Black Carbon Effects on Climate with Different Emission and Model Treatments

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Scientific Questions

What is the difference in climate response of BC when

- a different BC emission inventory is used?
- BC deposition to snow in size-resolved precipitation is treated, and the albedo containing BC inclusions is calculated, rather than prescribed?
- BC in multiple-evolving distributions and energy diffusion to the deep ocean are treated?

What are the effects of all anthropogenic GHGs and aerosols on climate?

Estimated Global Direct Forcing (W/m^2)

Anthropogenic Greenhouse Gases (IPCC, 2001)

- Carbon Dioxide +1.46
- Methane +0.48
- Nitrous oxide +0.15

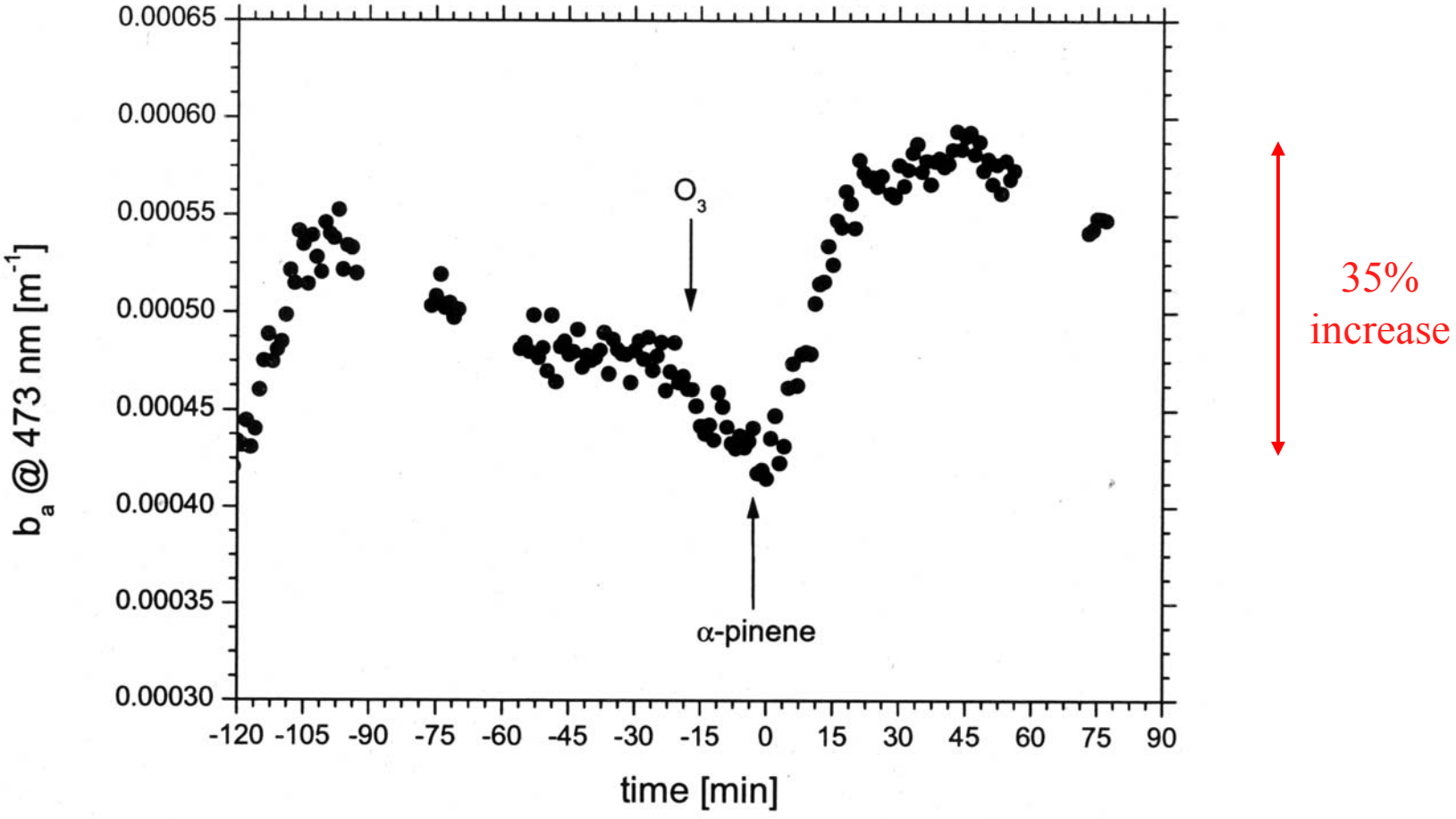
Fossil-fuel+Biomass-Burning BC (*Nature* 409, 695, 2001; *GRL* 27, 217, 2000)

- Internally mixed as a core +0.62
- Multiple distributions (int.+ext. mix) +0.55 (Best estimate)
- Externally mixed +0.31

Ff+bb BC (Chung and Seinfeld *JGR* 107, D19, 2002)

- Well-mixed internally +0.8
- Externally mixed +0.51

Increase in Absorption Coefficient due to Condensation of Organic onto Soot



Schnaiter et al., J. Aer. Sci. 34, 1421 (2003)

Comparison of ff BC Climate Responses

1. Jacobson (JGR 107, D19, 2002). Size resolved (1 distribution) multi-compon. aerosols, size-resolved cloud formation on aerosols, size-resolved treatment of first and part of second indirect effects, climatological snow/ice albedo, emissions of Cooke et al. (1999), 2-D ocean module, many feedbacks.

- Fossil fuel BC+OM: +0.3 K (5-y average)
  +0.35 K (last year)
  Range of all simulations (+0.15 to +0.5)

2. *Ibid.* (JGR 2004, in press). Same as (1) but treated first and second indirect effects, calculated snow/ice albedo, used early Bond et al. (2004) inventory.

- Fossil fuel + biofuel BC+OM: +0.27 K (10-y avg. snow contrib. +0.06 K)

3. *Ibid.* Recent results. Same as (2) but used most recent Bond et al (2004) emission,, used two distributions (emitted ff+bf BC+OM and emitted other + heterocoagulated BC) and 10 layers of energy diffusion to deep ocean.

- Fossil fuel + biofuel BC+OM: +0.29 K (6-y avg.)

GATOR-GCMOM

Gas, Aerosol, Transport, Radiation, General-Circulation, Mesoscale, Ocean Model
Unique processes (www.stanford.edu/group/efmh/GATOR/index.html)

- Treats size-resolved aerosol particles (number and mass). Solves nucleation/condensation/coagulation/chemistry among multiple distributions. Treats internal mixing of BC due to size-resolved growth and coagulation.

  Other climate response studies treat bulk or modal aerosols, which do not account for size-dependence of aerosol composition, optical effects, or cloud formation. Such studies also treat internal mixing of BC empirically rather than through size-resolved microphysics and chemistry.

- Treats the first and second indirect effect through growth of size resolved liquid and ice on size-resolved aerosols to form hydrometeors, size-resolved hydrometeor-hydrometeor and aerosol-hydrometeor coagulation, size-resolved contact freezing, homogeneous-heterogeneous freezing, and evaporative freezing, size-resolved melting and drop breakup, release of aerosol cores upon cloud/precipitation evaporation/sublimation)

  Other climate response studies either ignore indirect effects or treat with empirical functions (e.g., CC N as a function of NSS sulfate, etc.)

GATOR-GCMOM

- Treats gas-, size-resolved aerosol, moisture, and energy convection in multiple subgrid clouds, each with different base and top height.

  Published aerosol climate response studies treat thermodynamics of one cloud per grid column.

- Treats size-resolved aerosol, cloud, snow, and sea ice optics allowing for BC core and mixed shell in all media. Calculates albedo of snow, ice, water.

  Published studies treat external mixture or well-mixed internal mixture of aerosols, modal instead of size-bin-resolved aerosol optics, no radiative transfer through snow/ice with inclusions, no radiative transfer through size-bin and composition-resolved clouds, and few wavelengths.

- Solves gas chemistry in stratosphere and troposphere with actinic fluxes affected by size-resolved aerosols and clouds and with stiff ODE solver.

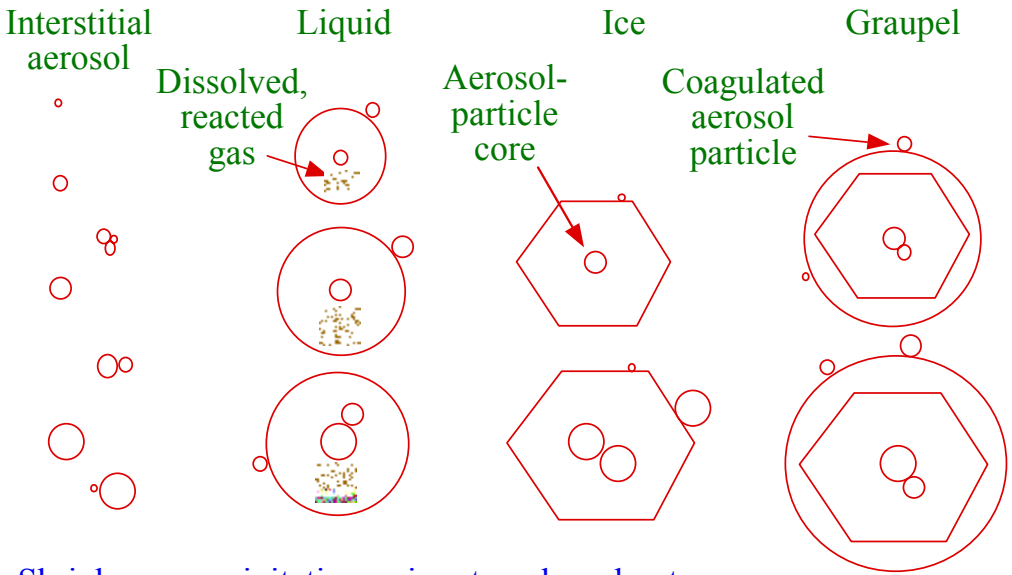
  Published 3-D response studies do not treat both stratospheric and troposphere size-resolved aerosols and gas chemistry, nor calculate effects of size-resolved aerosols and clouds on wavelength-dependent actinic fluxes.

