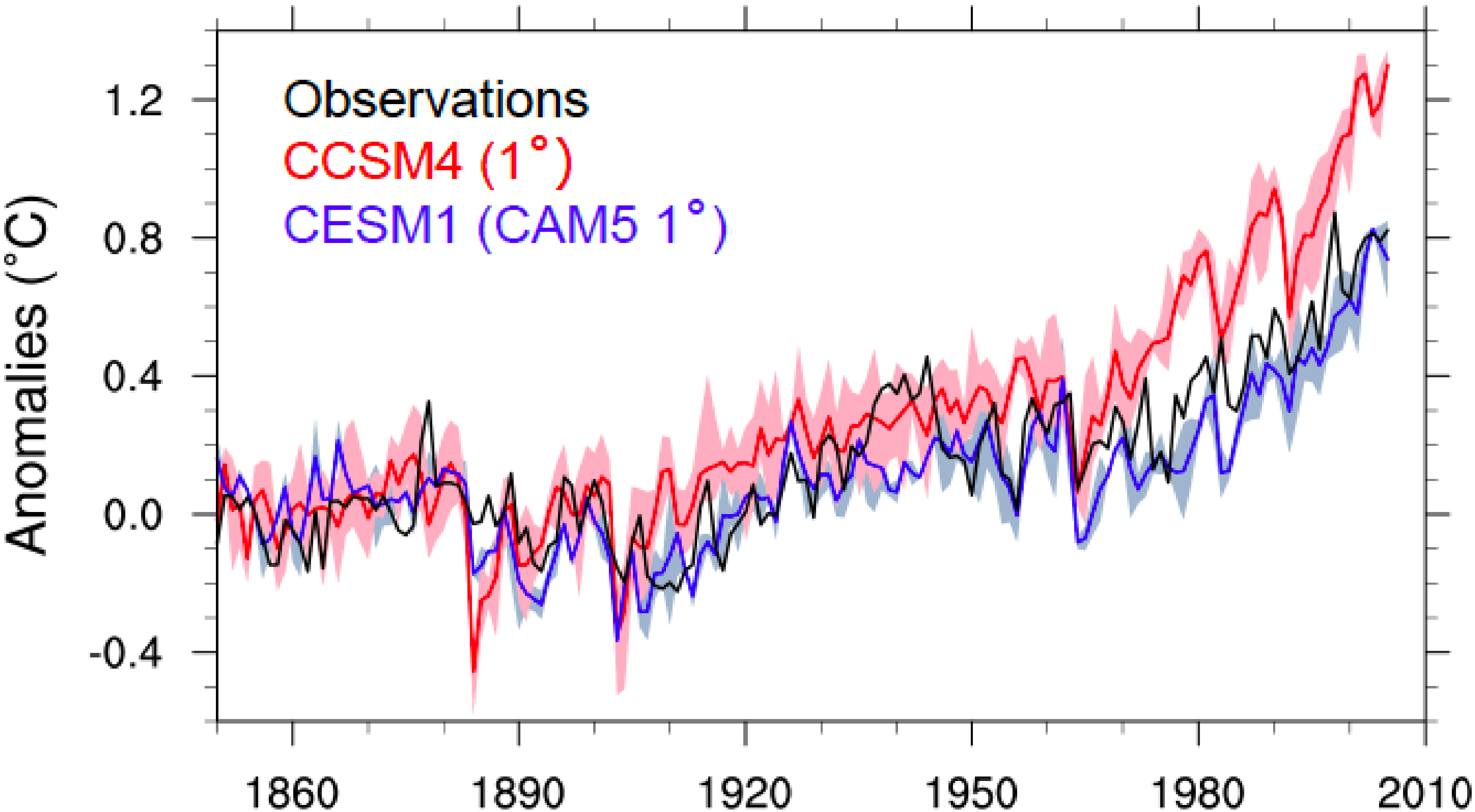


Further developments

- Feedbacks/Interactions between surface and climate/chemistry, e.g.
  - Changes in methane wetland emissions
  - Changes in ocean emissions (halogen chemistry)
  - Ozone poisoning
- Methane driven by emissions

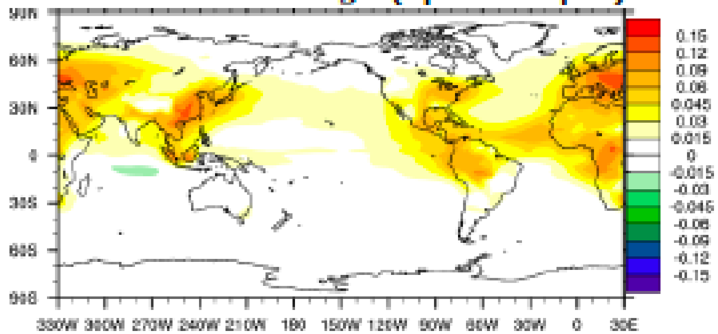
MODAL AEROSOLS

Climate impact: Surface temperature (1850-2005)

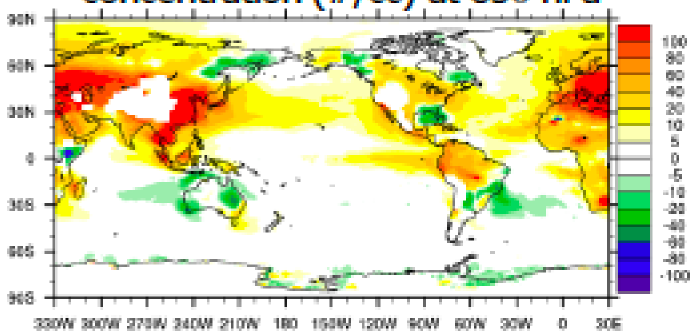


Aerosol and clouds

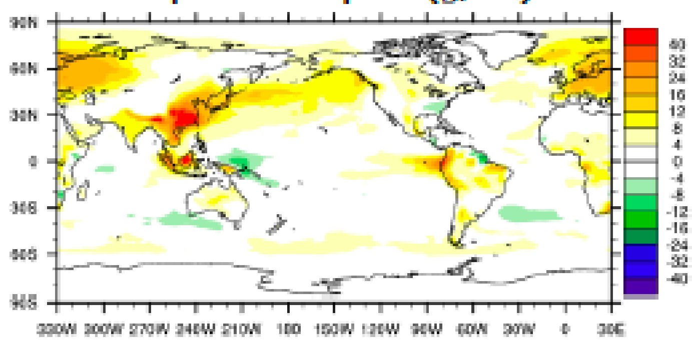
Total aerosol change (optical depth)



