Effects of Black Carbon and CO_2 Domes on Climate and Air Quality

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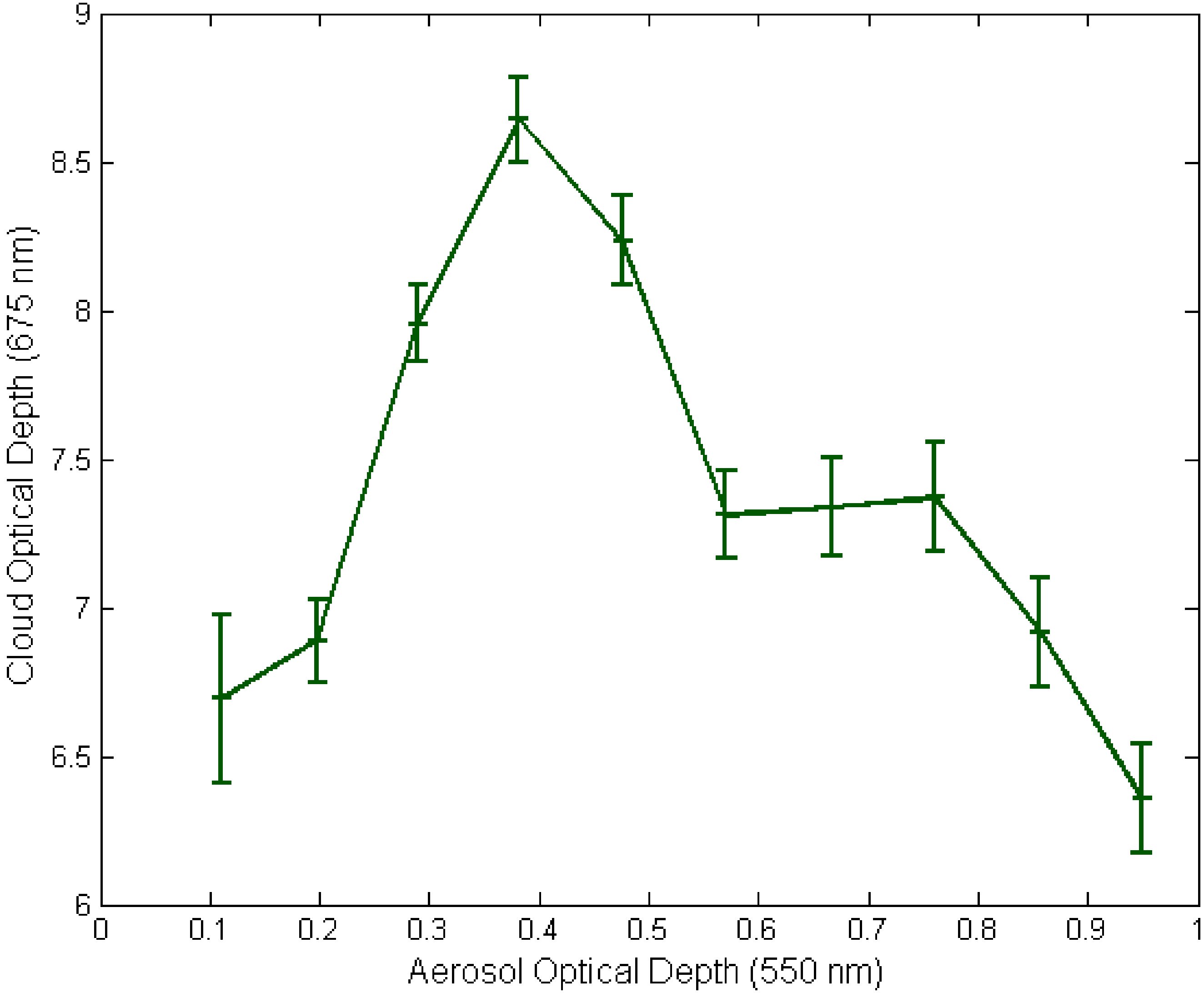
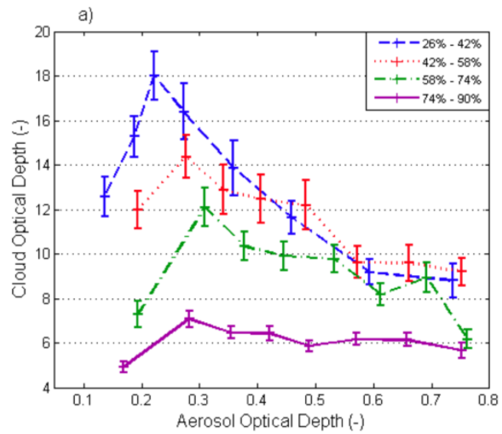
Consequences of Global Change for Air Quality Progress Review
Oct. 4, 2010, U.S. EPA, Research Triangle Park, North Carolina

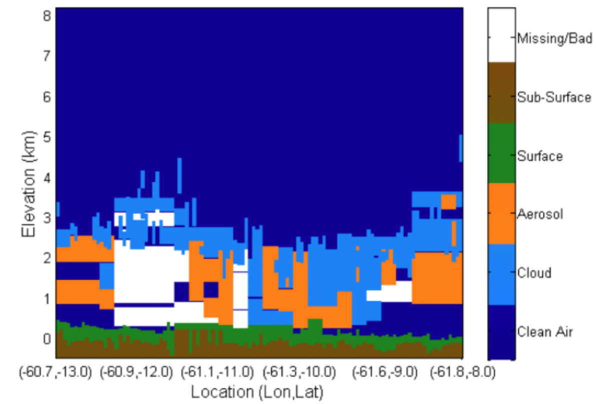
MODIS Aqua Cloud Optical Depth vs. AOD Over Biomass-Burning Region Brazil Sep '06

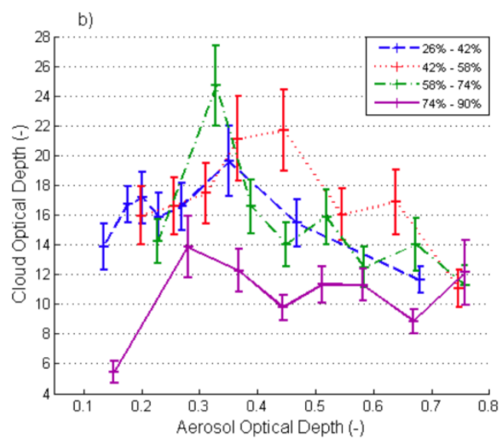


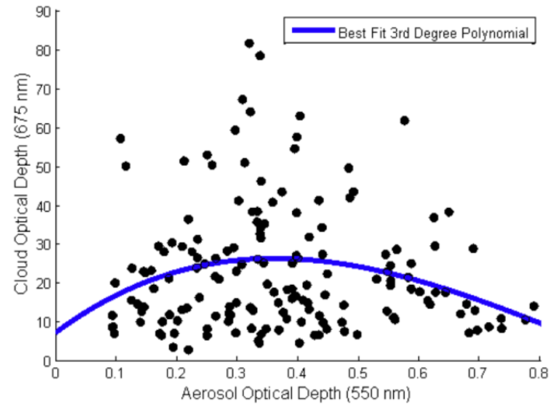
Ten Hoeve, Remer, and Jacobson (2010)

Boomerang Effect: Satellite COD vs. AOD







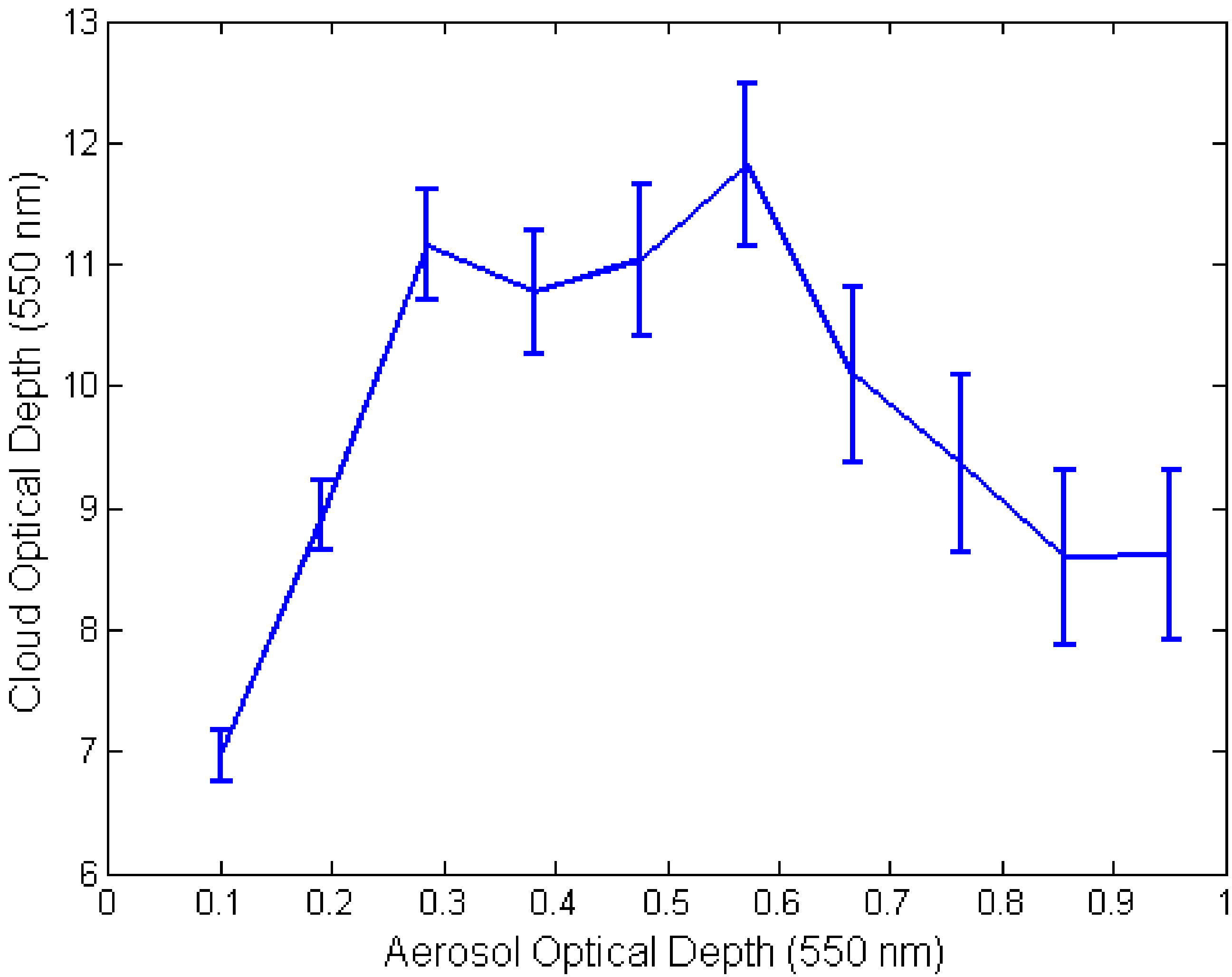


MODIS, binned by percentile column water vapor 2004-07 for (a) all clouds (b) low clouds → boomerang for all water bins

Calipso Lidar Aug. 12, 2006 → aerosols below/within clouds → boomerang from MODIS

Ten Hoeve, Remer, and Jacobson (2010)

GATOR-GCMOM Model COD vs. AOD Sep. '06



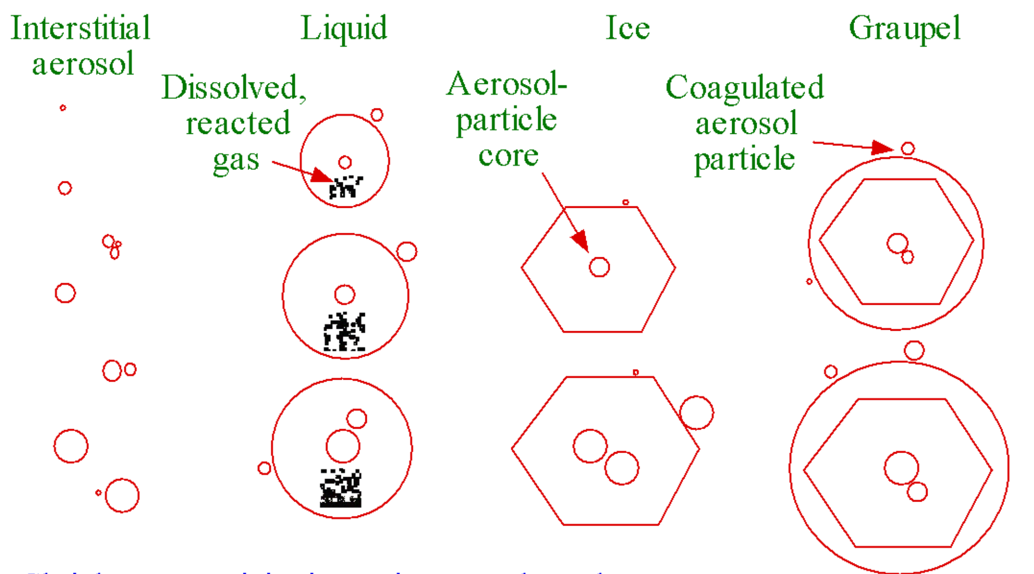
Ten Hoeve, Remer, and Jacobson (2010)