Cloud Microphysical and Chemical Processes

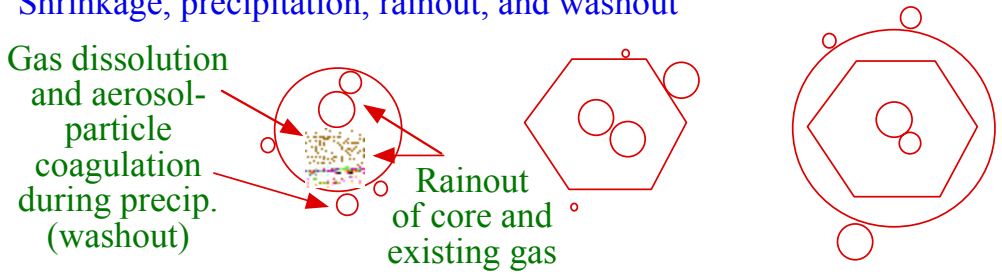
Condensation/deposition of water vapor onto aerosol particles

Coagulation: Aerosol-aerosol, Aerosol-liquid, Aerosol-ice, Aerosol-graupel, Liquid-liquid, Liquid-ice, Liquid-graupel, Ice-ice, Ice-graupel, Graupel-graupel

Gas dissolution. aqueous chemistry, hom.-het. freezing, contact freezing

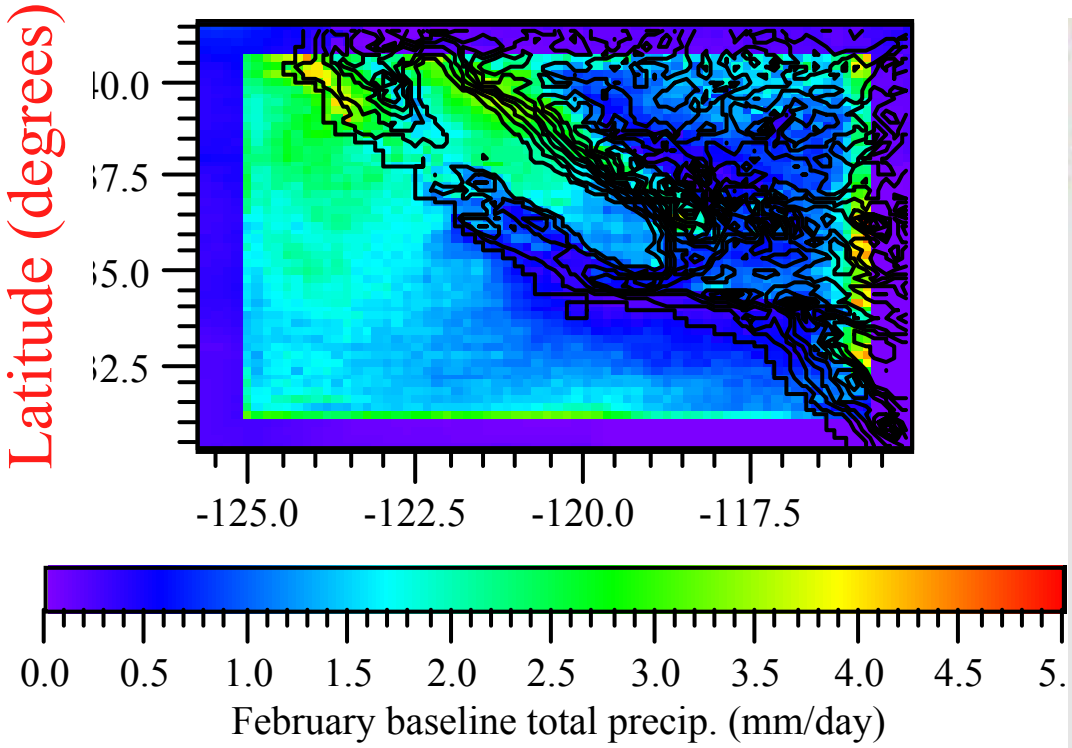


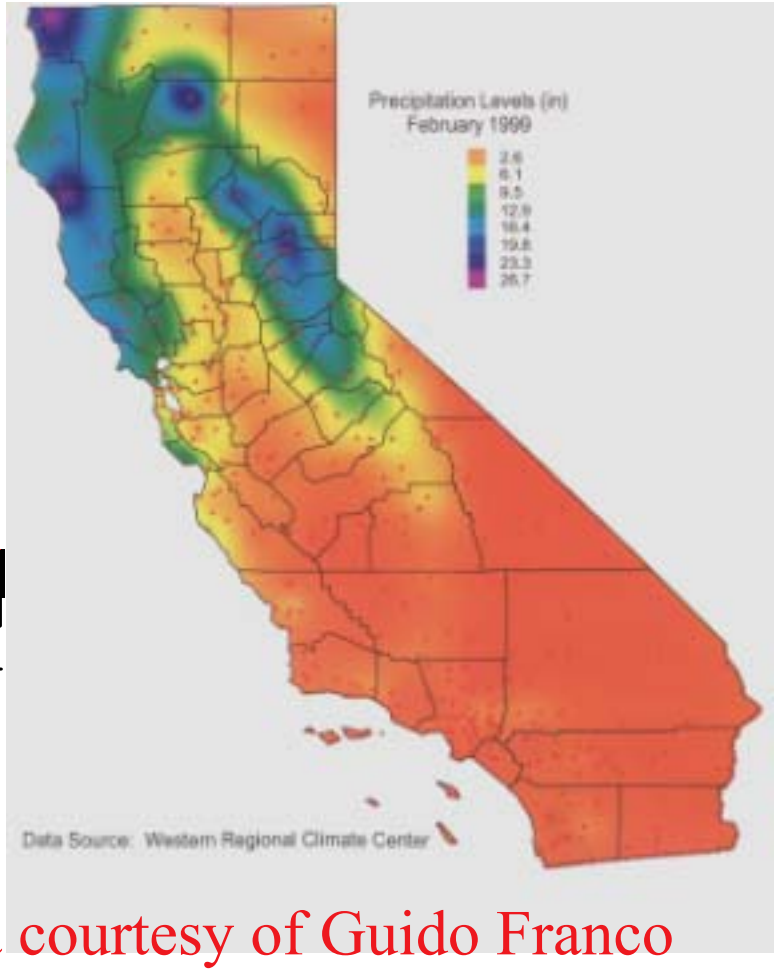
Shrinkage, precipitation, rainout, and washout



Cloud evaporation --> interstitial aerosol plus evaporated cores

Modeled vs. Measured Feb. 1999 Precip.