Cloud water droplet number concentration (#/cc) at 850 hPa

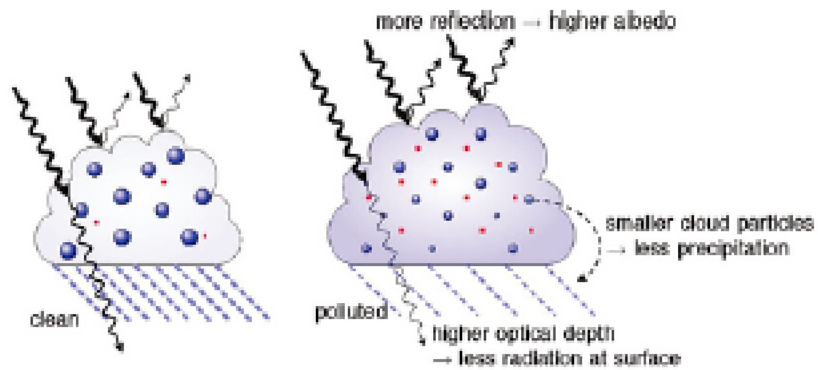


Liquid water path (g/m²)



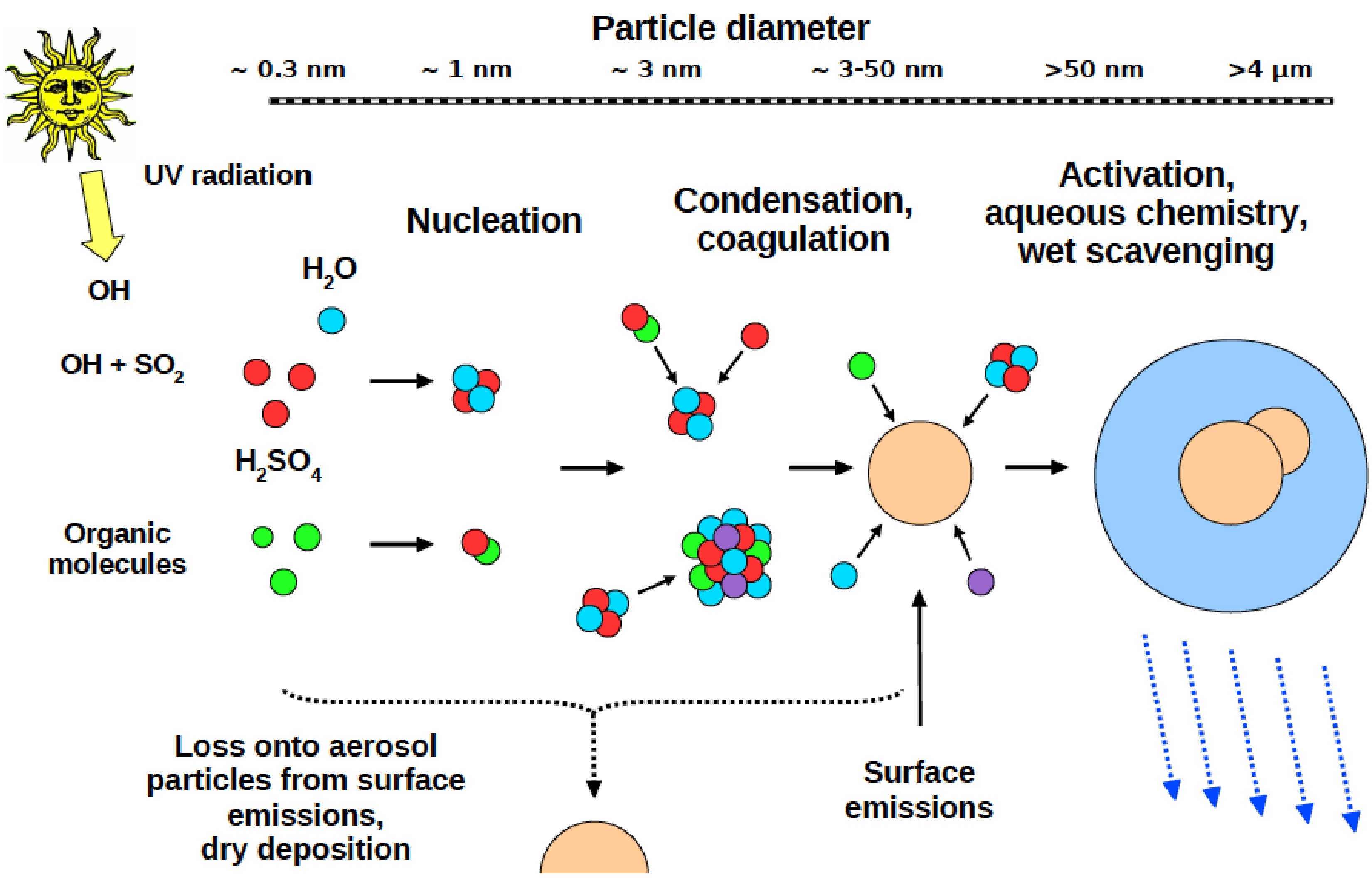
- ✓Increased aerosol burdens in SE Asia, Europe, NE North America, Brazil
- ✓Increased cloud droplet number concentration; strongest over land
- ✓ Increased numbers of smaller drops; thus brighter low clouds with more liquid