Cloud Microphysical and Chemical Processes

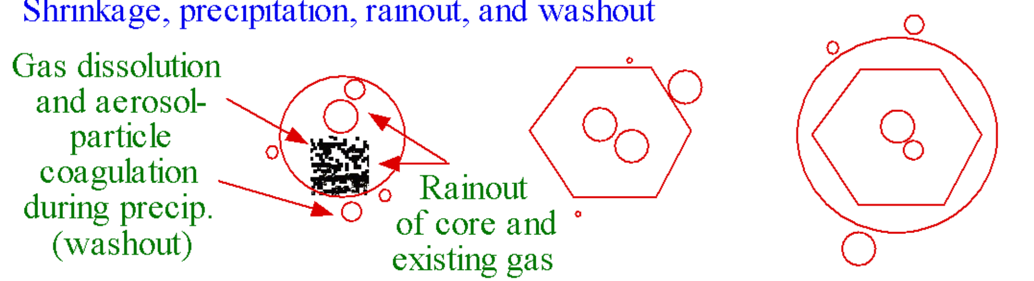
Condensation/deposition of water vapor onto aerosol particles

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



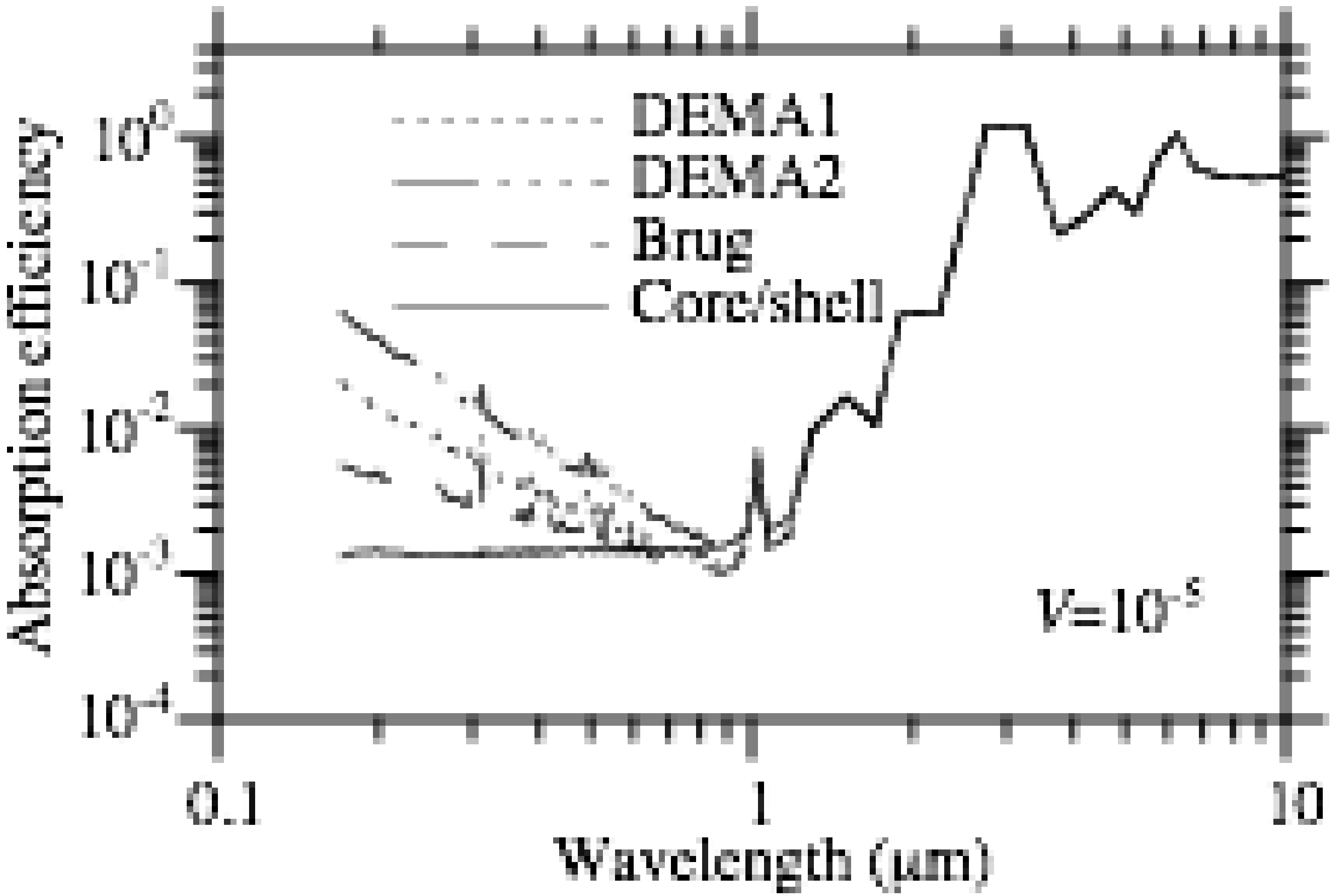
Shrinkage, precipitation, rainout, and washout



Cloud evaporation --> interstitial aerosol plus evaporated cores

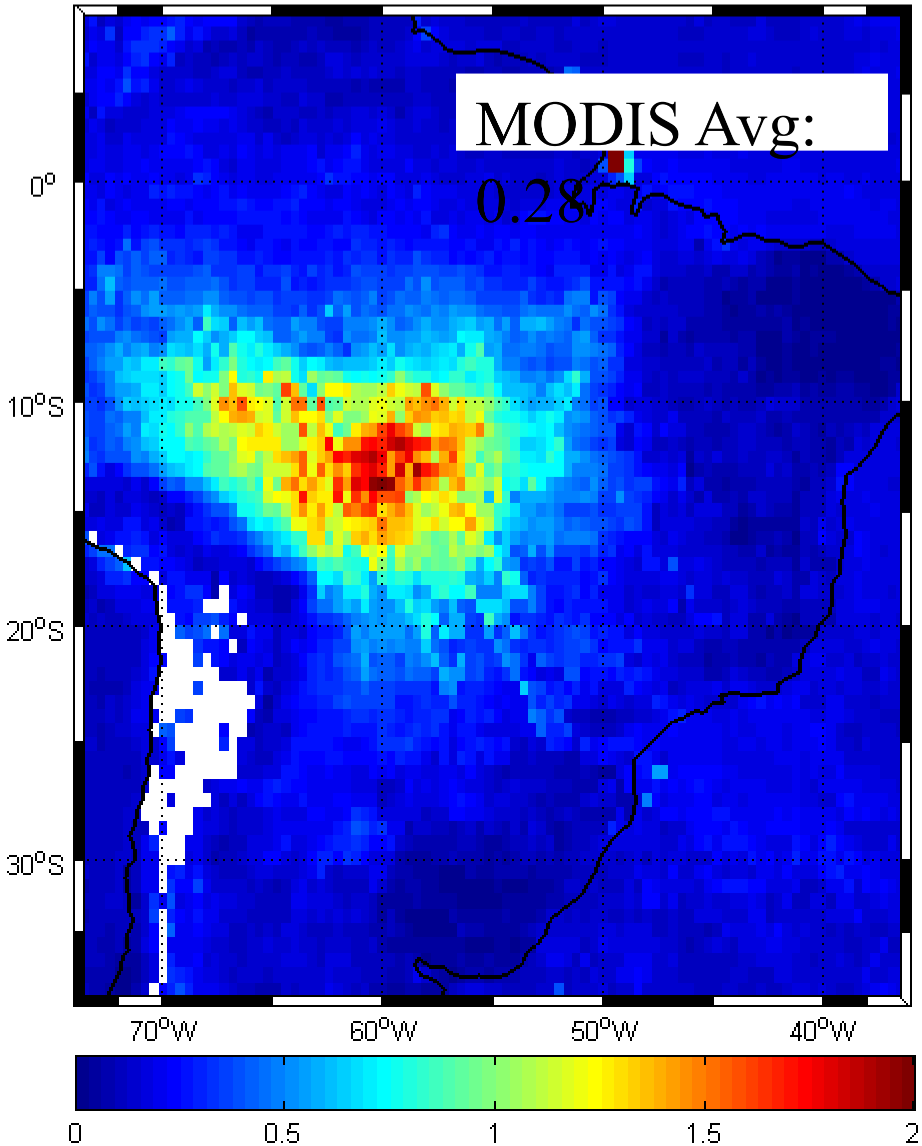
Absorption Efficiency 12.6-micron cloud drops

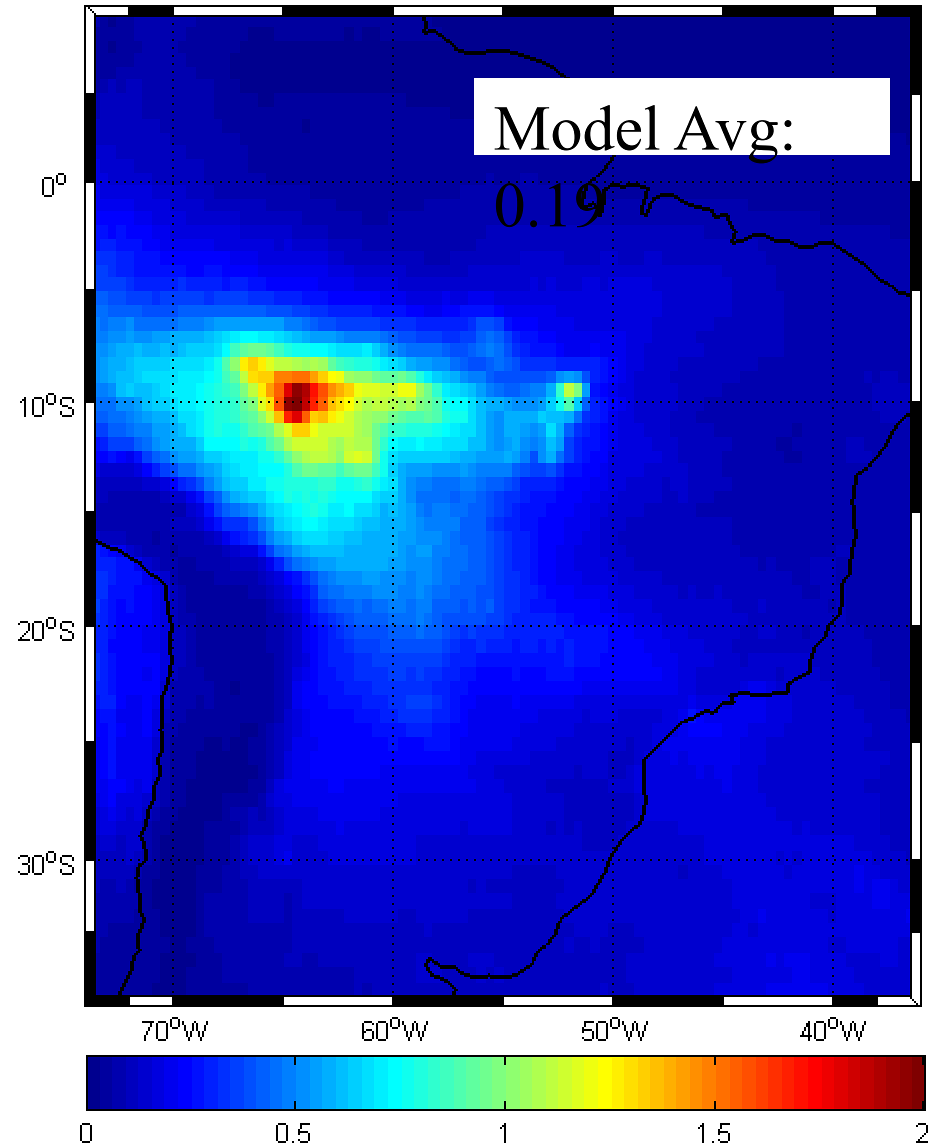
DEMA1,2=0.1-, 0.2-micron BC inclusions; Brug=Bruggeman (BC well-mixed); Core/shell=single BC core