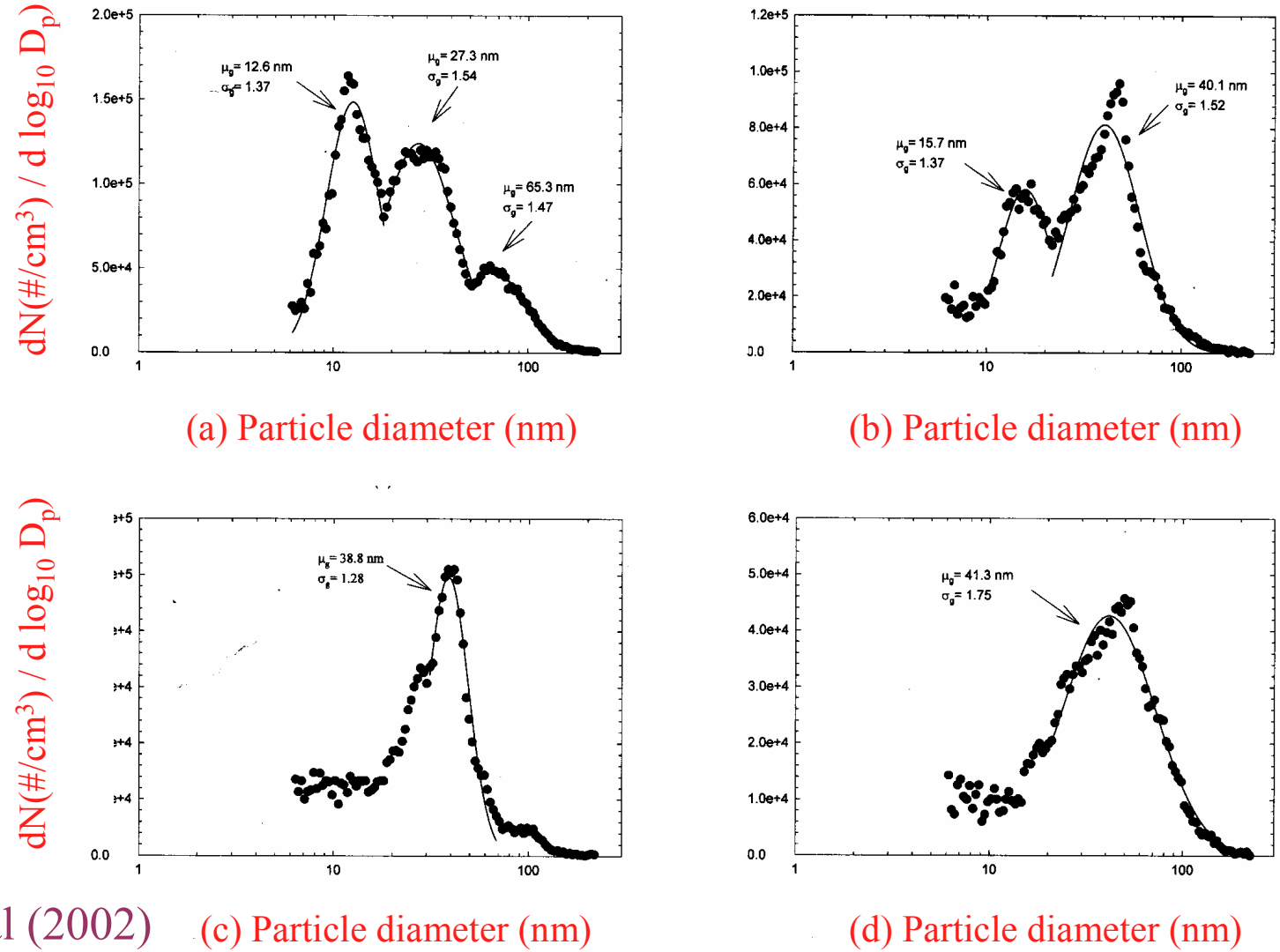




Data courtesy of Guido Franco

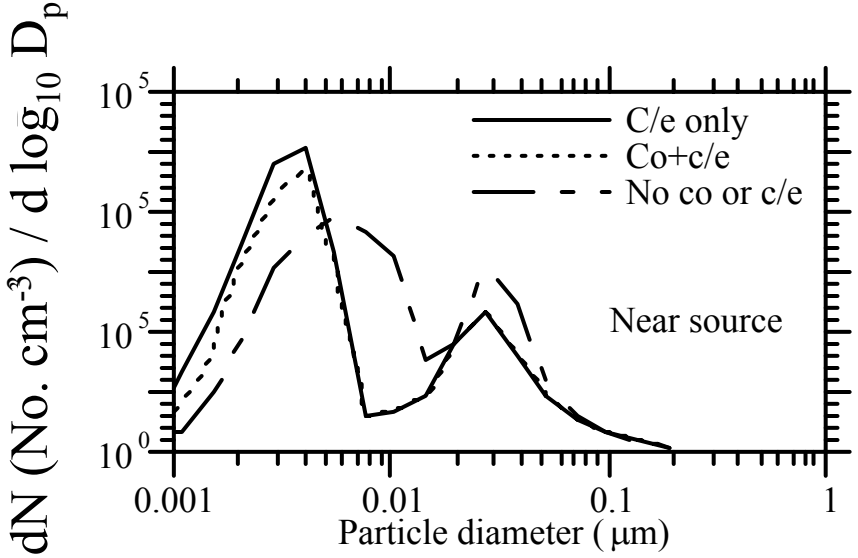
Measurement of Particle Size Distribution Evolution Near Freeway

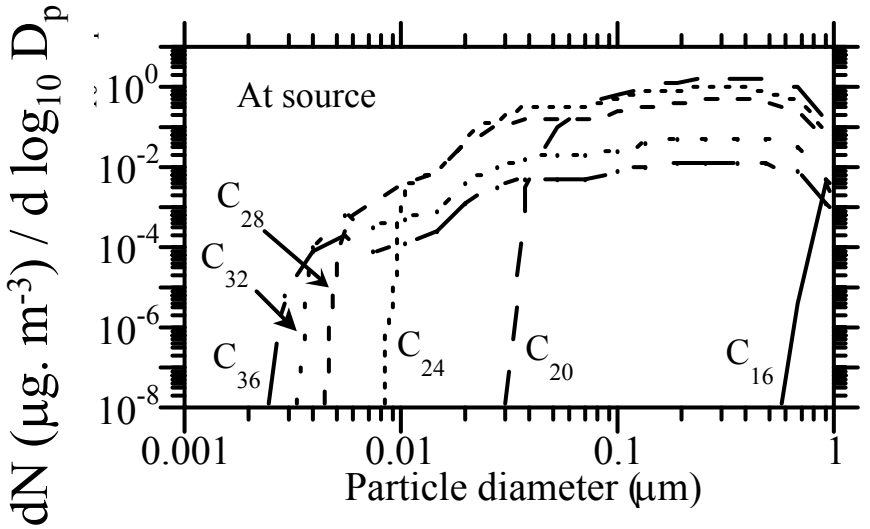
(a) 30, (b) 60, (c) 90, (d) 150 m downwind

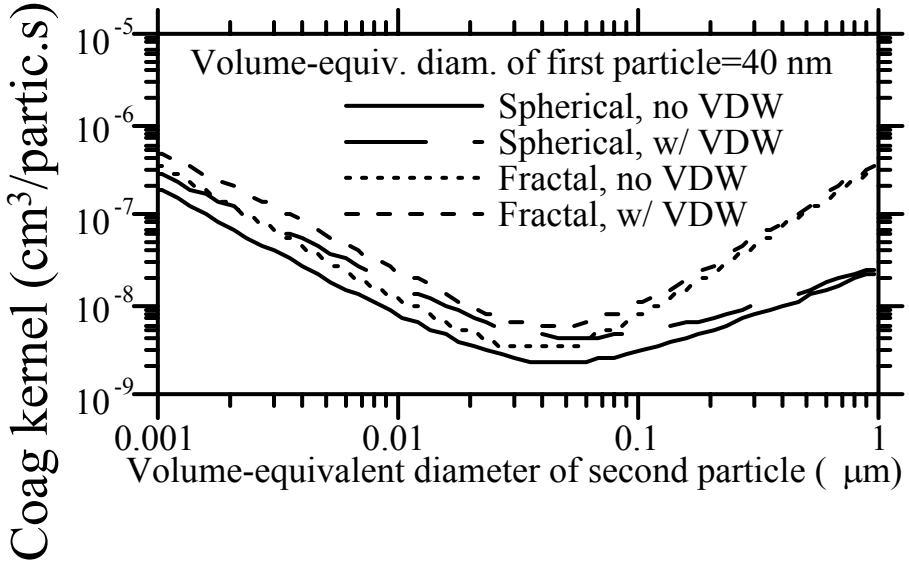


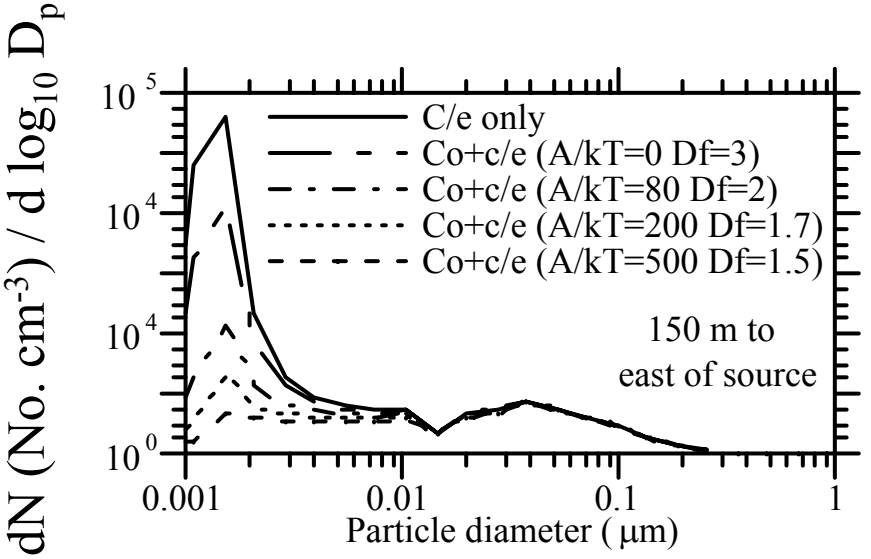
Zhu et al (2002)