Low cloud affects: net cooling over 20th century



From J. Hurrell

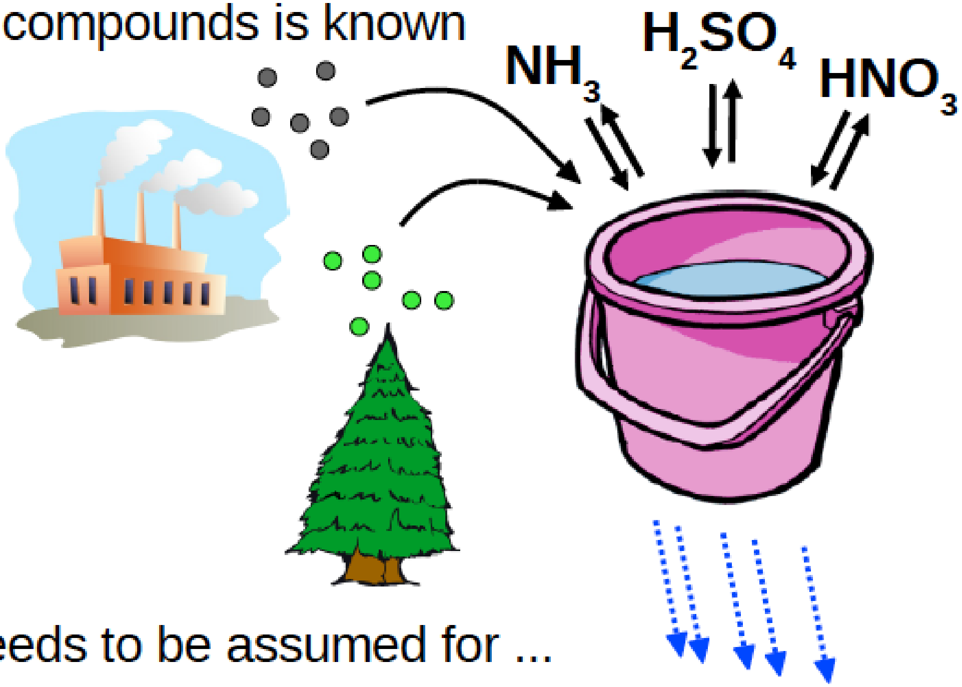
Aerosol processes



From J. Kazil, CIRES

Bulk aerosol scheme

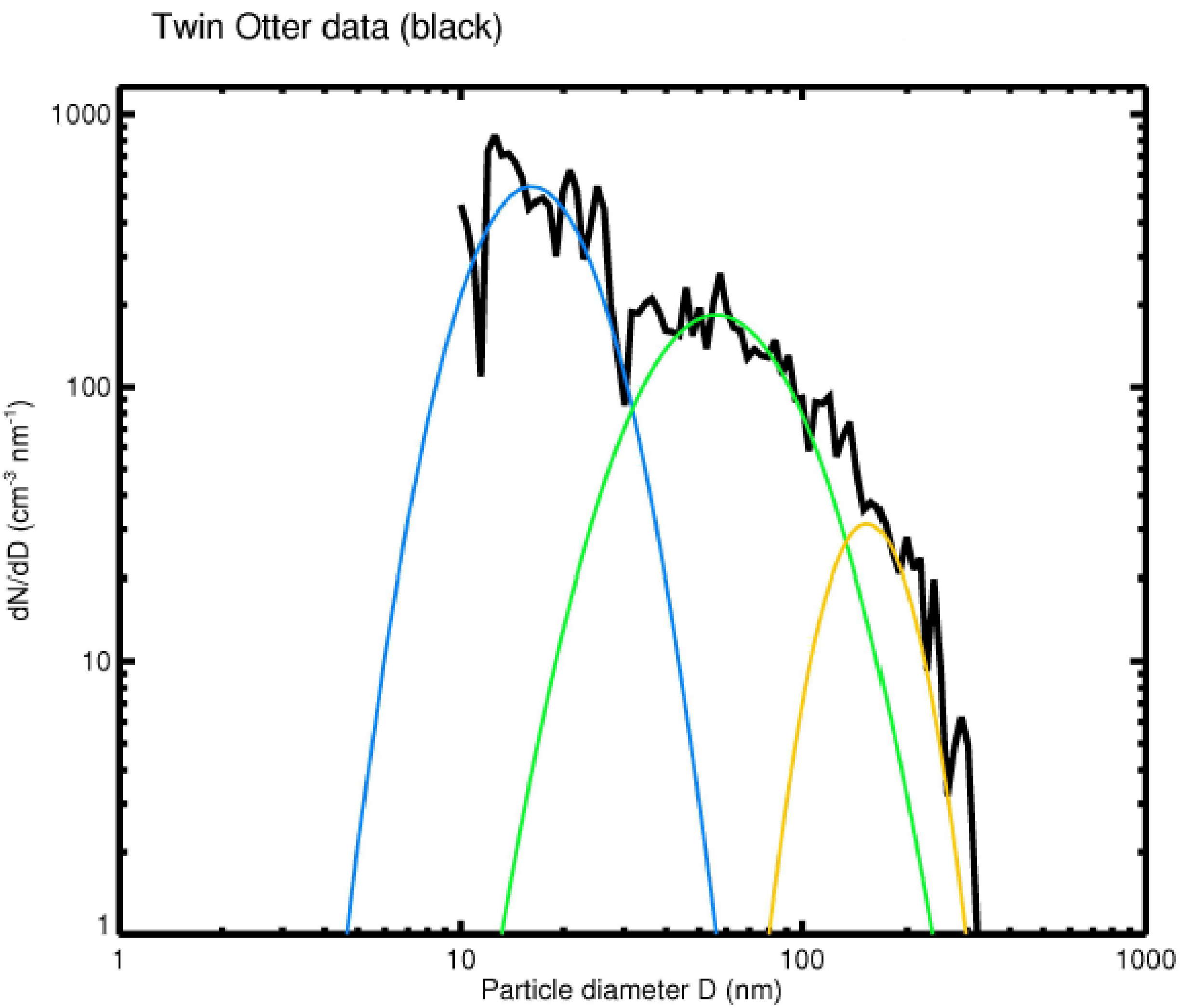
- Only total mass of aerosol compounds is known