Jacobson, J. Phys. Chem. (2006)

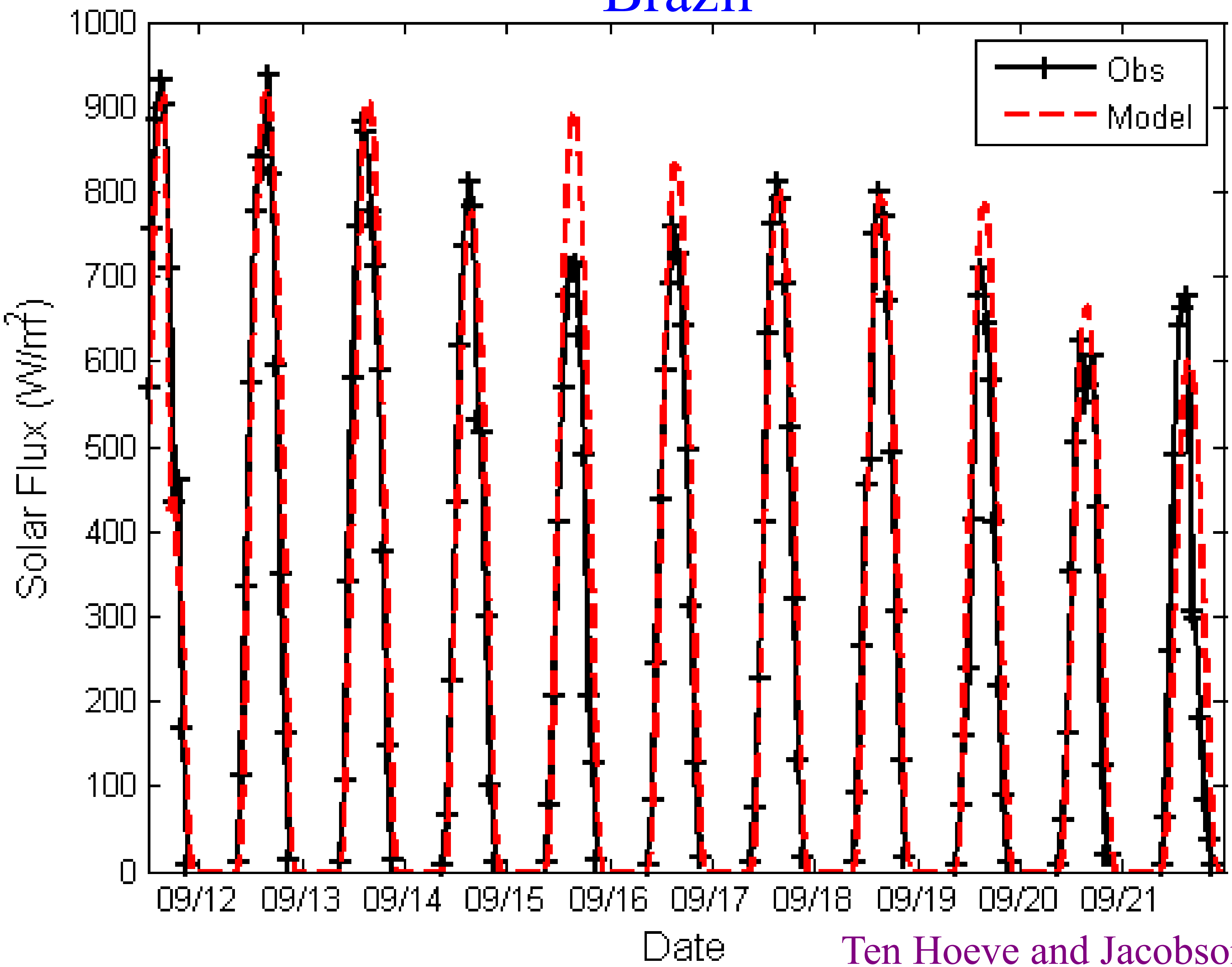
MODIS / Model Aerosol Optical Depth





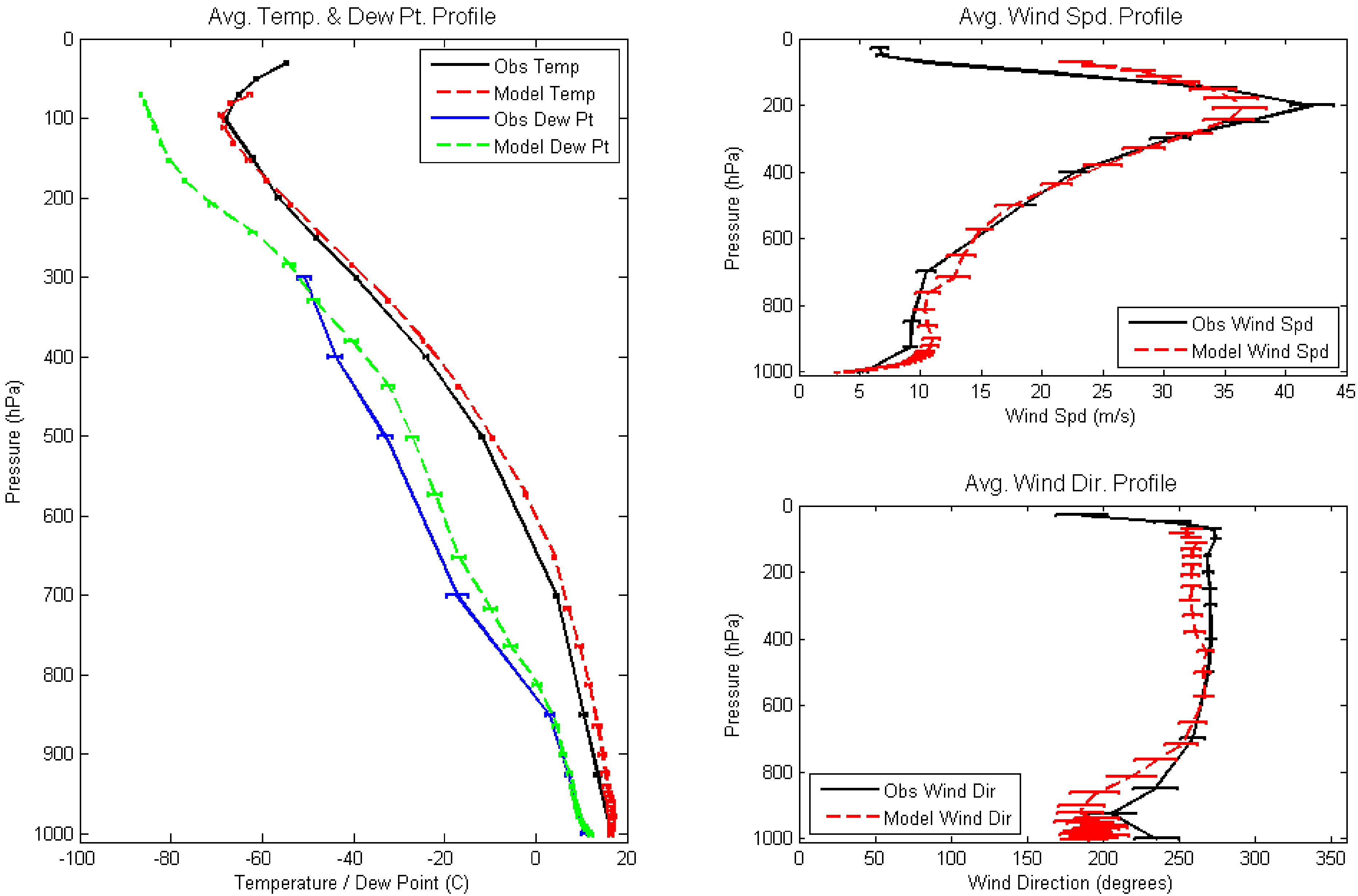
Ten Hoeve, Remer, and Jacobson (2010)

Modeled vs. Aeronet Solar Irradiance at Cuiaba-Miranda, Brazil



Ten Hoeve and Jacobson (2010)

Model vs. Radiosonde Downwind of Biomass Burn, Sep. 2006



Ten Hoeve and Jacobson (2010)

Global Simulations

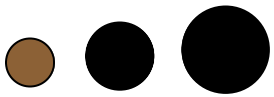
Simulate the relative effects of controlling fossil-fuel soot (FS), biofuel soot and gases (BSG), and methane on global and Arctic climate and human health.

Simulations run

1) Baseline (all gases, particles from all sources)
2) Time-dependent simulations without FS
3) Time-dependent simulation without FS or BSG
4) Equilibrium climate simulations without methane, CO_2.

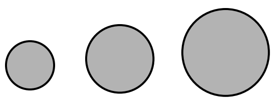
Aerosol Size Distributions

Two distributions, each with multiple size bins and components per bin



Emitted fossil-fuel soot (EFFS)

Emission sources: fossil-fuel combustion



Internally-mixed (IM)

Emission sources: biofuel burning, biomass-burning, sea spray, soil dust, road dust, volcanos, pollen, spores, bacteria

Homogeneous nucleation: H_2SO_4-HNO_3-H_2O into IM distribution

Coagulation:

EFFS + EFFS = EFFS

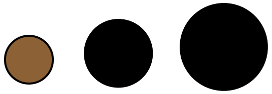
EFFS + IM = IM

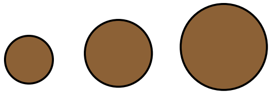
IM + IM = IM

Growth: Organic matter, H_2SO_4, HNO_3, HCl, NH_3 H_2O grow on both EFFS & IM

Clouds: Both distributions activate size-resolved liquid, ice, graupel clouds

Fine Fossil-, Bio-fuel Emissions (Tg/yr)

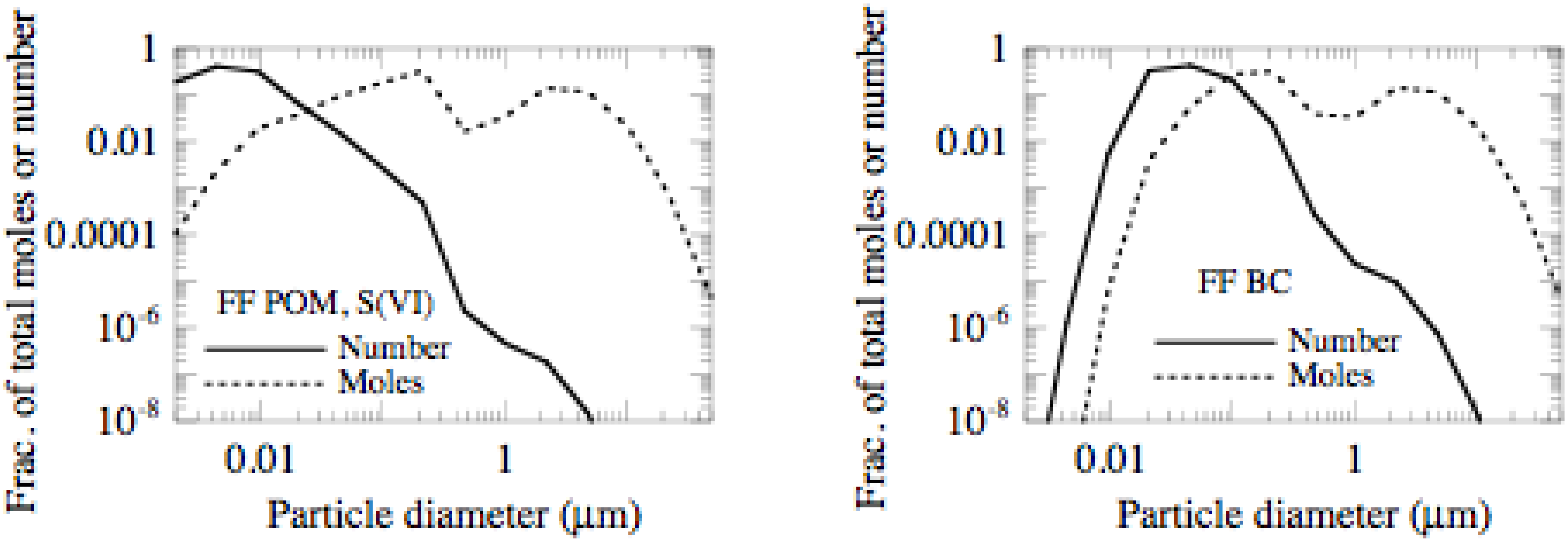




	Fossil-Fuel	Biofuel
BC	3.2	1.6
POC	2.4	6.5
S(VI)	0.03	0.3
Na^+		0.023
K^+ as Na^+		0.14
Ca^{2+} as Na^+		0.18
Mg^{2+} as Na^+		0.08
NH_4^+		0.018
NO_3-		0.16
Cl-		0.30
H_2O-hydrated	calculated	calculated
H+	calculated	calculated
		+ 43 gases