Near-Source Particle Evolution

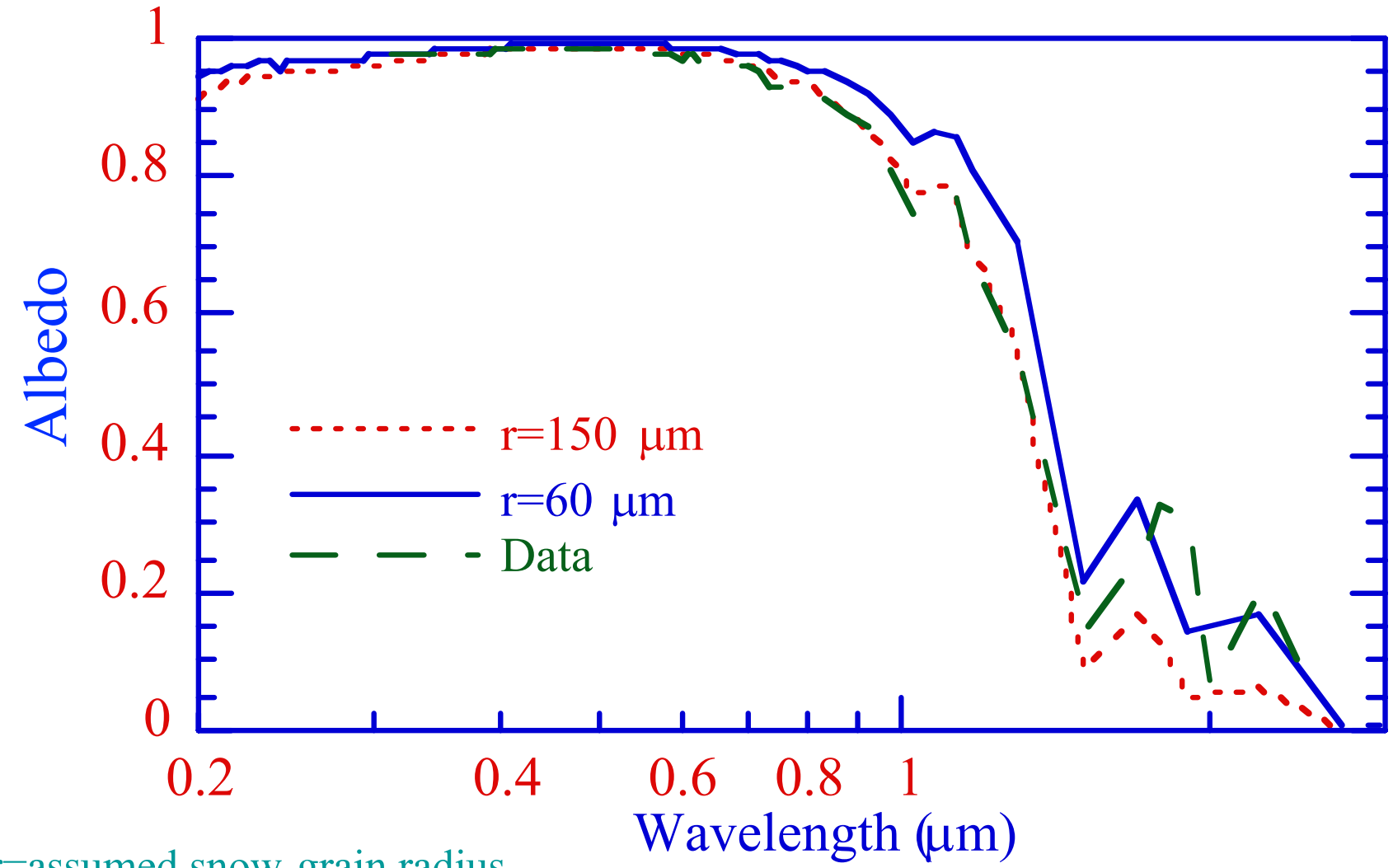








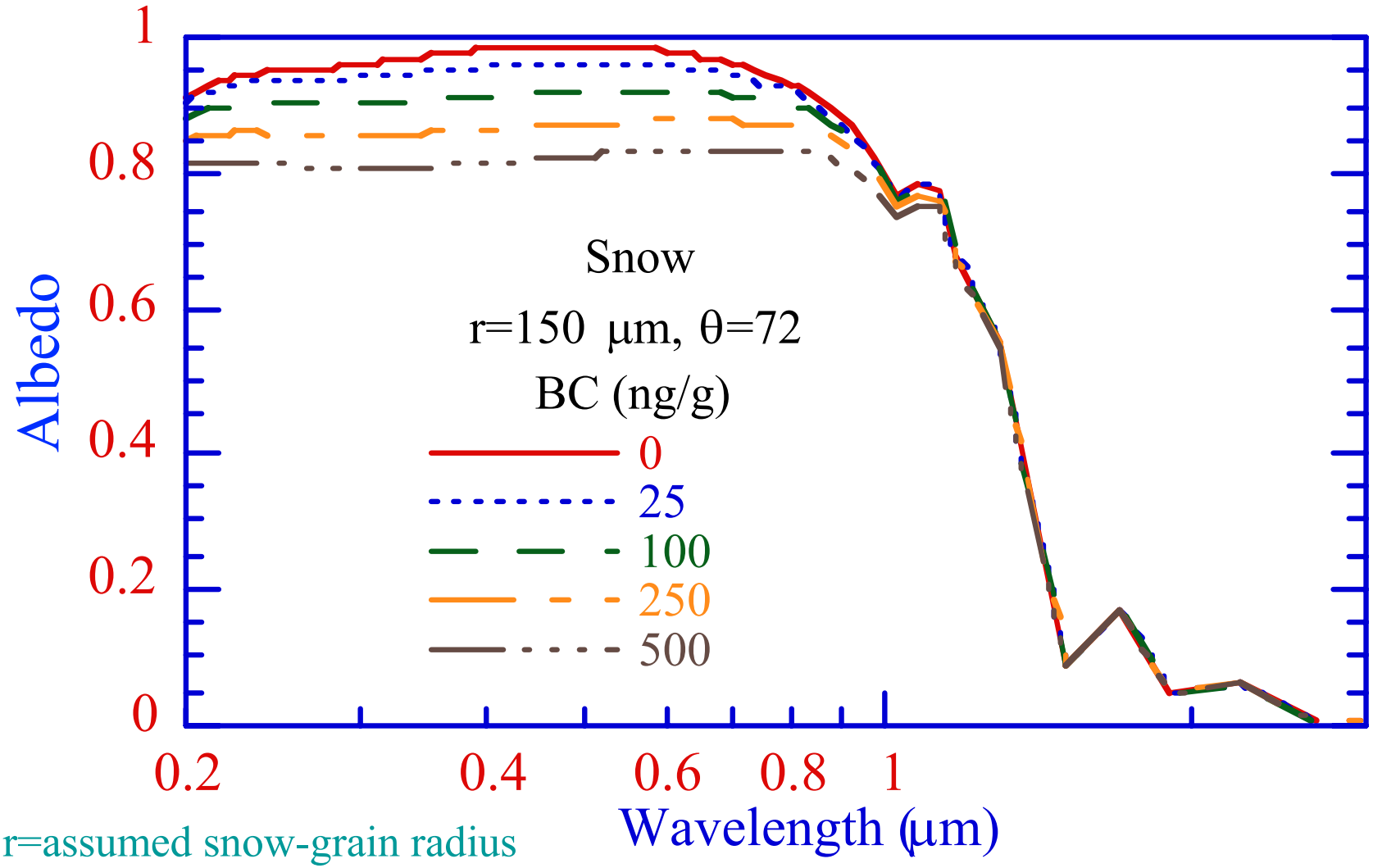
Modeled (from Radiative Transfer)Versus Measured Pure-Snow Albedo



r=assumed snow-grain radius

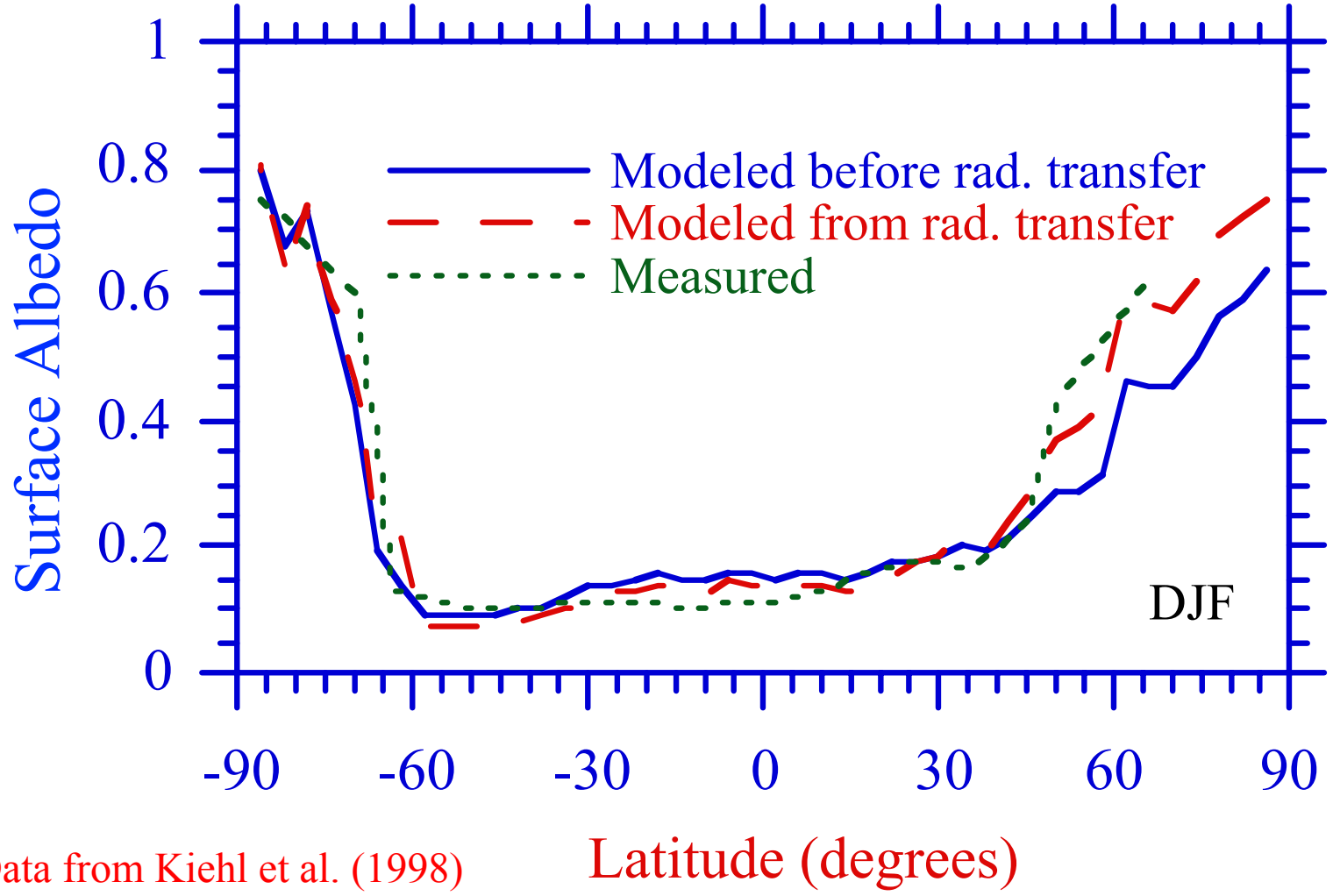
Data from Grenfell et al. (1994)

Modeled (from Radiative Transfer)Albedo Of Snow With Internally+Externally-Mixed BC Inclusions