- 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**

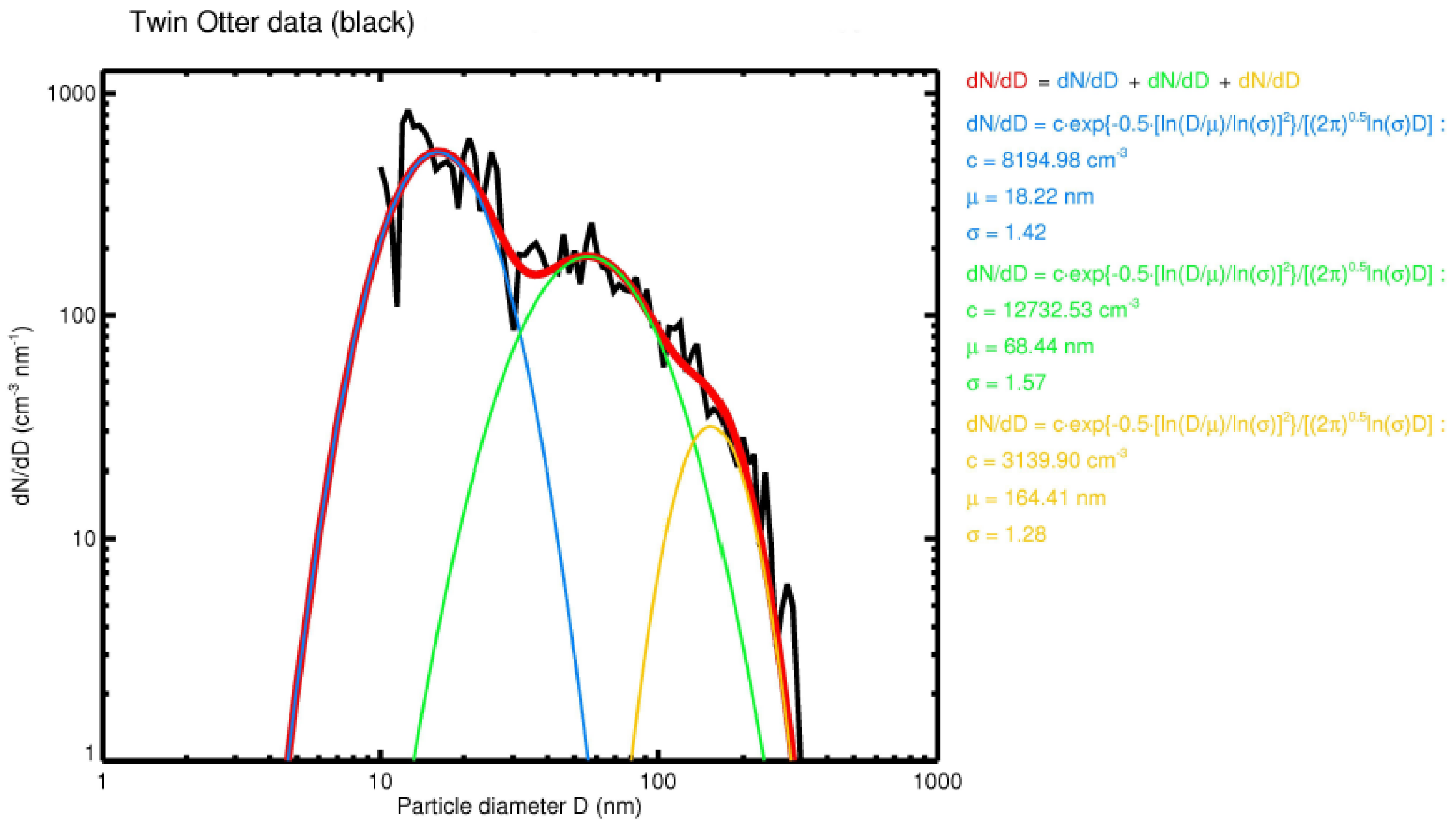
From J. Kazil, CIRES

Modal aerosol scheme



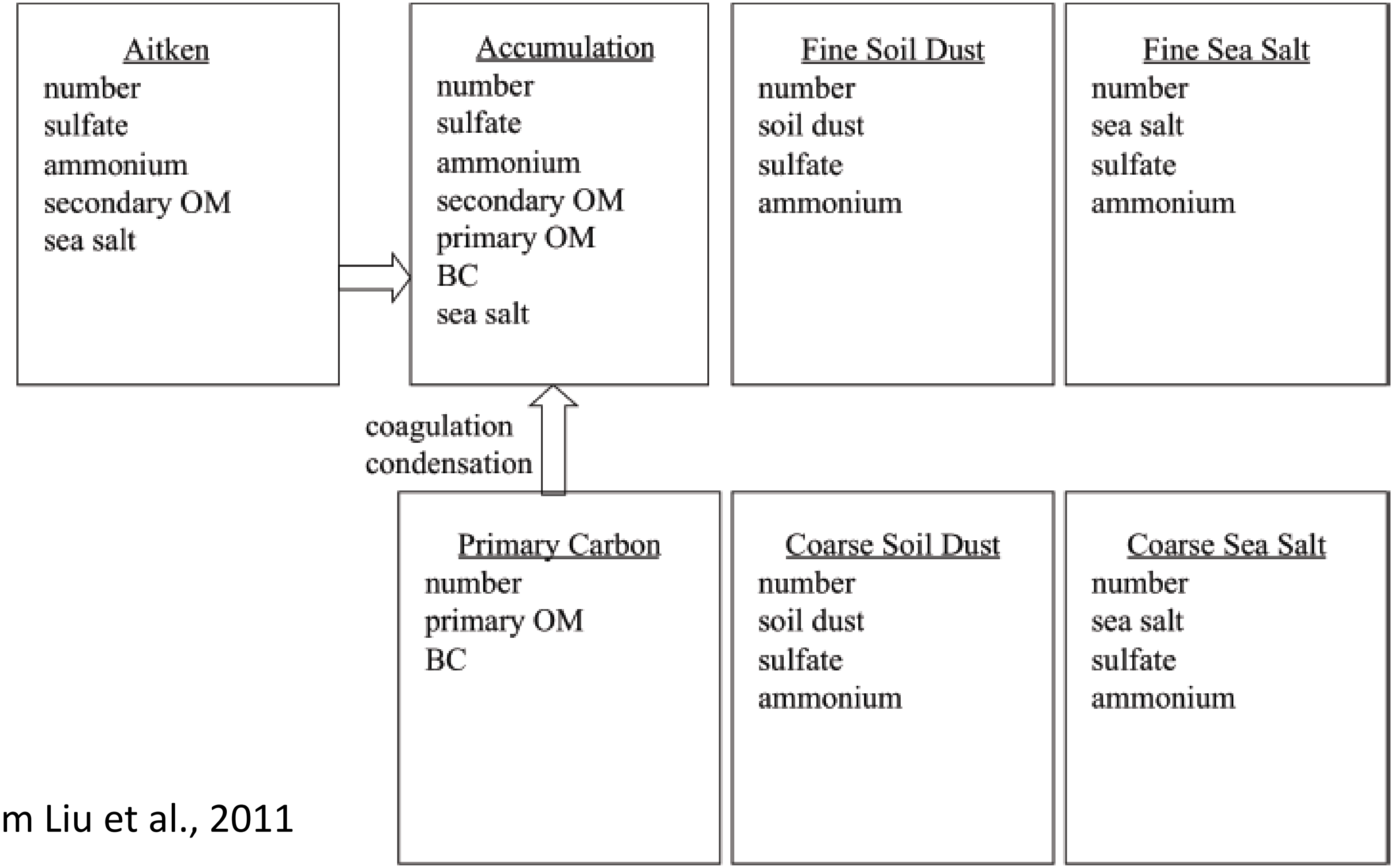
From J. Kazil, CIRES

Modal aerosol scheme



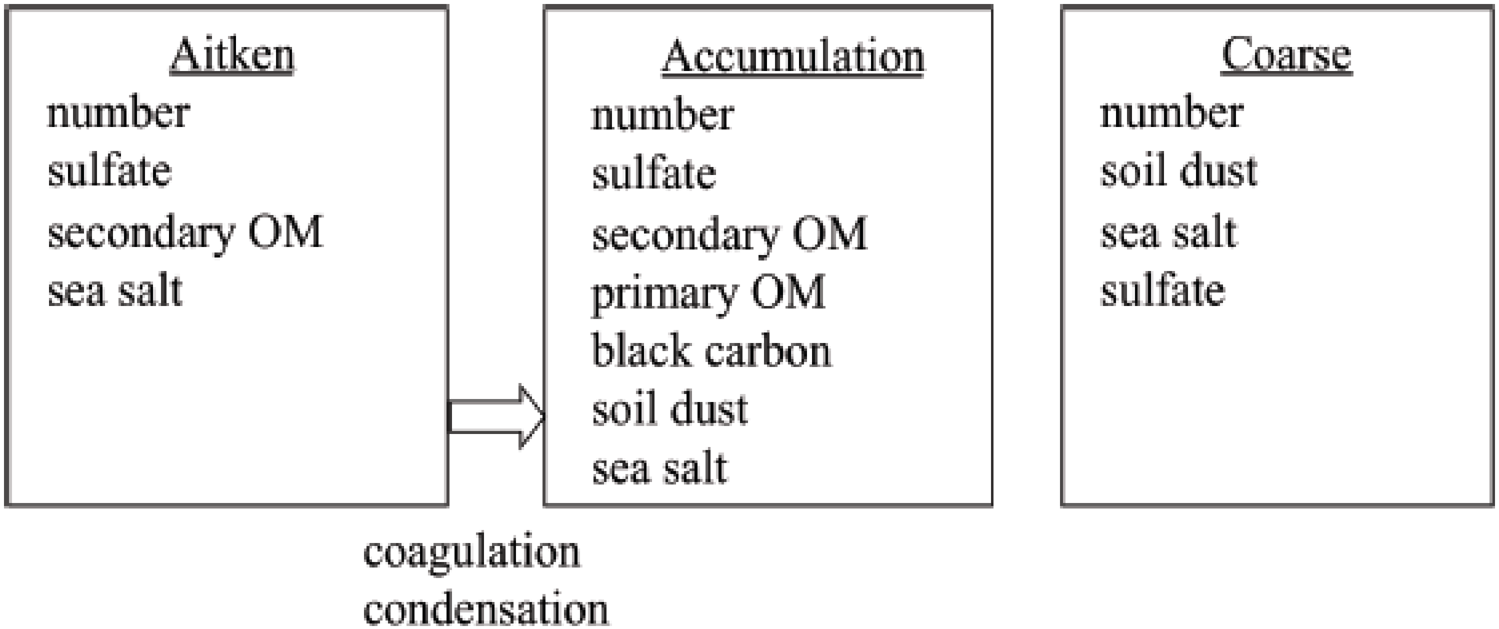
From J. Kazil, CIRES

Modal aerosol scheme from PNNL