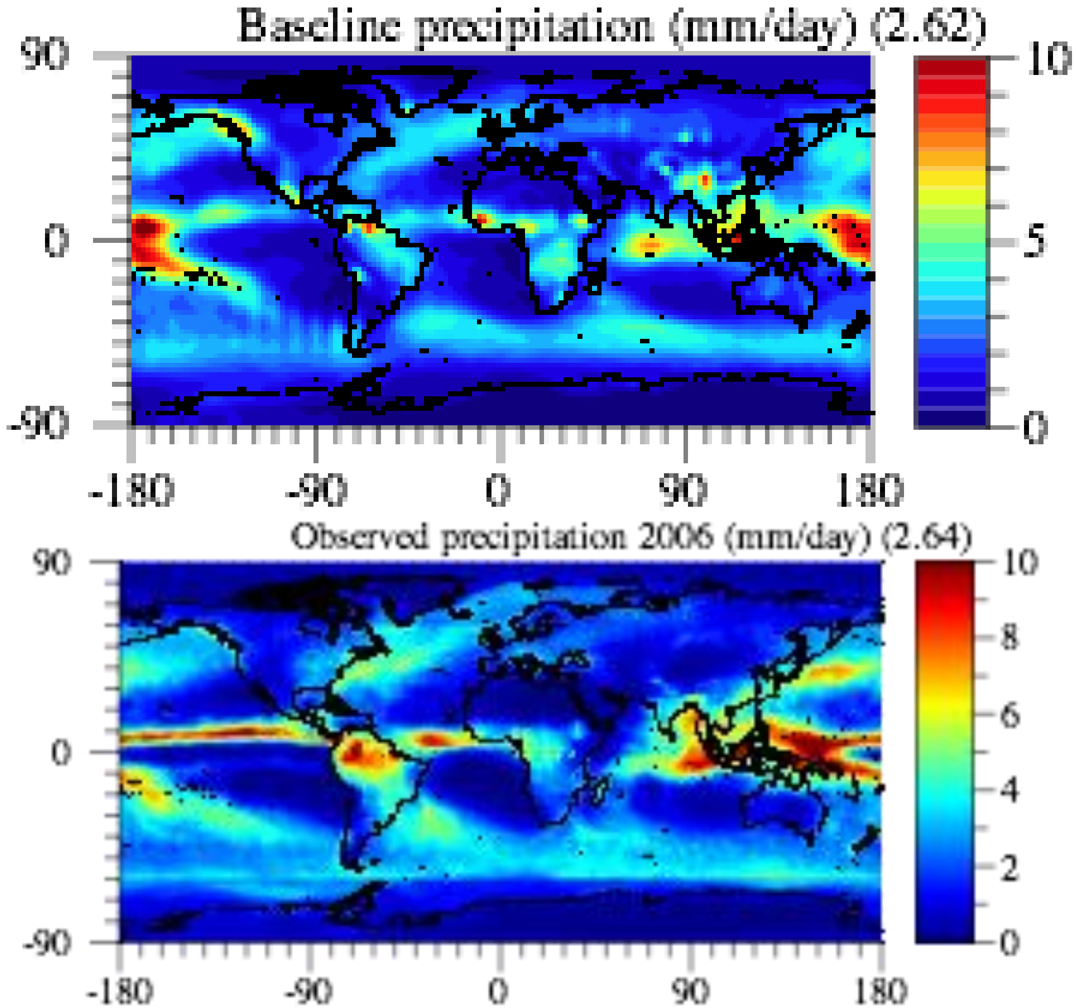
BC/POC from Bond et al. (2004); other emis factors Andreae, Ferek

Relative Fossil-Fuel POM, S(VI), BC Emission Size Distributions



Distributions based on fits to EEPS data for vehicles and BC spherule size limits from EST 39, 9486, 2005, except that a coarse mode was added for FF-sources that emit coarse PM (e.g., tire particles, stationary sources).

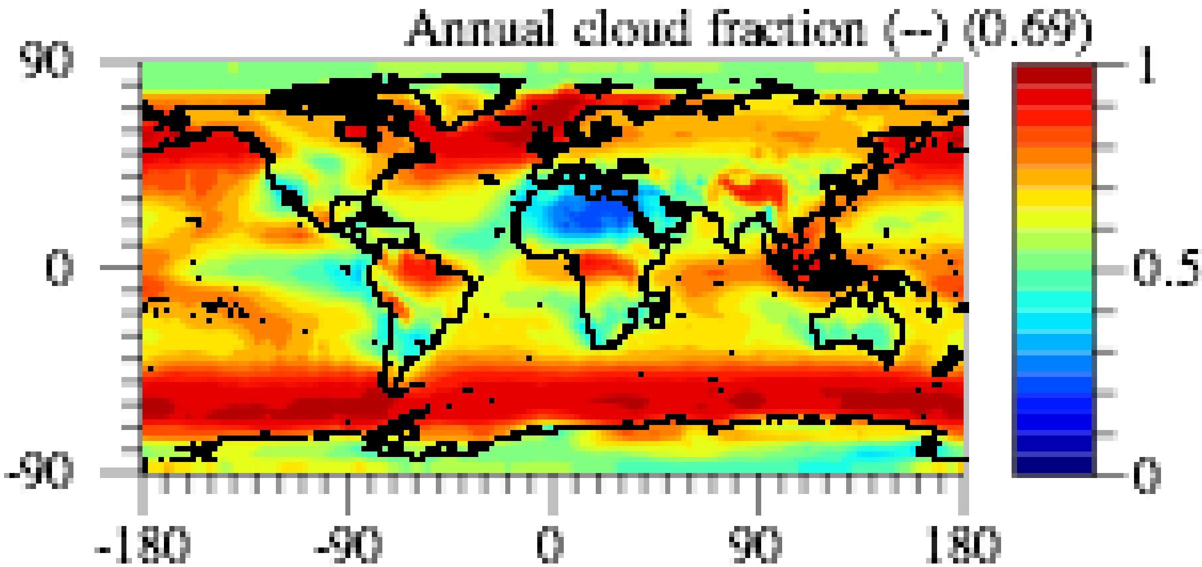
Baseline Modeled vs. Measured Precip.

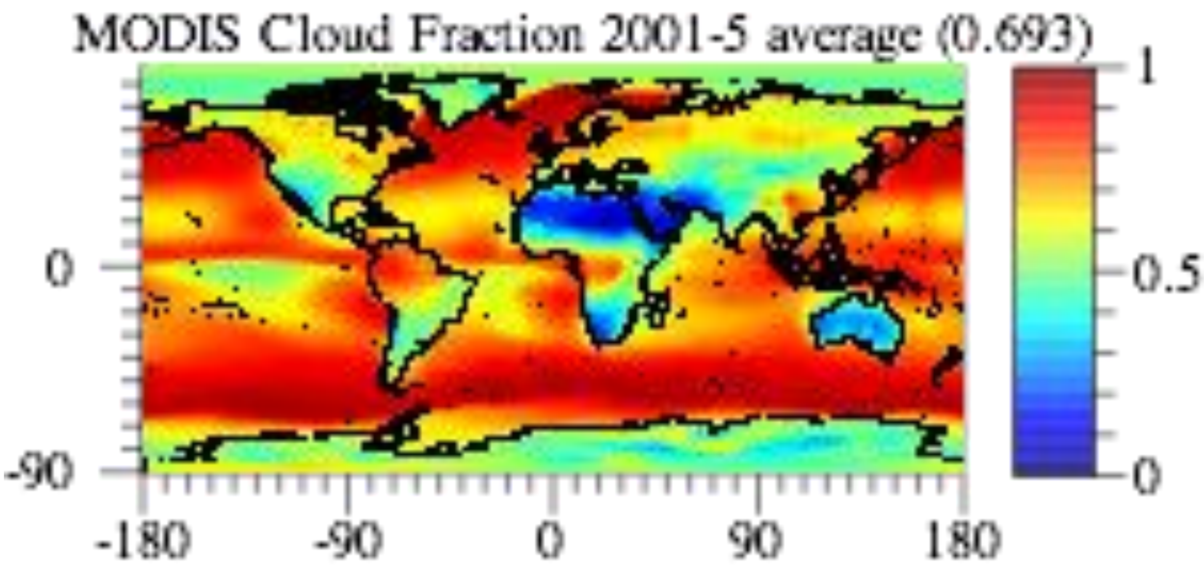


Data from Huffman et al. (2007)

Despite factor of 20 lower resolution than data, model predicts locations of main features of observed precipitation and, with no flux adjustment, correctly does not produce a double ITCZ as nearly all models at coarse resolution do.