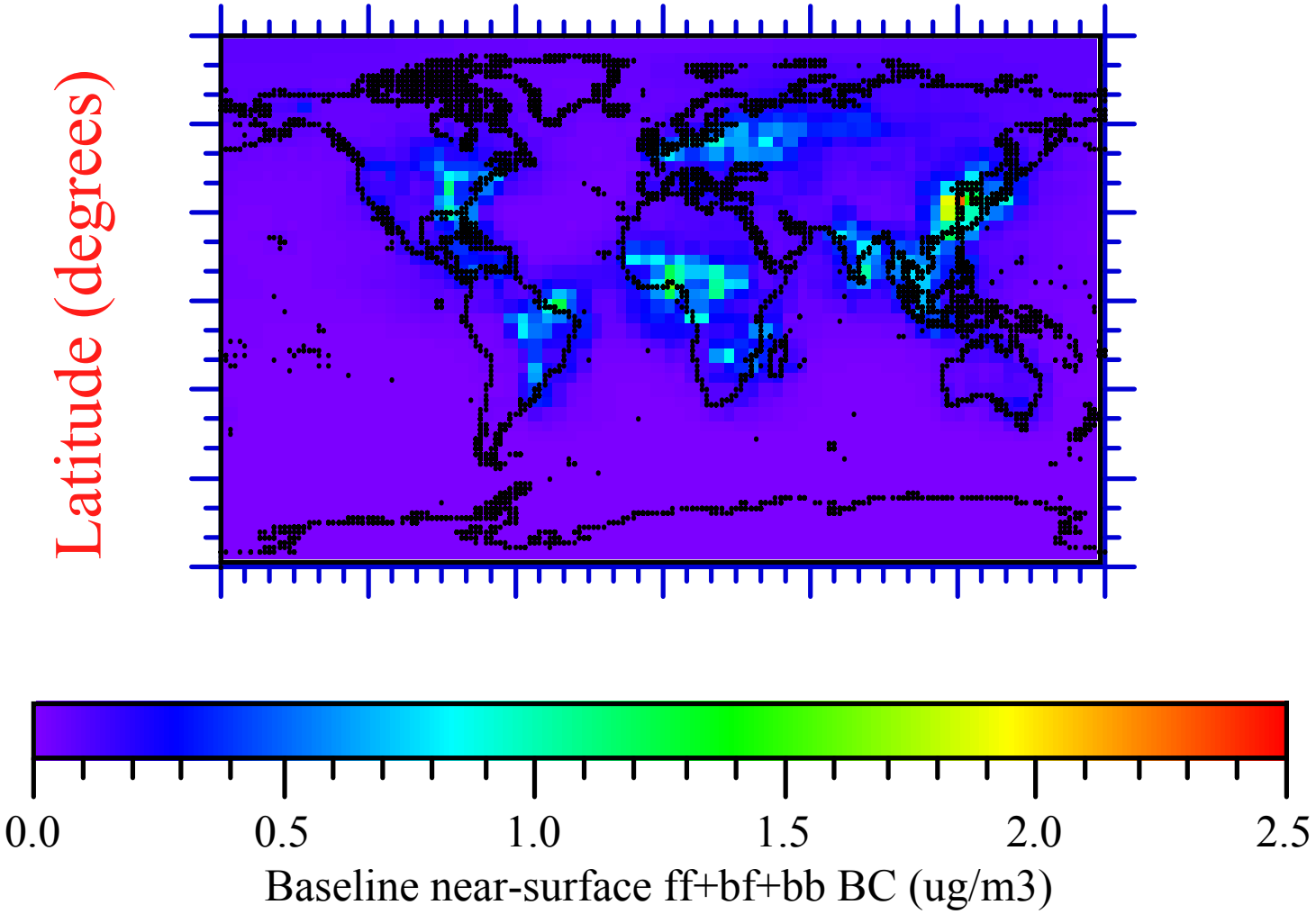
r=assumed snow-grain radius

Ten-Year-Avg. Modeled v. Measured DJF Albedo



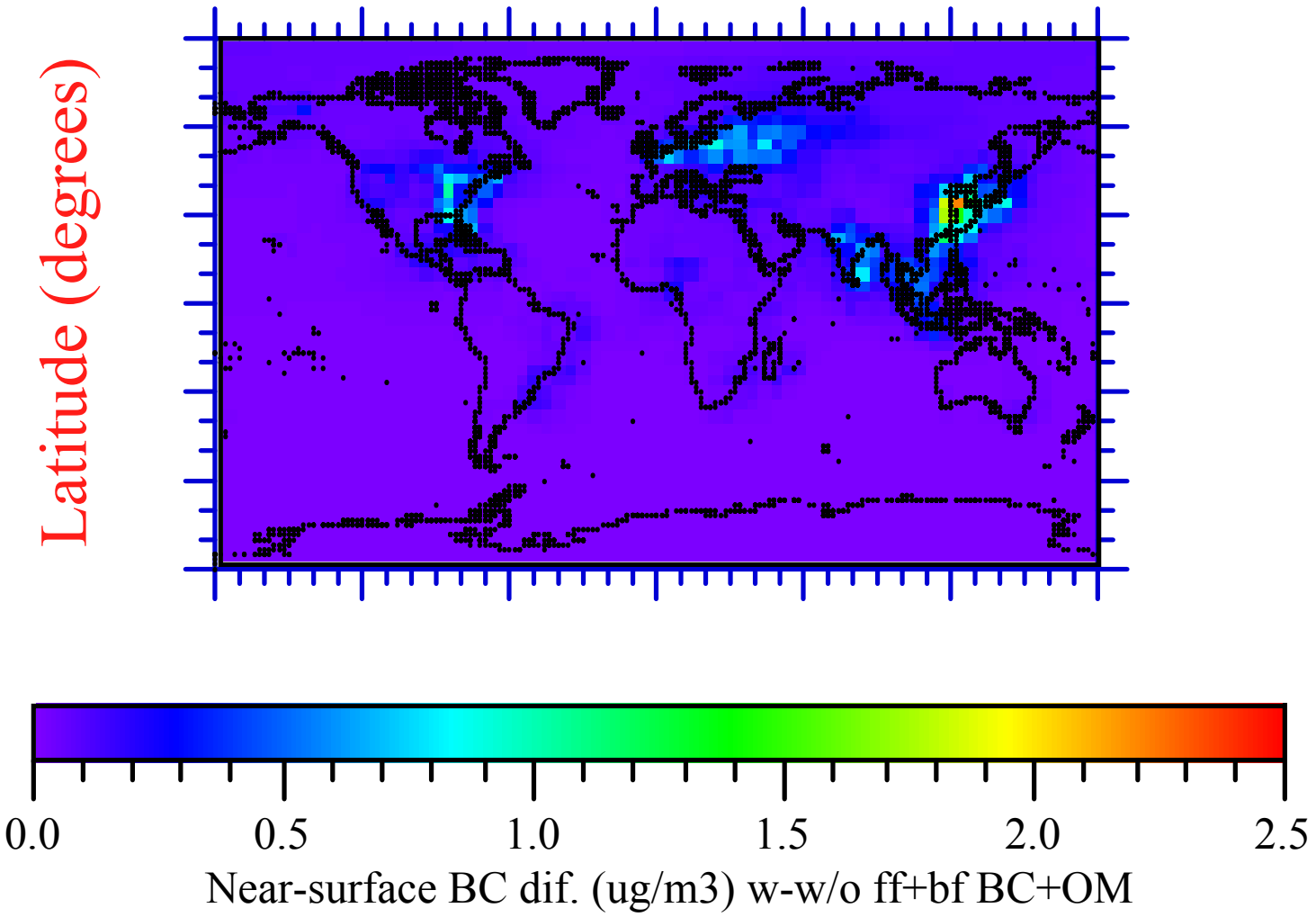
Data from Kiehl et al. (1998)

Ten-Year- Avg. Modeled BC From Fossil Fuels, Biofuels, and Biomass

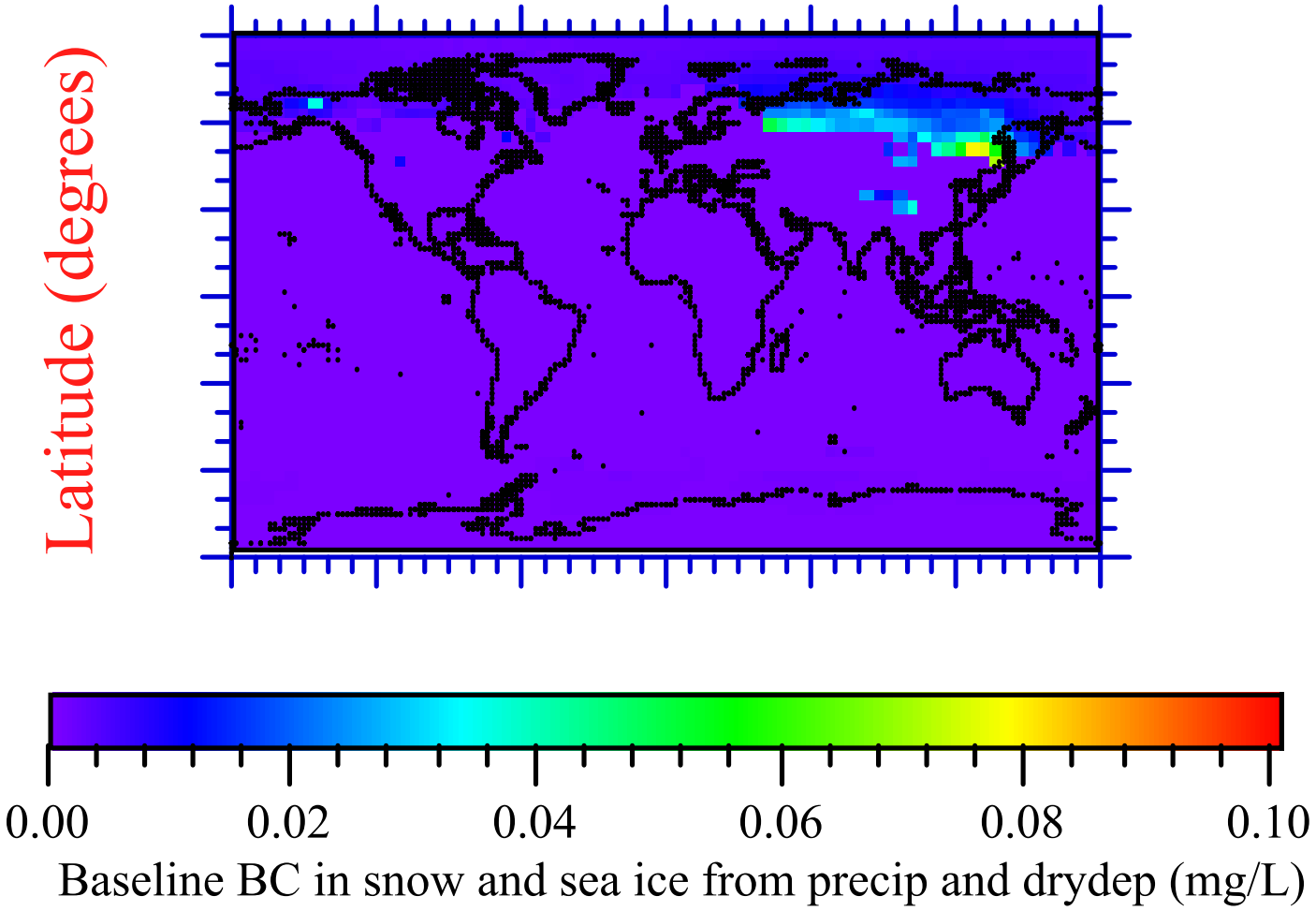


Emissions from early version of Bond, Streets et al. (2003):
3.9 Tg-ff+bf-BC-C, 6 Tg-ff+bf-OC-C, 3.1 Tg-bb-BC-C, 25.6 Tg-bb-OC-C