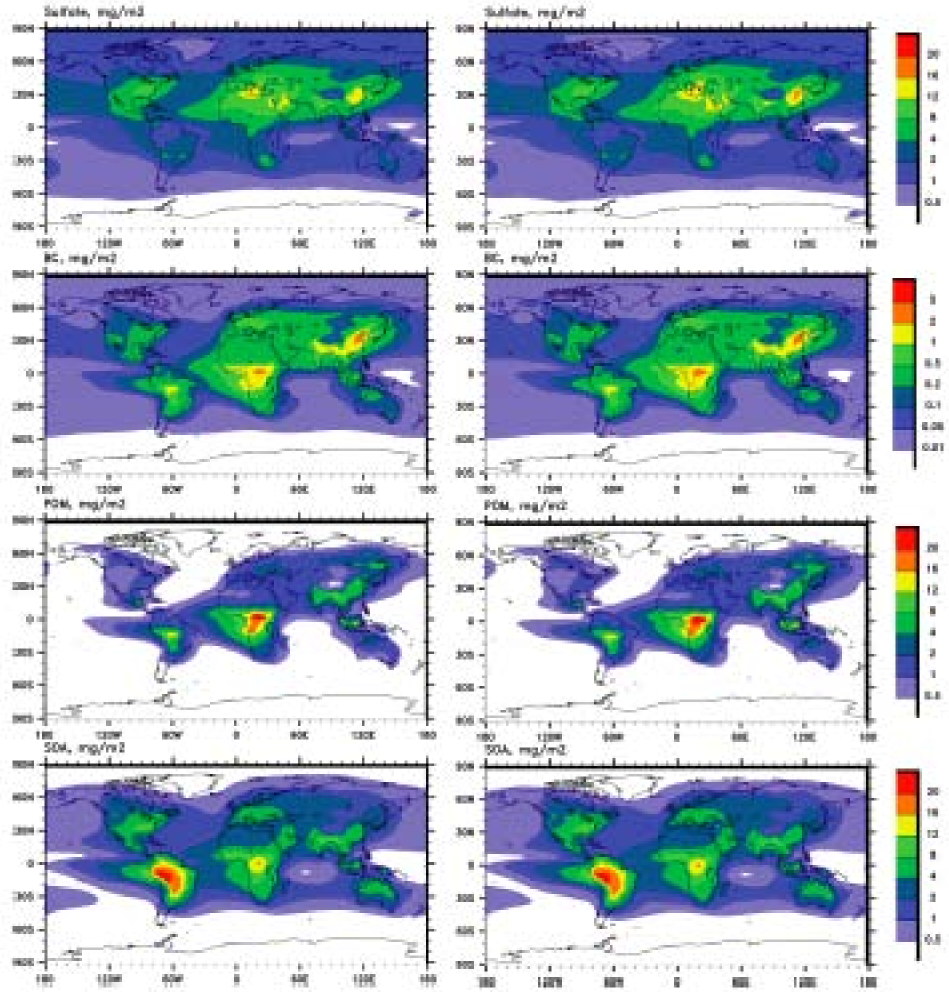
From Liu et al., 2011

Simplified version: 3-modes



From Liu et al., 2011

Comparison MAM3-MAM7



From Liu et al., 2011

MAM configuration

- Available with CAM5 physics
- MAM-3 adds approx. 25 tracers
- Very simplified chemistry (“fixed” oxidants)