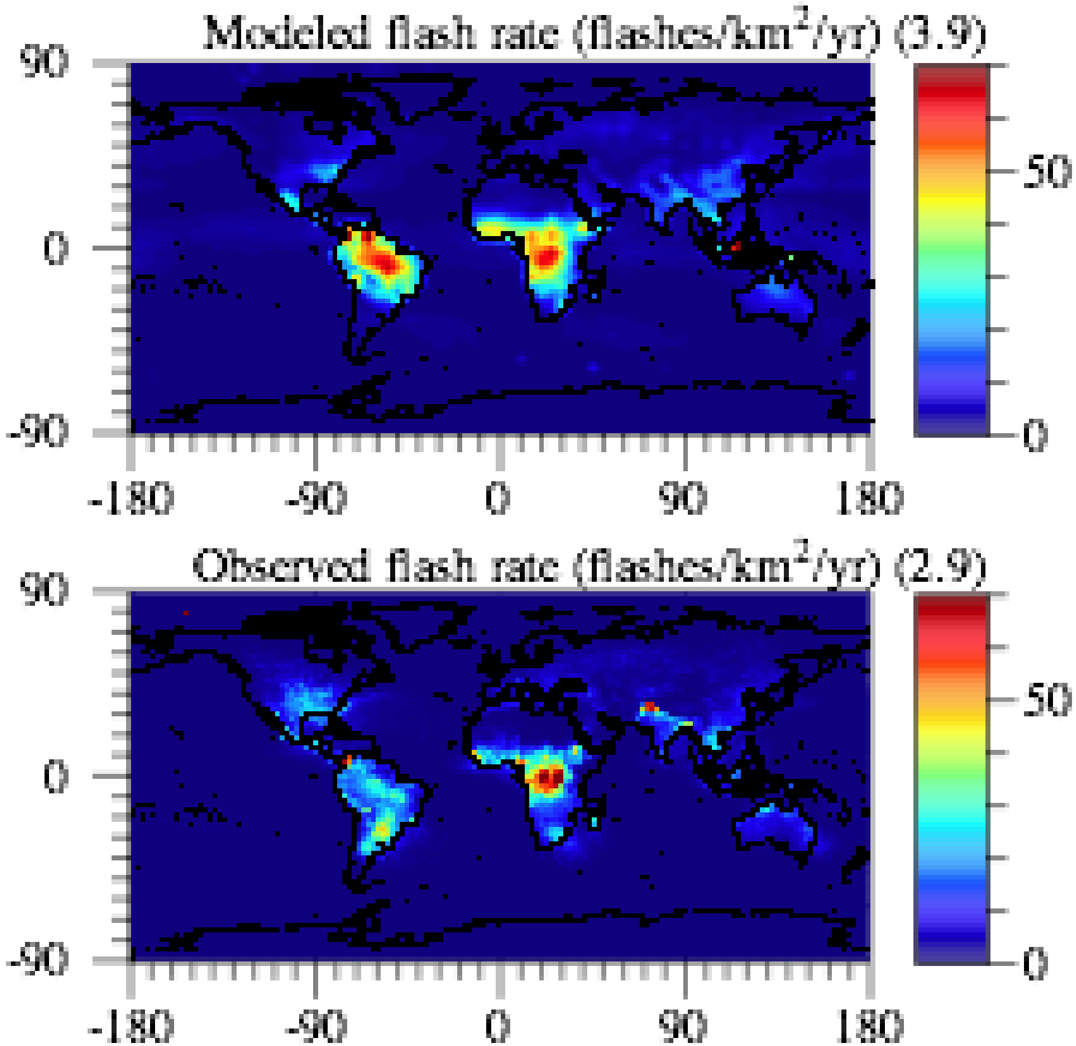
Modeled vs. Measured Cloud Fraction





Data from MODIS

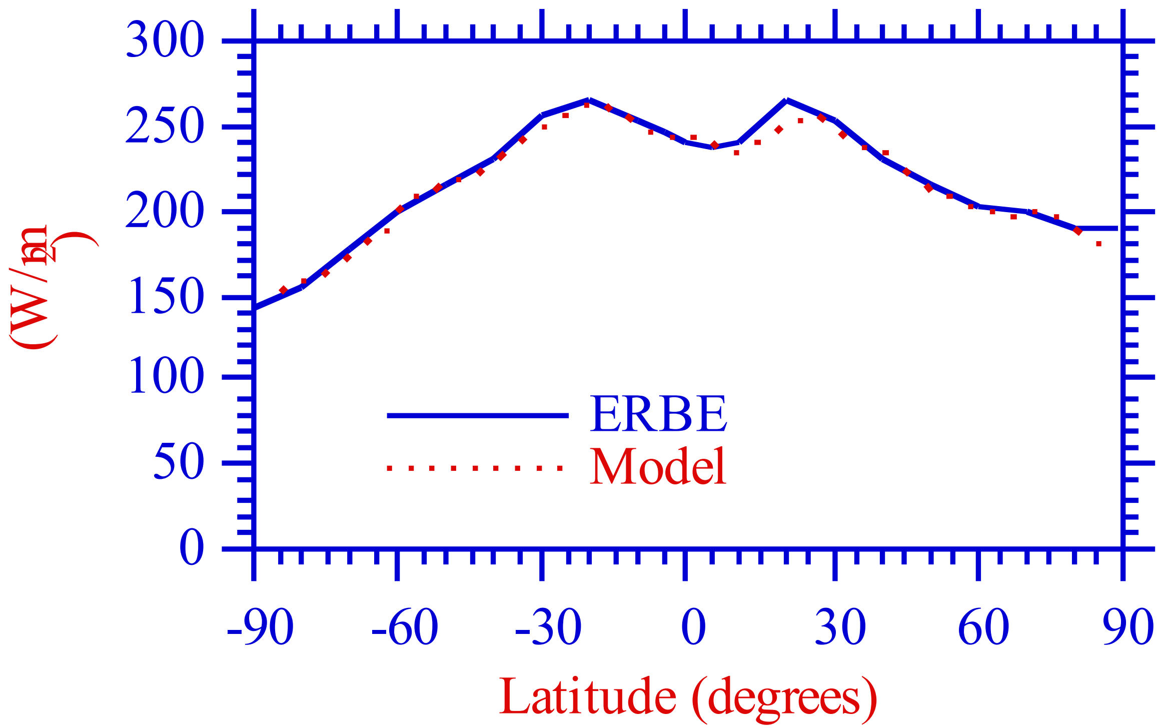
Modeled vs. Measured Annual Lightning Flash Rate



Data from NASA LIS/OTD Science Team

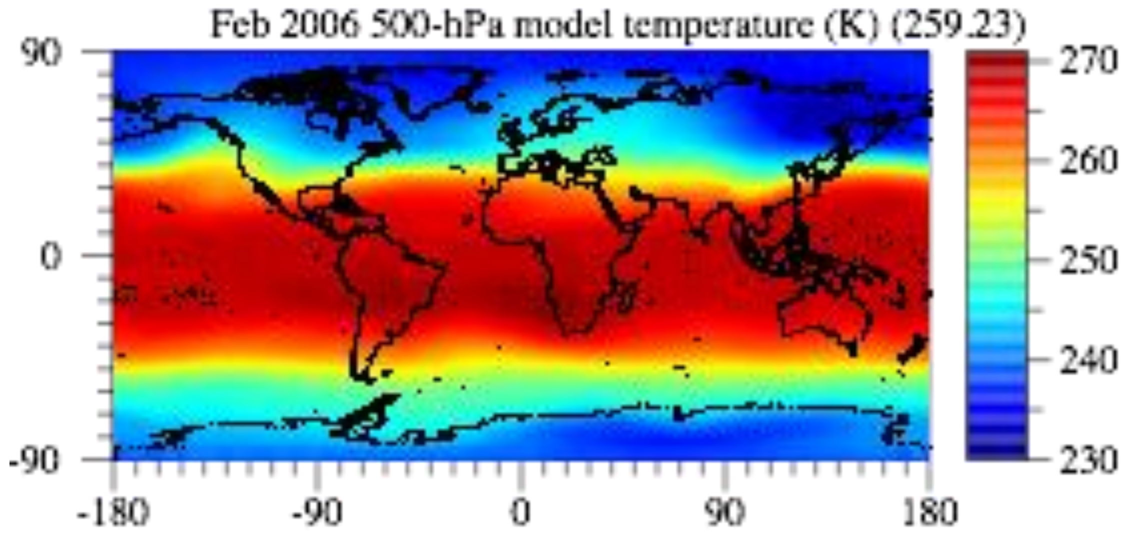
Model calculates lightning by accounting for size-resolved bounceoffs and charge separation in clouds. It predicts nearly the magnitude and the location of the peak observed lightning (Congo) and most locations of lightning.

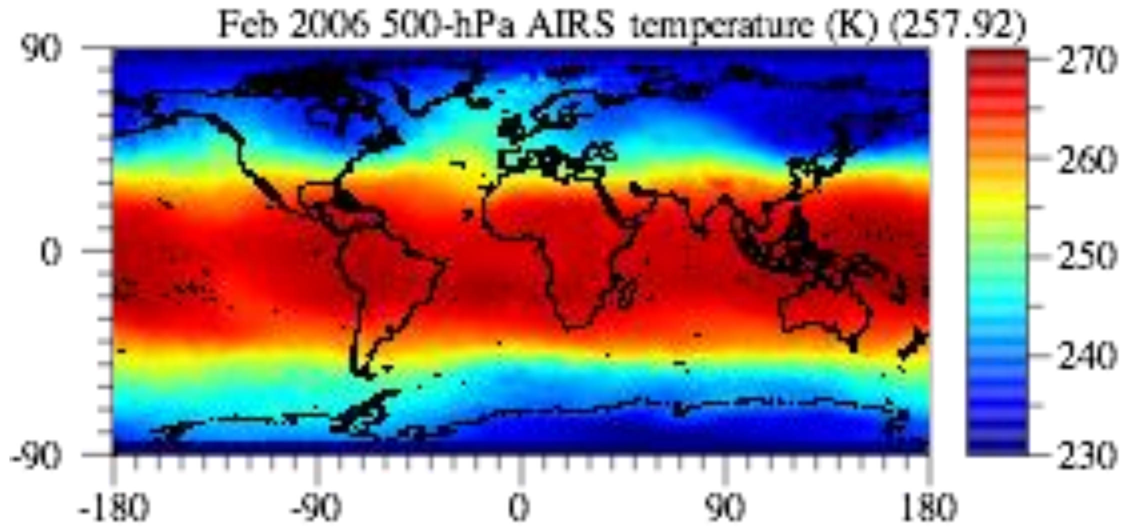
Modeled vs. Measured Thermal-IR



Data from Kiehl et al., 1998

Modeled vs. Measured 500-hPa Jan Temperature



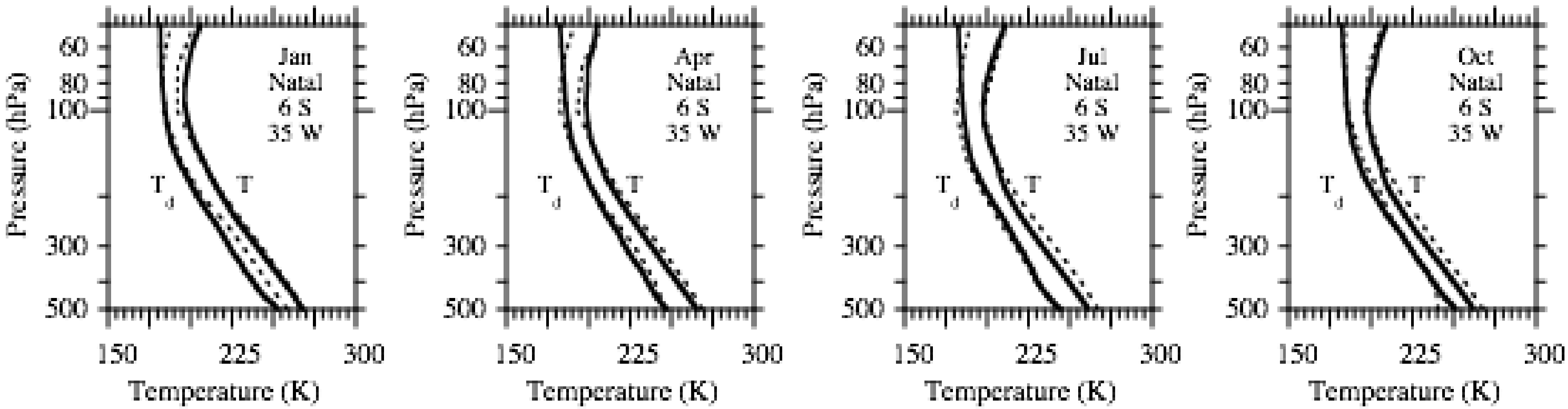


Data from AIRs

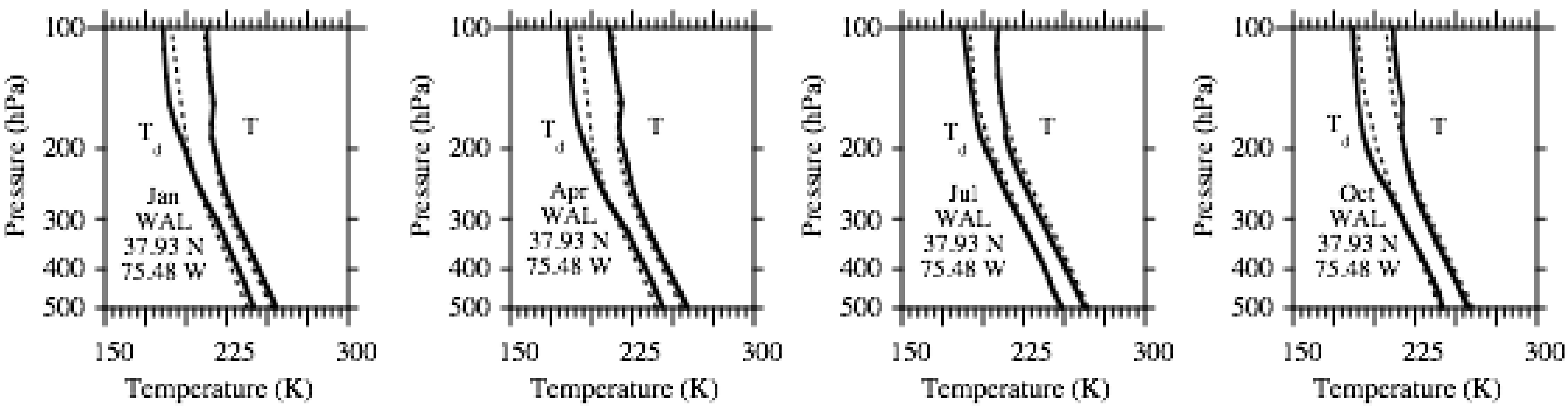
Modeled vs. Measured Paired in Space Monthly T/T_d

Global domain

Data from FSL (2008)