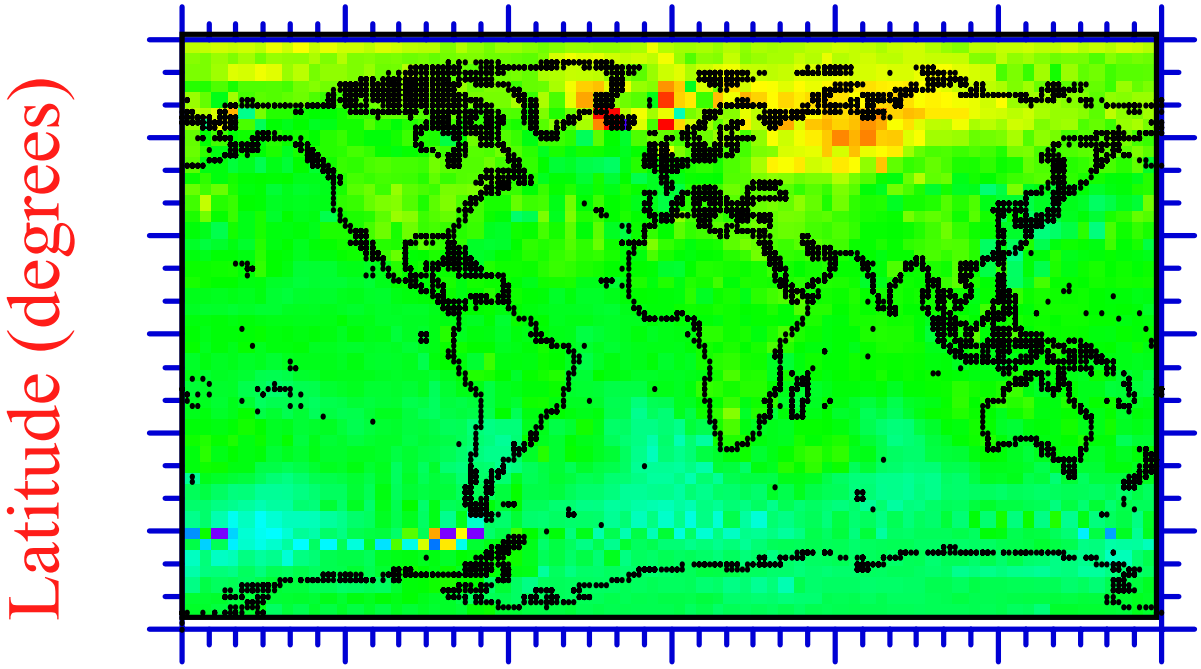
Ten-Year- Avg. Modeled BC From Fossil Fuels and Biofuels

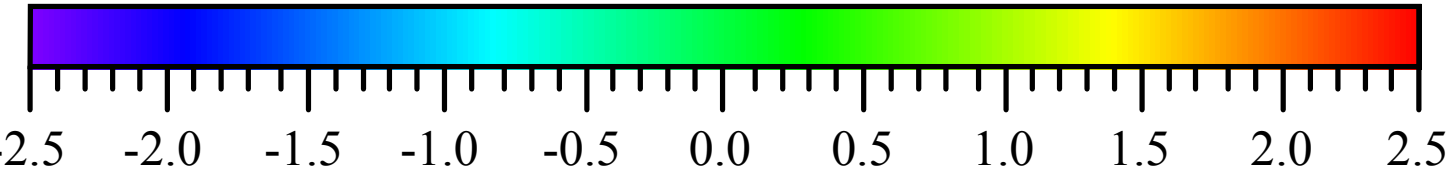


Modeled BC in Snow and Sea Ice



Ten-year Avg. Temperature Difference w-w/o ff+bf BC

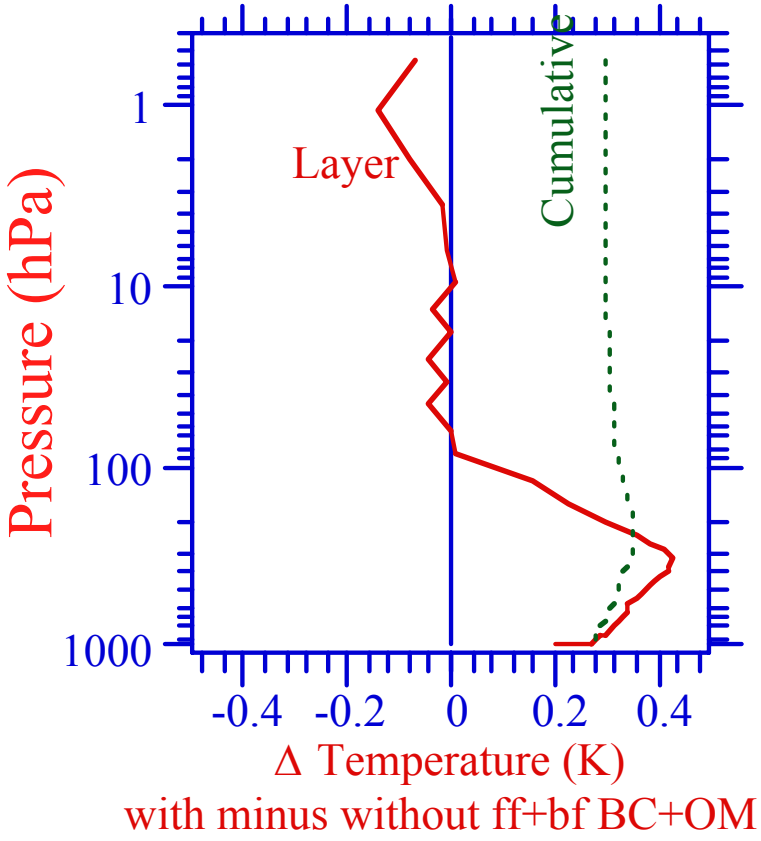




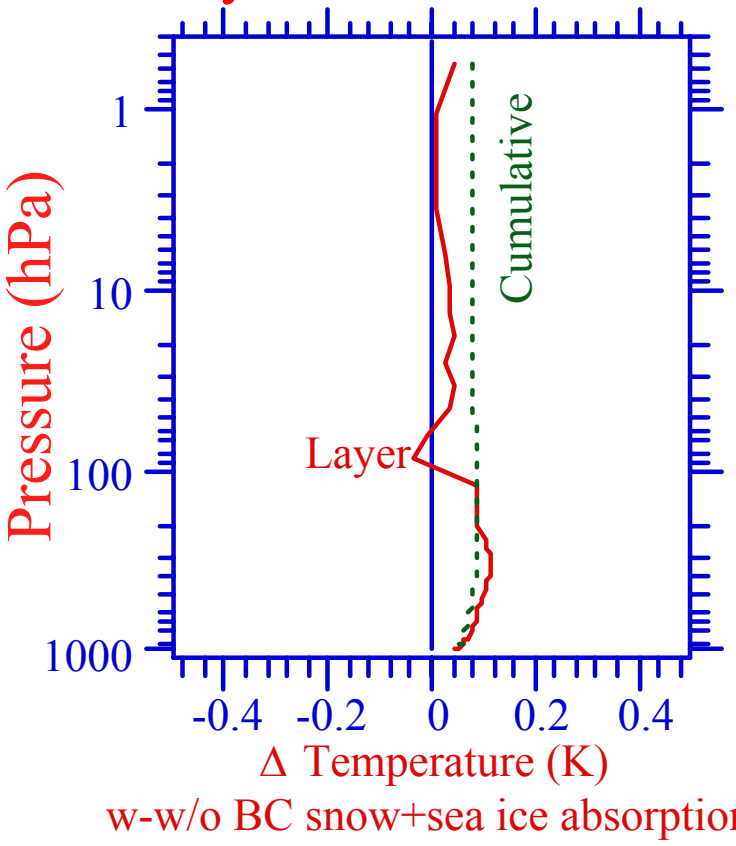
Near-surface temp. dif. (K), w-w/o ff+bf BC+OM, with snow/ice absorption

Ten-Year-Avg. Globally-Averaged Temperature Profile Differences

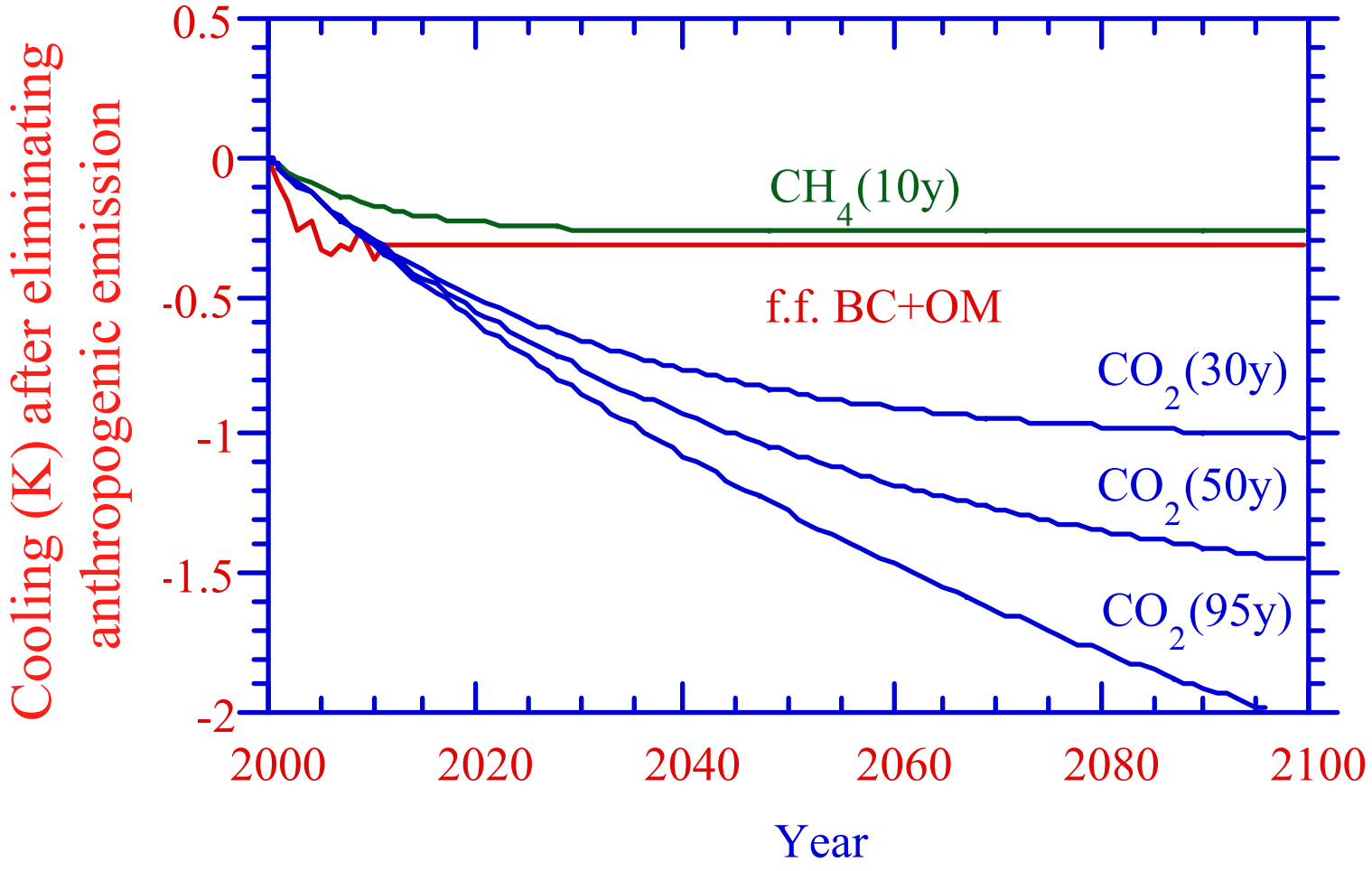
With snow/sea ice absorption and with-w/o ff+bf BC+OM