- Organic aerosols represented by a specified yield applied to the emissions of isoprene and other VOCs

Further developments

- Better representation of SOA
- Integration of tropospheric chemistry in MAM

WACCM: WHOLE ATMOSPHERE CHEMISTRY-CLIMATE MODEL

WACCM Motivation

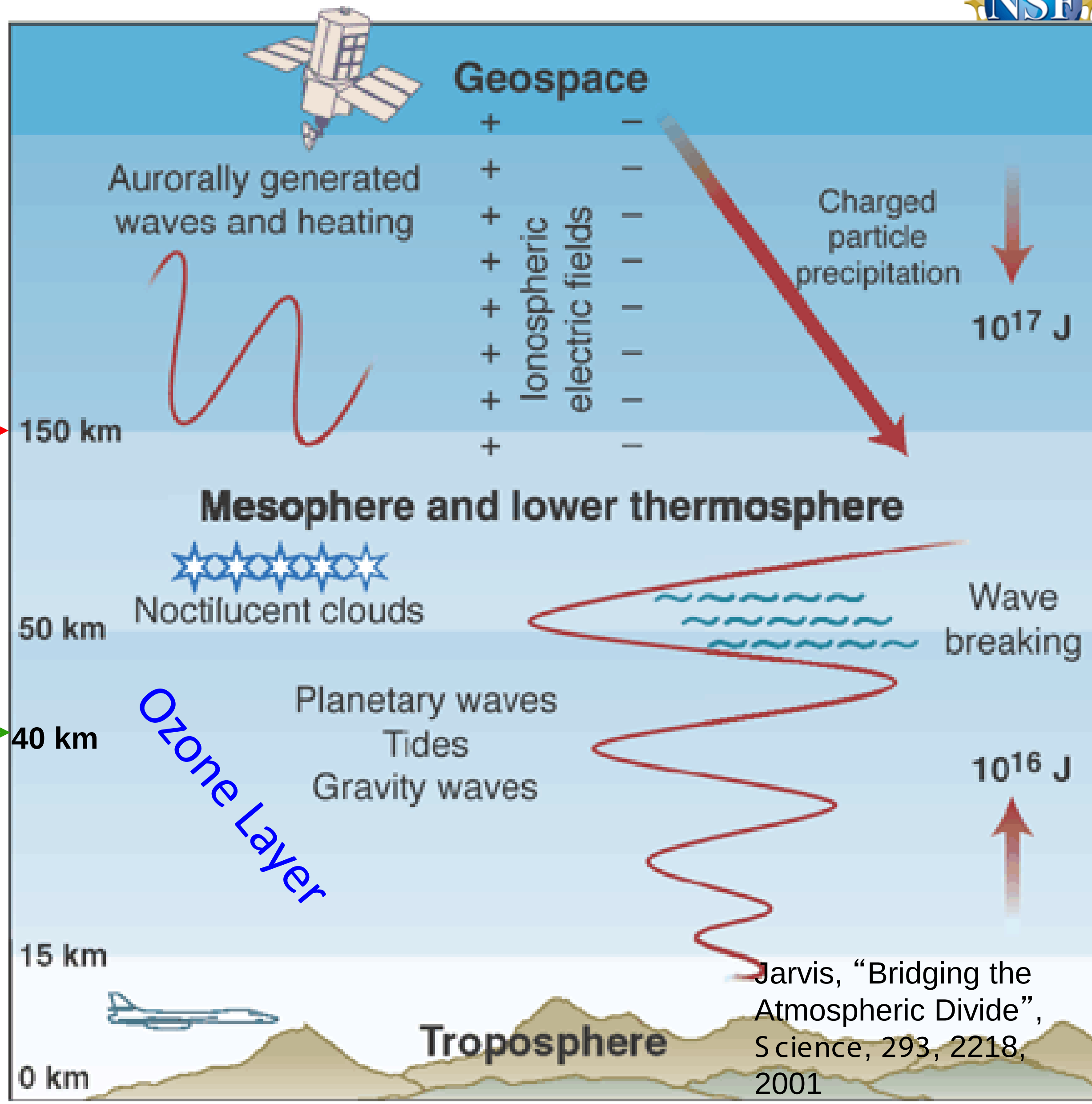
Roble, Geophysical Monograph, **v. 123**, p. 53, 2000