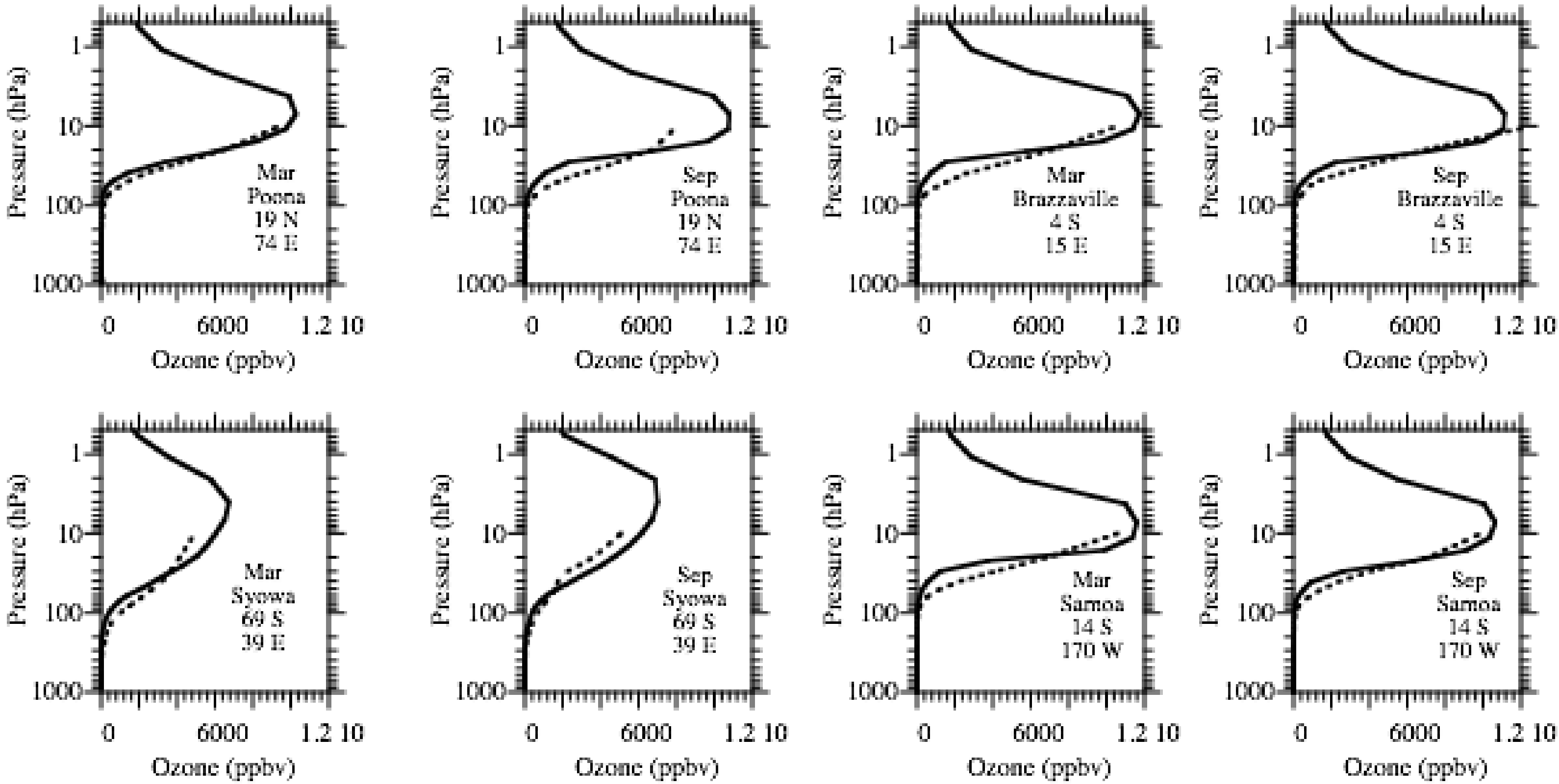
U.S. domain



Despite coarse resolution, model captures data features at exact location of data
- Little numerical diffusion of water vapor or energy to stratosphere

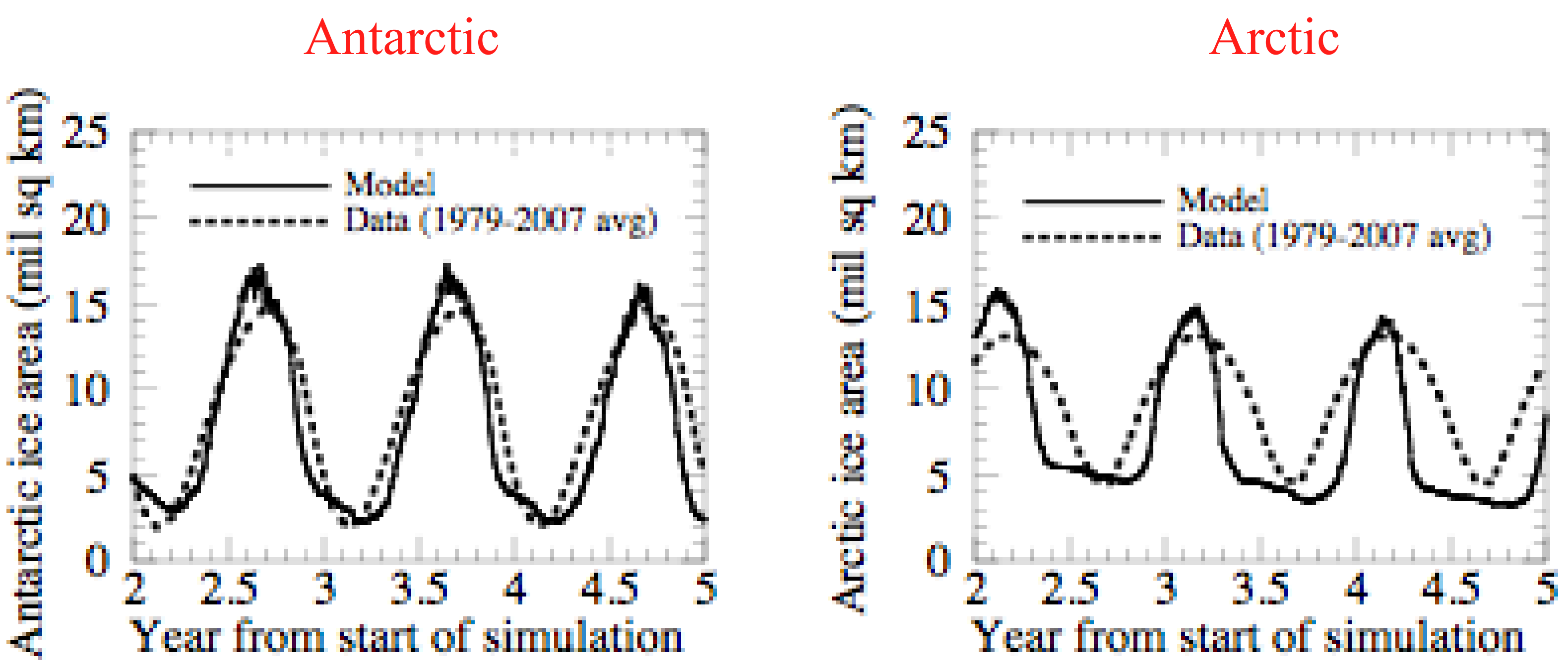
Modeled vs. Measured Paired in Space Monthly O_3

Data from Logan et al. (1999)



Model predicts the magnitude and altitude of the lower-stratospheric ozone layer

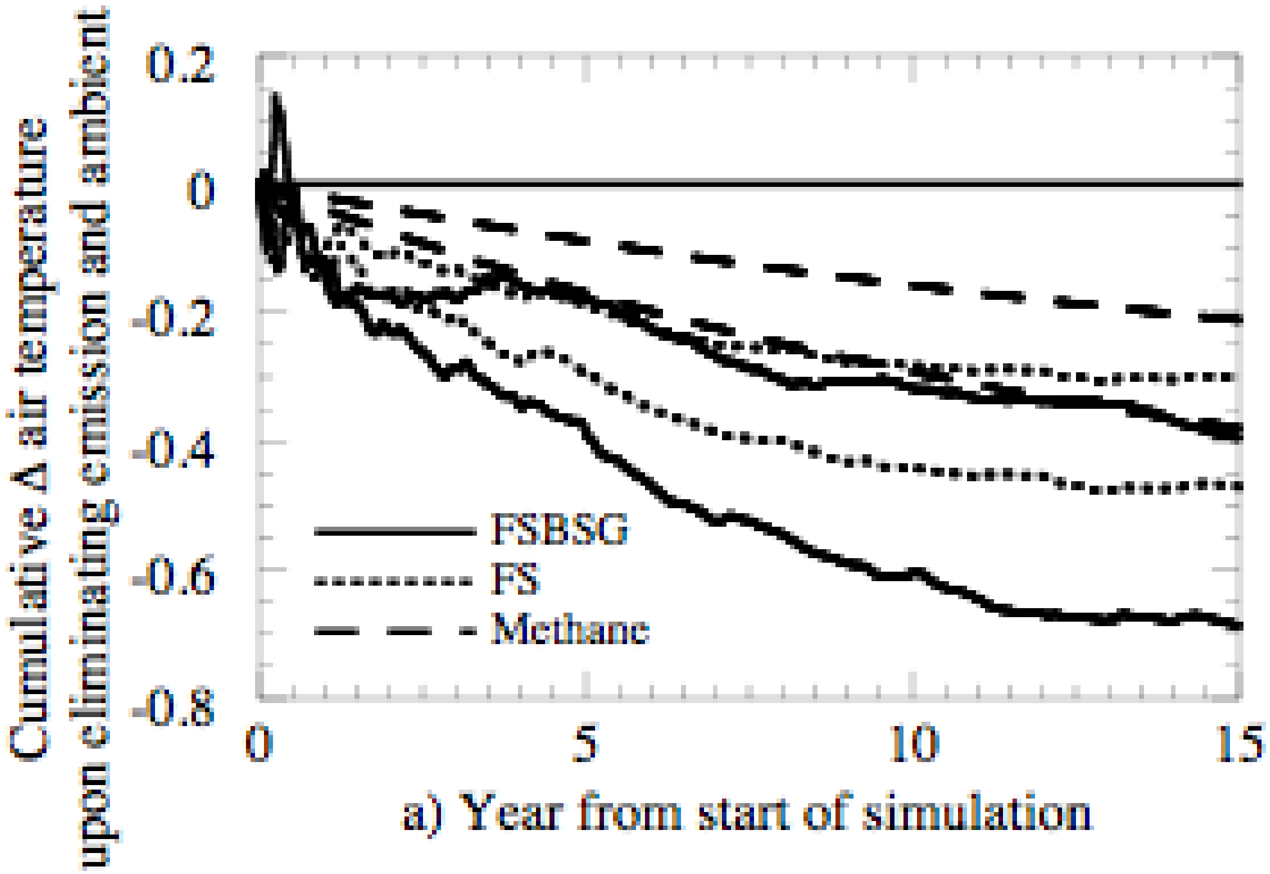
Modeled vs. Measured Sea Ice Area



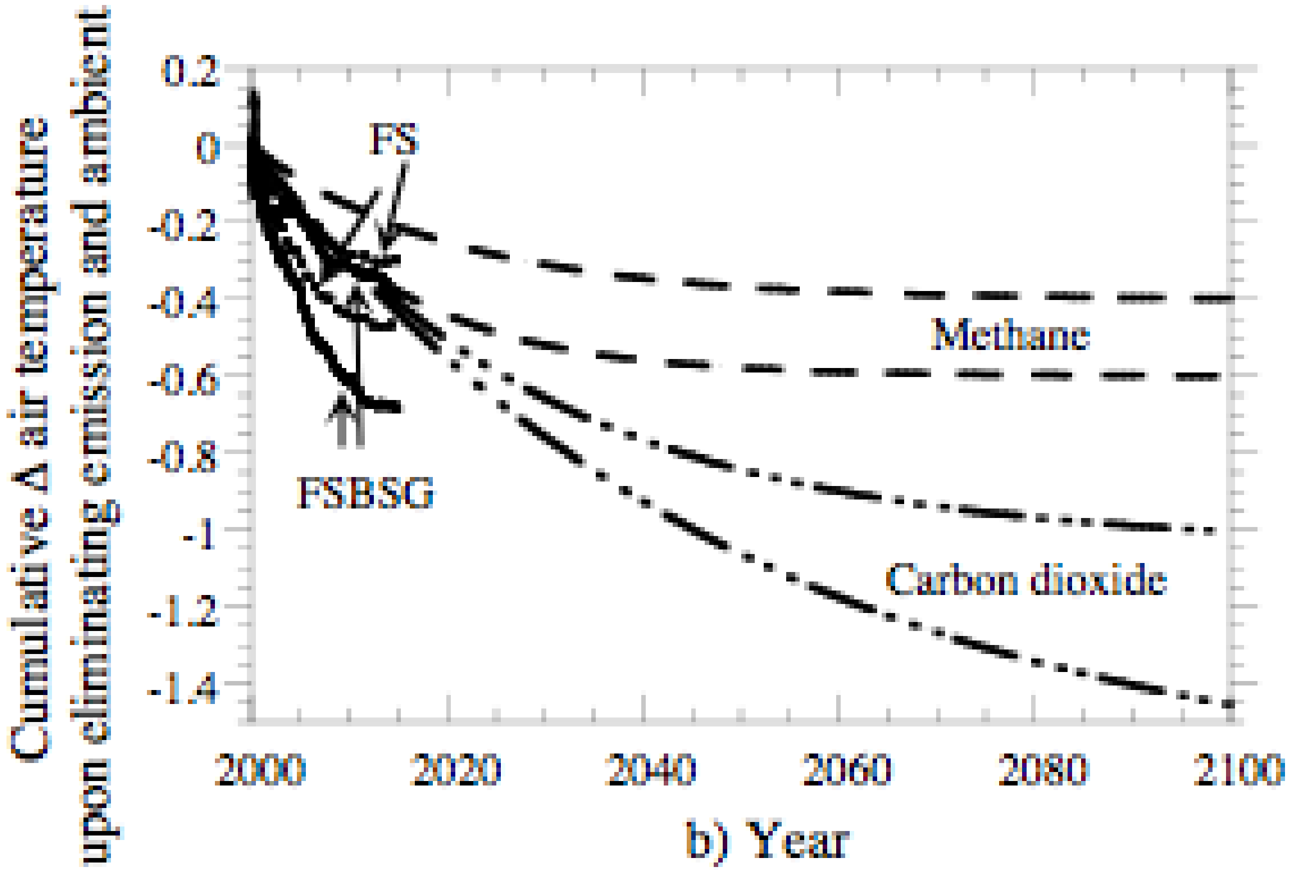
Model (at 4 x 5 degree resolution) predicts stable sea ice area after only two years of simulation