Contribution of BC absorption by snow/sea ice

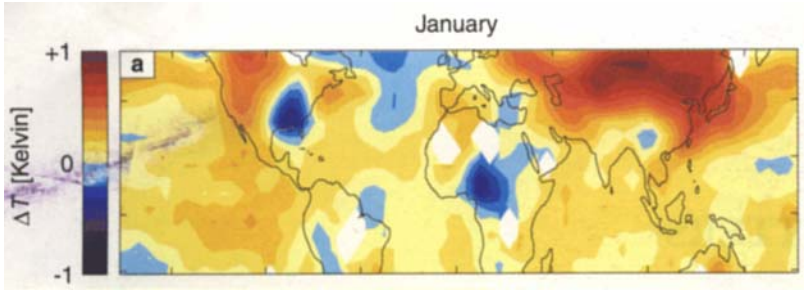


Temperature Changes Due to Eliminating Emission of Anthropogenic CO_2, CH_4, and f.f. BC+OM

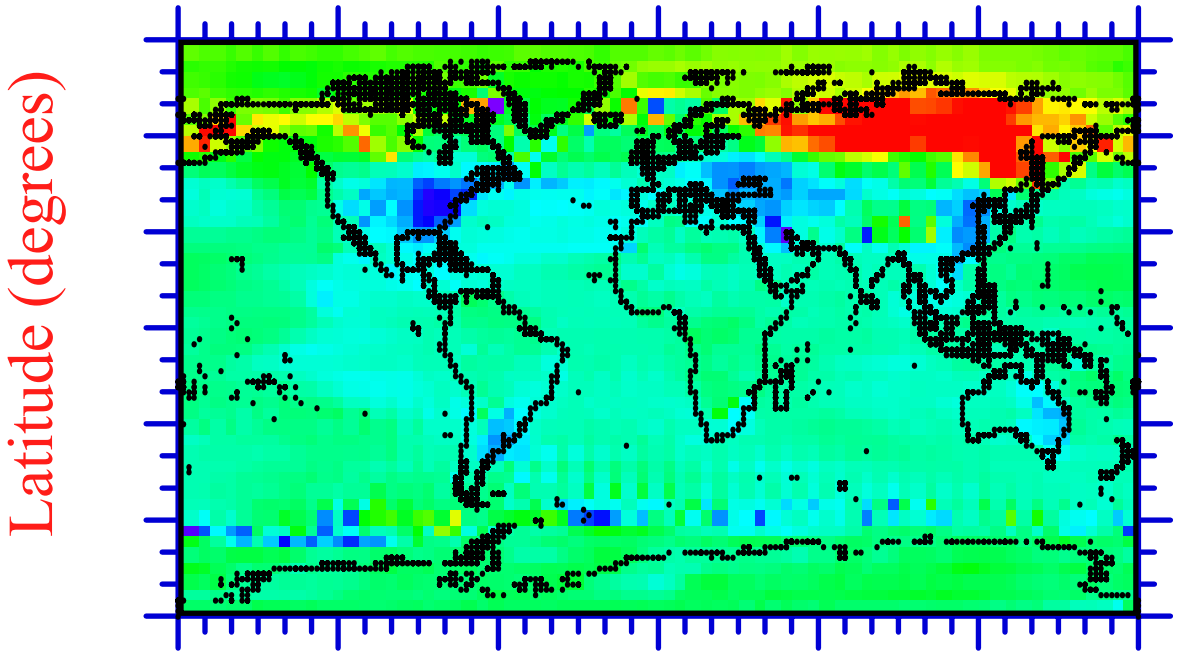


Observed and Modeled Temp. Diff. w-w/o GHG and Aerosols

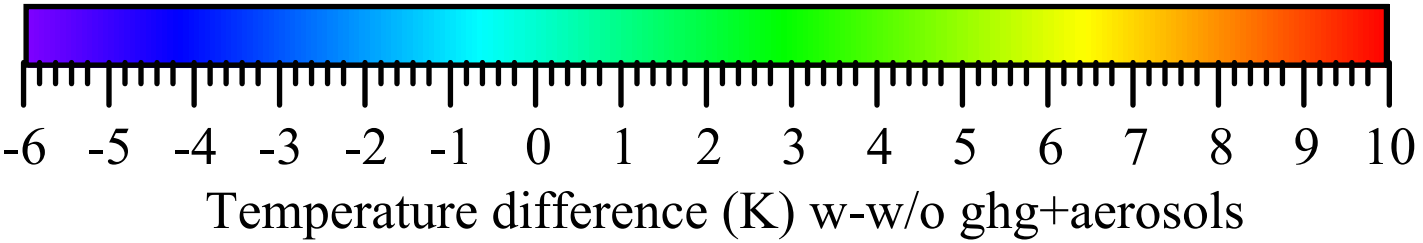
(January only



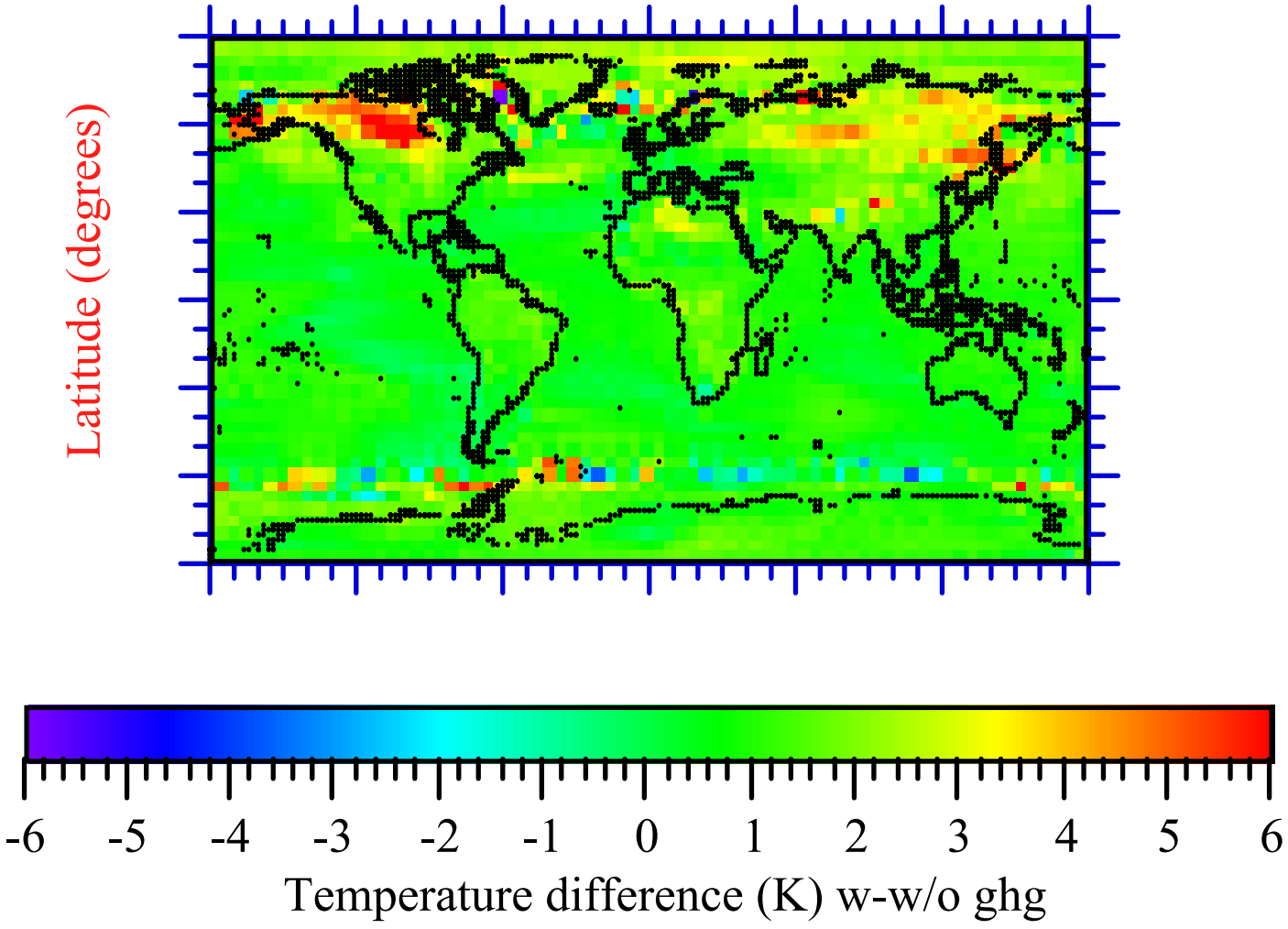
Schneider and Held (2001)