- Coupling between atmospheric layers:
  - Waves transport energy and momentum from the lower atmosphere to drive the QBO, SAO, sudden warmings, mean meridional circulation
  - Solar inputs, e.g. auroral production of NO in the mesosphere and downward transport to the stratosphere
  - Stratosphere-troposphere exchange
- Climate Variability and Climate Change:
  - What is the impact of the stratosphere on tropospheric variability?
  - How important is coupling among radiation, chemistry, and circulation? (e.g., in the response to O_3 depletion or CO_2 increase)
  - Response to solar variability: impacts mediated by chemistry?
- Interpretation of Satellite Observations

WACCM: The High-Top Model

WACCM top →

CAM top →



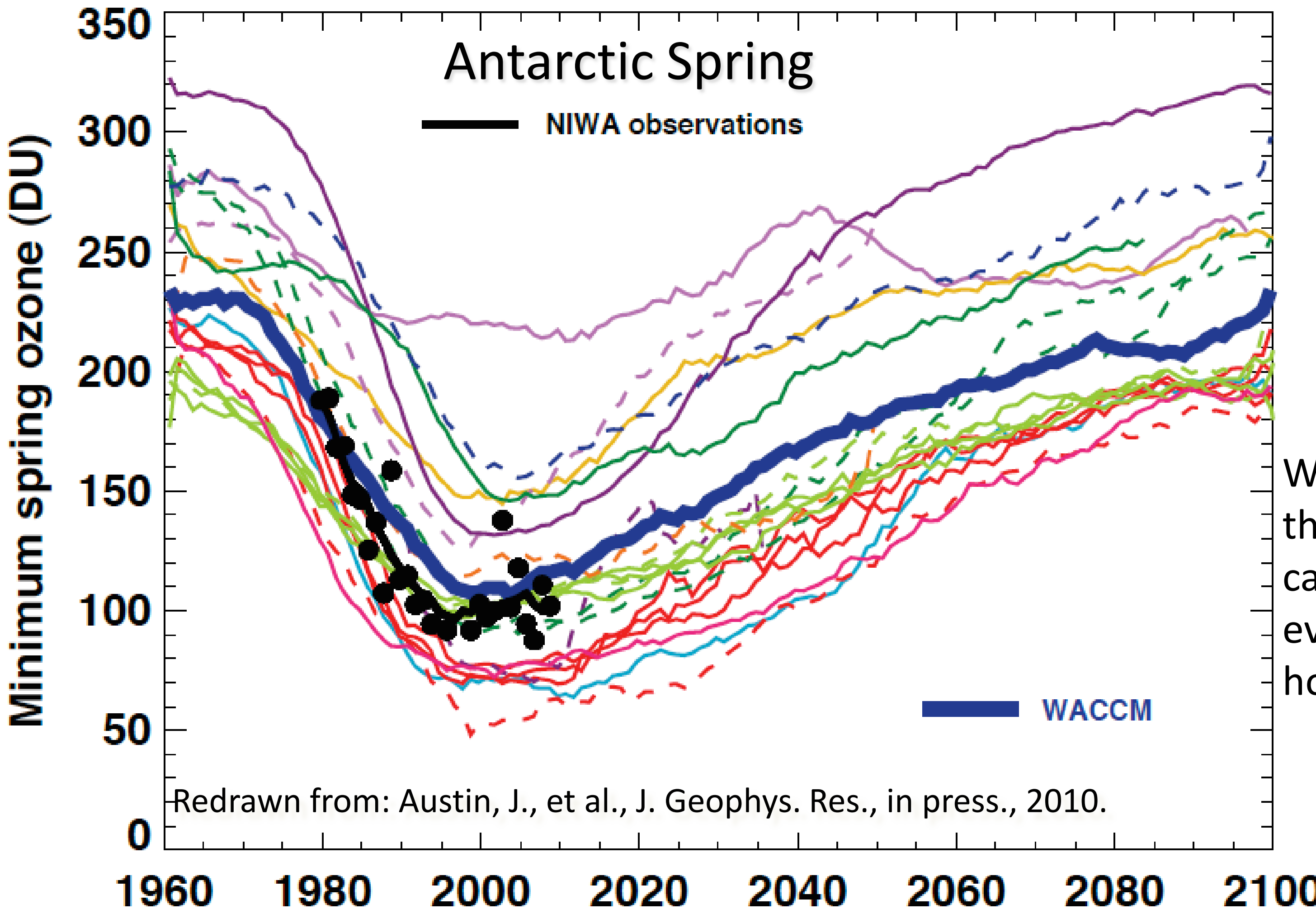
- Michael Mills
- WACCM Liaison
- mmills@ucar.edu
- (303) 497-1425
- http://bb.cgd.ucar.edu/