Data from NASA Team (2009)

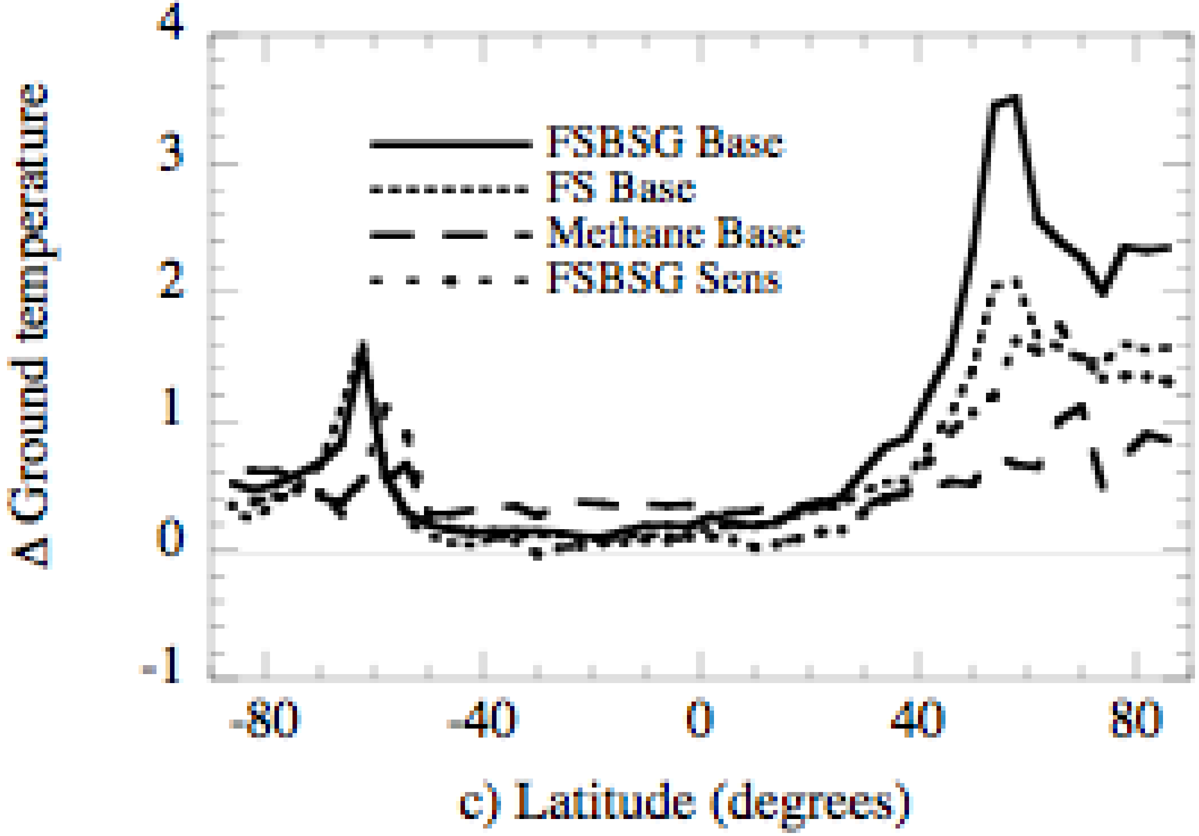
Global Cooling Due to Eliminating Anthropogenic CH_4, Fossil Soot and Biofuel Soot+Gases (FSBSG) and FS Emissions only



Global Cooling Due to Eliminating Anthropogenic CO_2, CH_4, FSBSG, and FS Emissions only



Arctic Warming Due to Anth. CH_4, Fossil Soot and Biofuel Soot+Gases (FSBSG), & FS



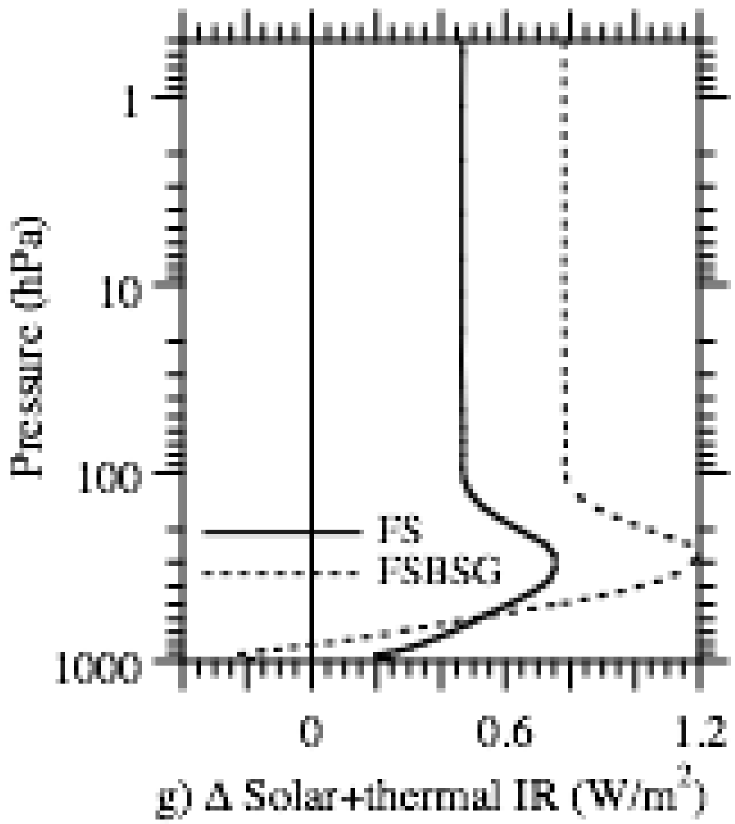
FF+BF soot + BF warm mid & high northern latitudes more than anthropogenic CH_4 or FF soot alone

Radiative Forcing Estimates due to 100%Fossil-Fuel Soot (BC+OM) (W/m^2)

	Chen et al (2010)	Jacobson (2010)	
Indirect forcing	-0.26	-0.26[a]	
Direct forcing	+0.14	+0.25[b]	Estimates
Semi-direct effect	0	+0.15[c]	
Cloud absorption effect	0	+0.15[d]	
BC-snow effect	0	+0.05[e]	
Increase in H_2O, CH_4	0	+0.10[f]	
Total	-0.12	+0.44 (Fig. 5g)	

[a]Assumed same as Chen et al. upon scaling their result from 50% to 100% soot forcing
[b]From Jacobson (JGR, 2002)
[c]Estimated from Jacobson (JGR, 2010) Hansen et al. 2002 estimate 0.3-0.6 for all BC)
[d]Estimated from Jacobson (JGR, 2010)
[e]From IPCC (2007) assuming fossil-fuel BC+OM is ~50% of the total BC-snow effect.
[f]Estimate from increase in water vapor (mostly) and methane from simulations

15-Year, Globally-Averaged Net Solar+Thermal-IR Irradiance Change due to FS and FSBSG



Net irradiance change for FS ~0.44 W/m^2

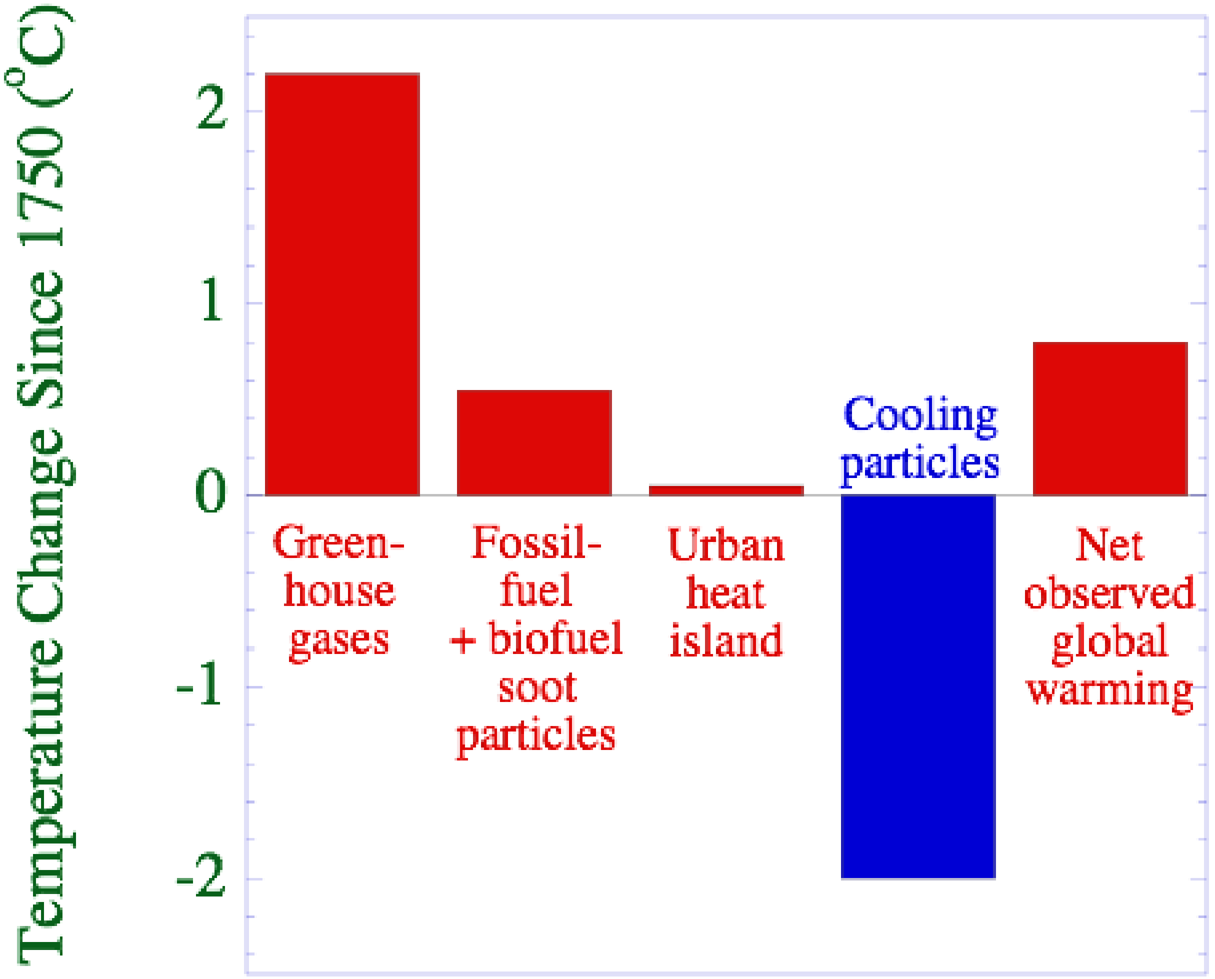
FF Soot, BC Global Warming Potential

	20-yr STRE	100-yr STRE
BC+POC in FS	2400-3800	1200-1900
BC in FS	4500-7200	2900-4600
BC+POC in BSG	380-720	190-360
BC in BSG	2100-4000	1060-2020
Methane	52-92	29-63

STRE = Surface Temperature Response per Unit Emission

= Near-surface temperature change after 20 or 100 years per unit continuous emission of X relative to the same for CO_2 (similar to GWP e.g., 20-, 100-yr

Contributors to Global Warming



Jacobson (2010, JGR 115, D14209)

Summary

Several factors affect soot's climate effect aside from indirect effects: cloud absorption, semidirect effect, snow albedo effect, water vapor effect, internal mixing effect.

With these effects, FSBSG soot may be the second-leading cause of global warming behind CO_2 and ahead of CH_4. FS causes 3 x the warming of BSG, but BSG causes ~7x more deaths than FS.