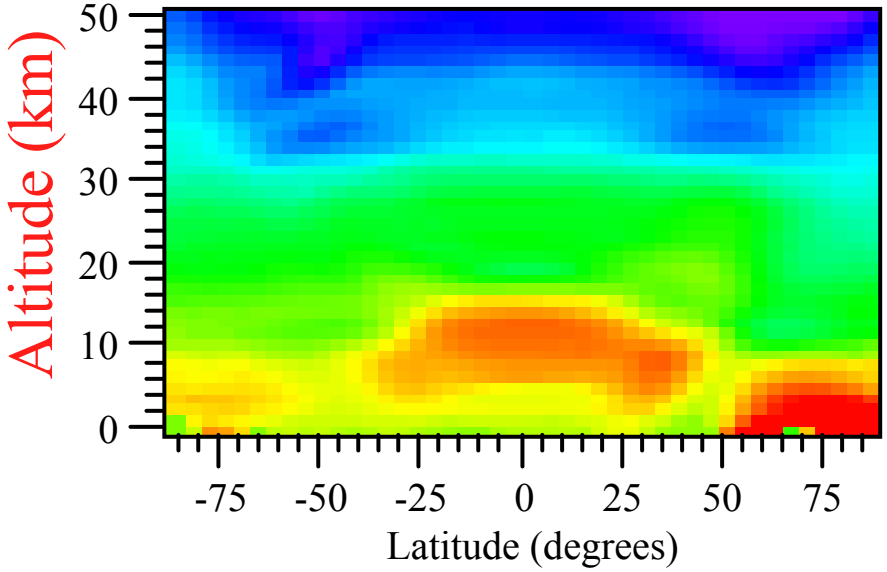
(4 y an. avg.)

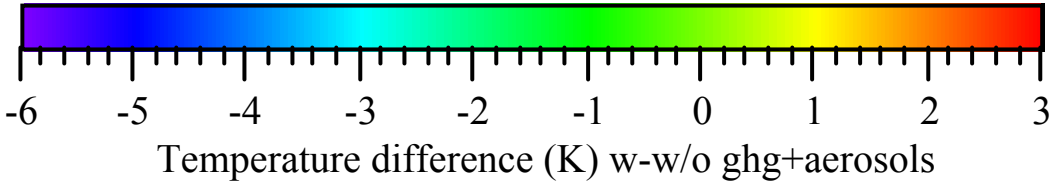


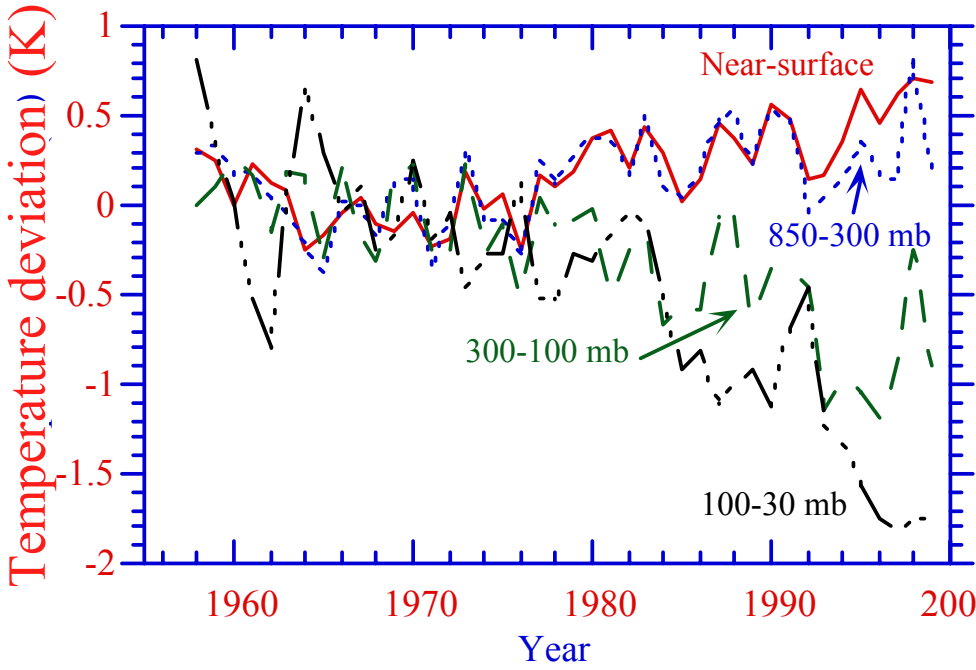
Modeled (4 y avg.) Temp. Diff. w-w/o Anth. GHG alone



Modeled (4 y avg.) and Radiosonde Vertical Temp. (K) dif. w-w/o GHG and Aerosols



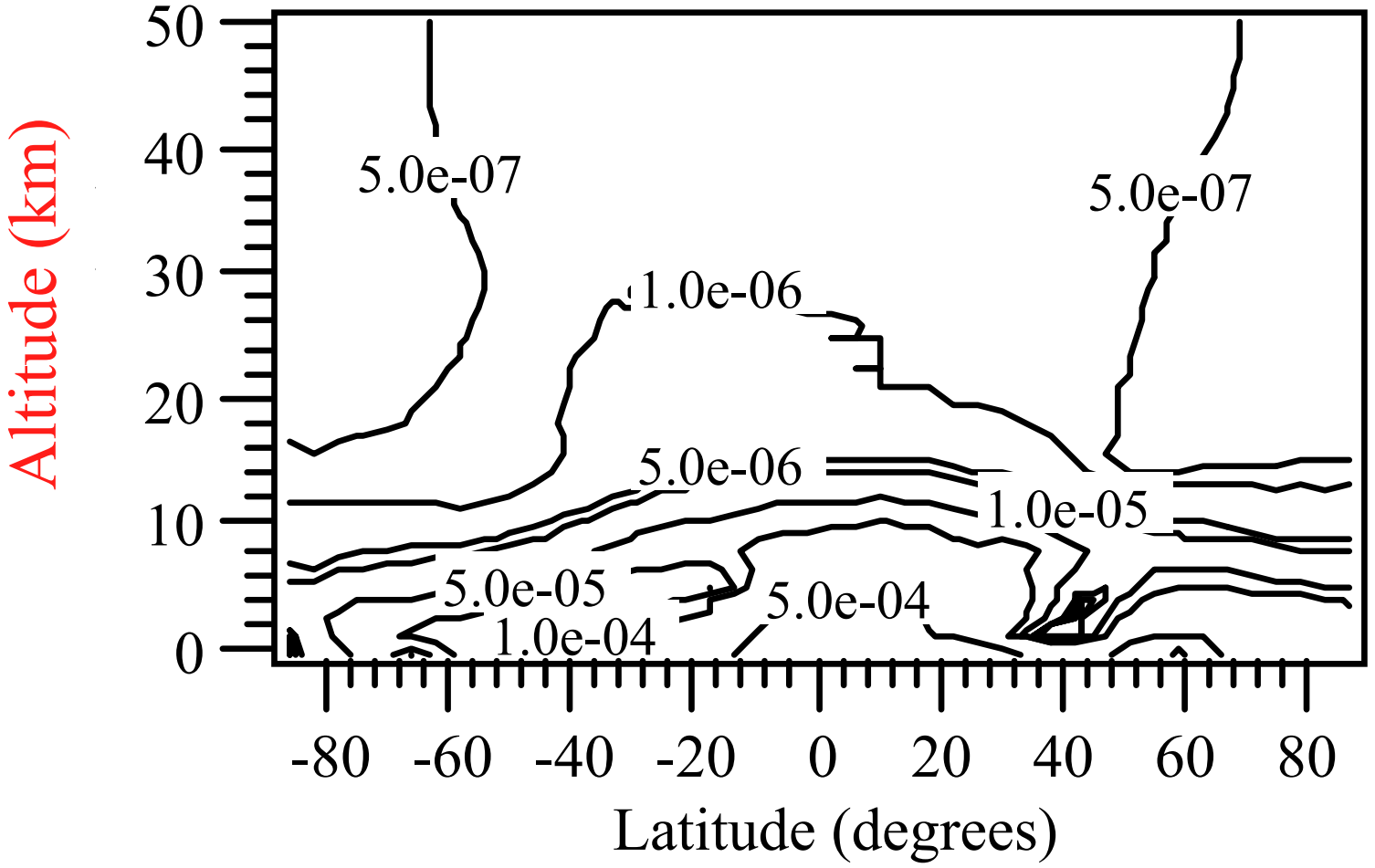




Radiosonde data
Angell et al. (1999)

300-100 mb ≈ 9-16 km
100-30 mb ≈ 16-24 km

Water Vapor Difference (kg/kg) With Minus Without Anth. GHG & Aerosols



Summary

- Simulations of the climate response of ff+bf BC+OM, all anthropogenic GHGs, and anthropogenic GHGs plus aerosols were run.
- Three baseline simulations gave warmings due to ff+bf BC of +0.25 to +0.3 K in the 5- to 10-year average. Additional results: +0.15 to +0.5 K
- Warming due to soot absorption in snow and sea ice was responsible for +0.06 K with a range of +0.03 to +0.11 K
- BC reduced snow and sea ice albedo by about 0.4% globally and 1% in N. Hem. The global model BC in snow and sea ice was about 5 ng/g; that in rainfall was about 22 ng/g. About 98% of BC removal from the atmosphere was due to precipitation; the rest, to dry deposition.
- Maximum warming and cooling due to anthropogenic GHGs and aerosols exceed those of GHGs alone. Aerosols act on top of GHGs to enhance extreme warm and cool climate conditions.
- Near source particle evolution appears to be due to coagulation, whose rate is enhanced by evaporation; condensation appears to play little role.

Ten-Year-Avg. Globally-Averaged Net Irradiance Diff. w-w/o ff+bf BC+OM