U.S. DEPARTMENT OF ENERGY | Office of Science

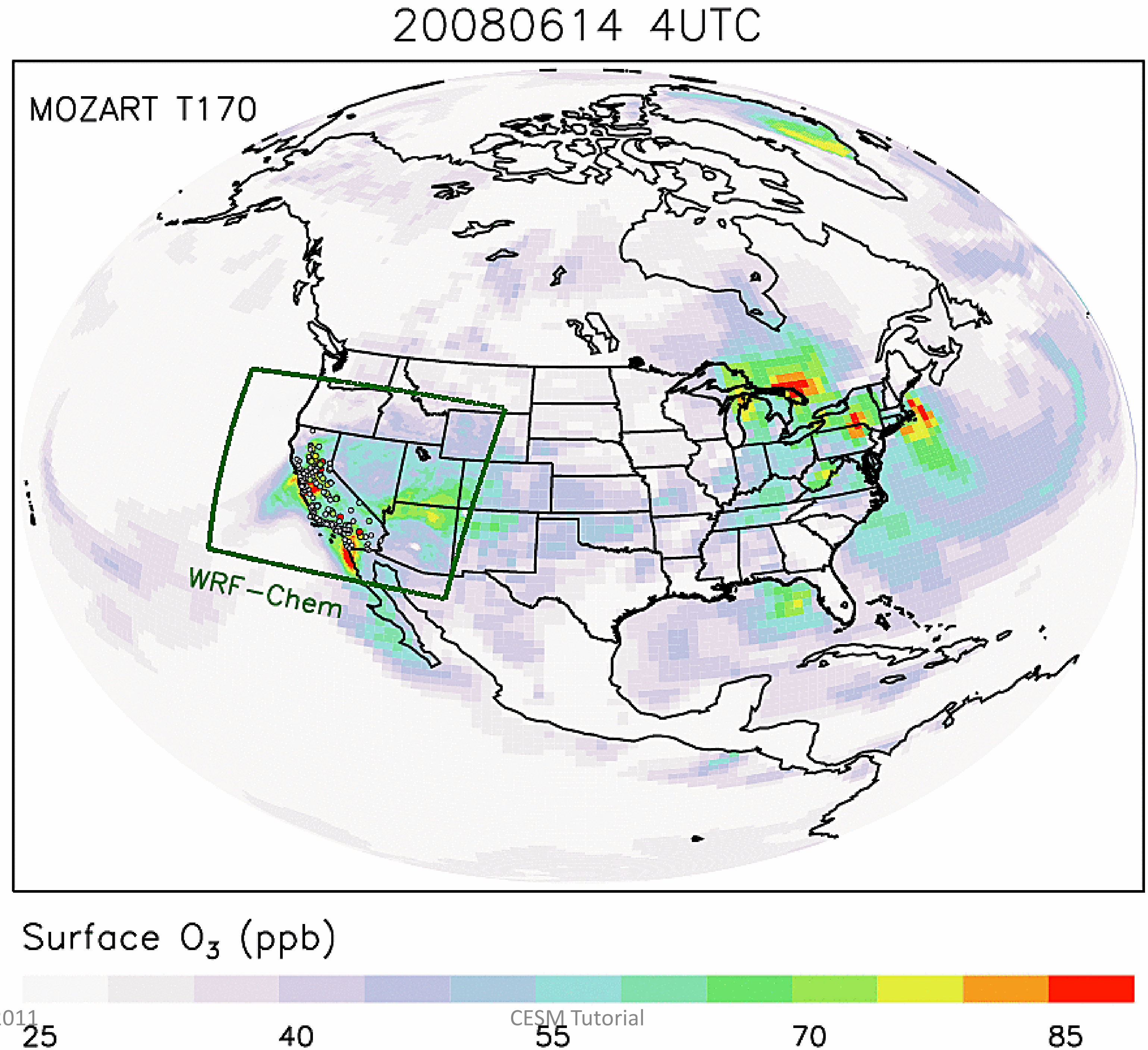
WACCM Additions to CAM

- Extends from surface to 5.1×10^{-6} hPa (~150 km), with 66 vertical levels
- Detailed neutral chemistry model for the middle atmosphere,
  - catalytic cycles affecting ozone
  - heterogeneous chemistry on PSCs and sulfate aerosol (available in CAM as well)
  - heating due to chemical reactions
- Model of ion chemistry in the mesosphere/lower thermosphere (MLT), ion drag, auroral processes, and solar proton events
- EUV and non-LTE longwave radiation parameterizations
- Imposed QBO, based on cyclic, fixed-phase, or observed winds
- Volcanic aerosol heating calculated explicitly
- Gravity wave drag deposition from vertically propagating GWs generated by orography, fronts, and convection
- Molecular diffusion and constituent separation

WACCM Ozone Trend: CCMVal and WMO



WACCM does better than most models at calculating the evolution of the ozone hole.


20080614 4UTC
MOZART T170
WRF–Chem
Surface O_3 (ppb)
25
40
55
70
85