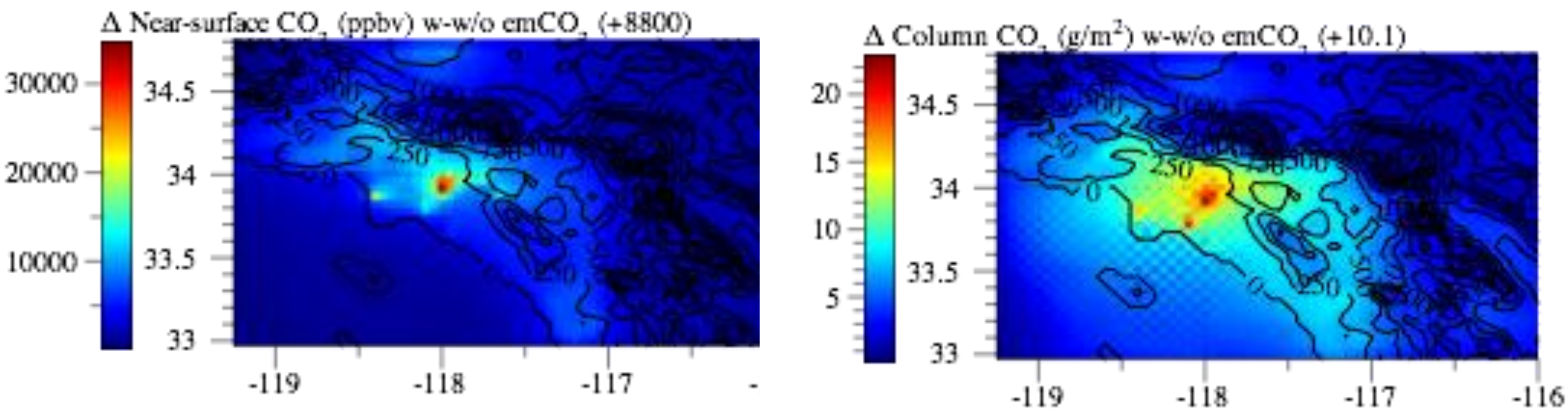
Net global warming (0.7-0.8 K) appears due primarily to gross warming from FF GHGs (2-2.4 K) and FSBSG (0.4-0.7 K) offset by cooling due to non-FSBSG aerosol particles (-1.7 to -2.3 K).

FS and FSBSG may contribute to 13-16% and 17-23% of gross warming from pollutants. Controlling FS, FSBSG may be the fastest and only method of preventing Arctic loss.

www.stanford.edu/group/efmh/jacobson/controlfossilfuel.html

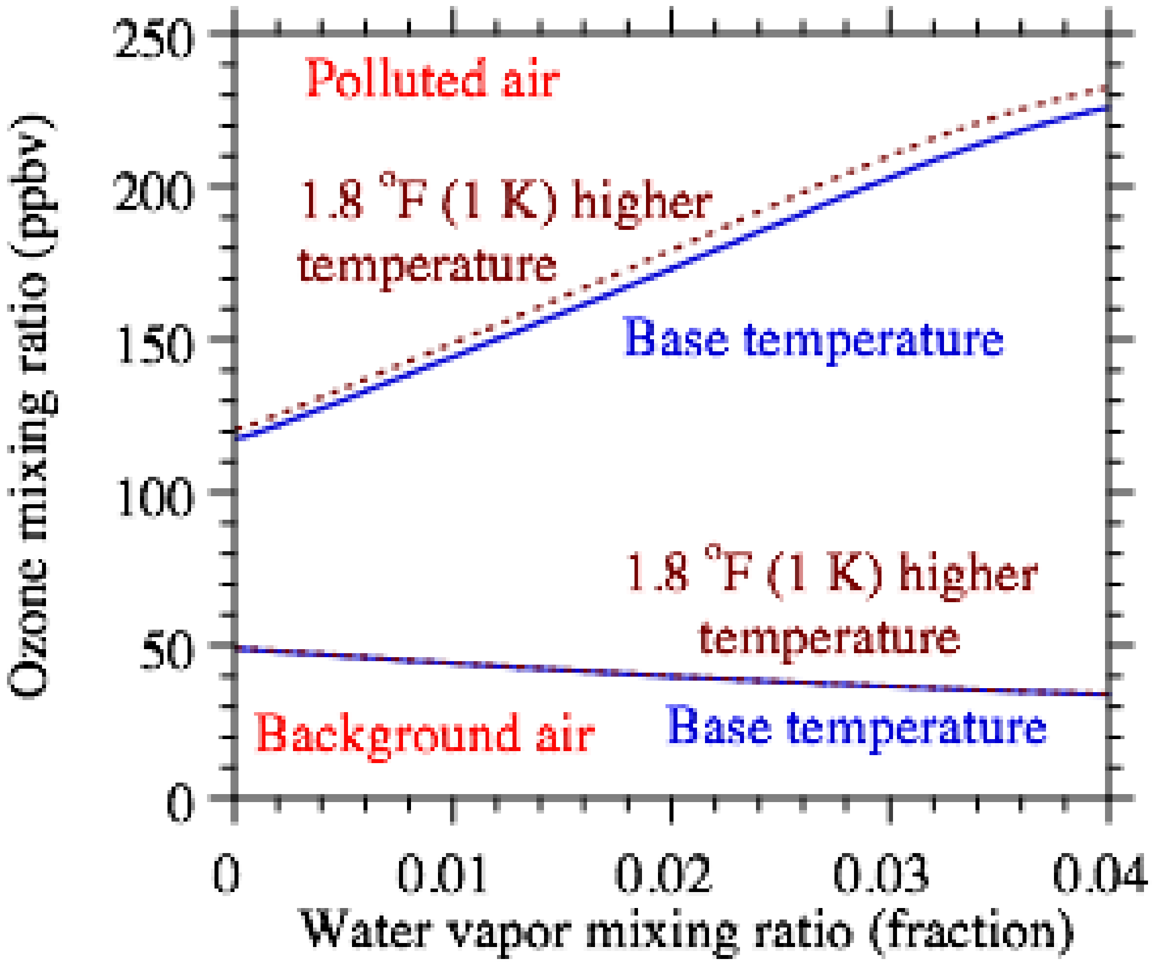
CO_2 Domes Over Cities

3-D modeled increases in CO_2 due to local emissions for February-April in Los Angeles - numbers in parentheses are population-weighted values



Change in surface/column CO_2 from local CO_2 emissions = “CO_2 Dome”

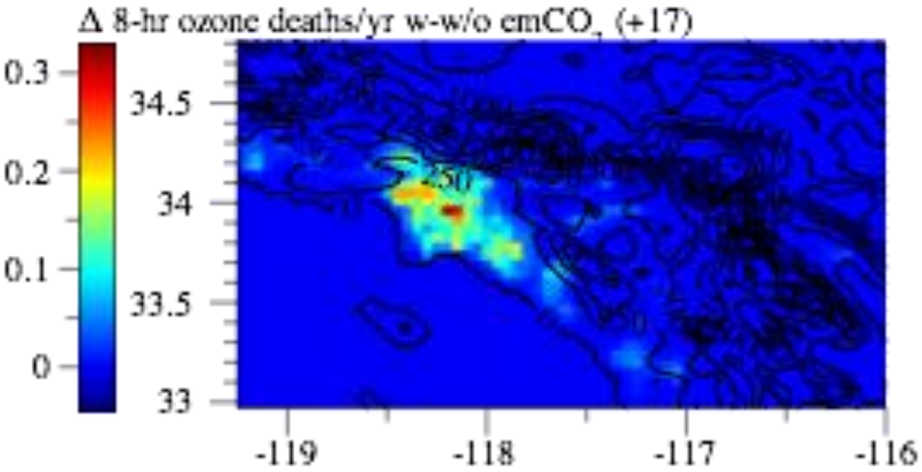
Increases in Water Vapor and Temperature Both Increase Ground-Level Ozone in Polluted Air But Not in Background Air



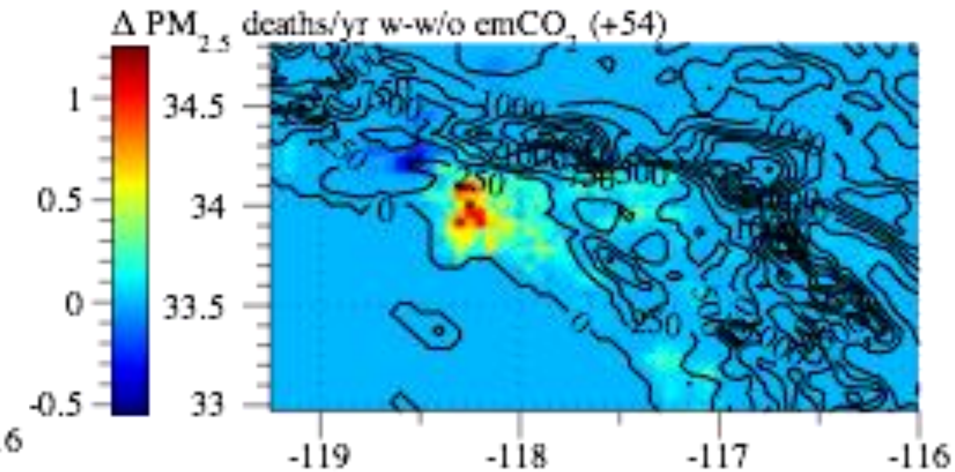
→ California has 6 of the 10 most polluted U.S. cities → Suffers largest impact of higher T, H_2O among states. GRL L03809 2008

Feb-Apr L.A. Death Increases Due to CO_2 Domes

3-D model results



Additional O_3 deaths/yr



Additional PM deaths/yr

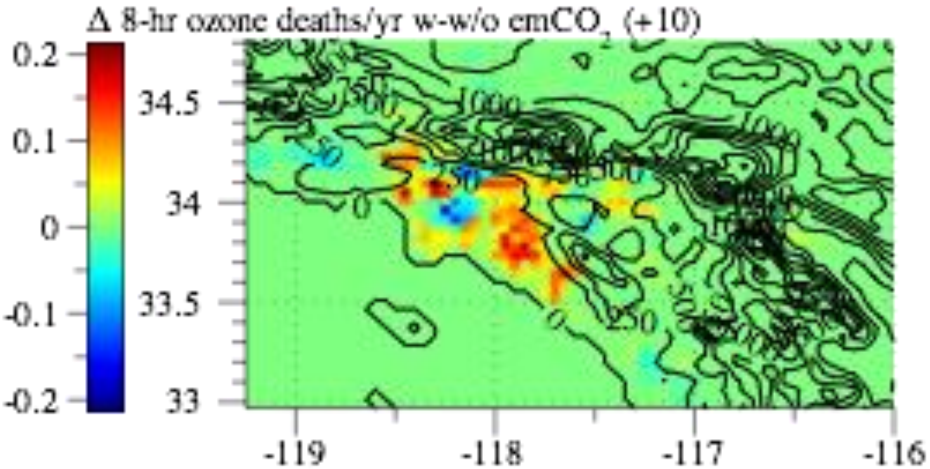
Local CO_2 emissions increase ozone and PM deaths

PM increases due to

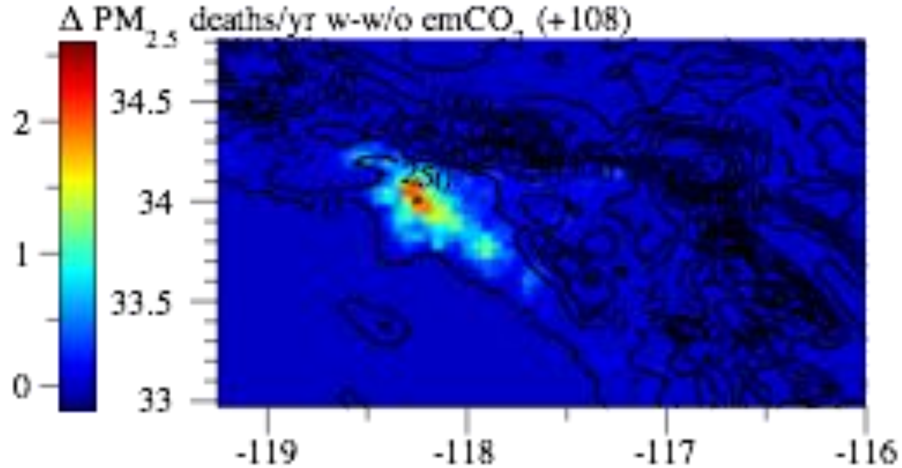
1) increased stability, thus reduced winds and diffusion
2) higher RH thus more gas uptake in aerosols many locations
3) Increased biogenic (not L.A.), evaporative emissions VOCs

Aug-Oct L.A. Deaths From CO_2 Dome

3-D model results



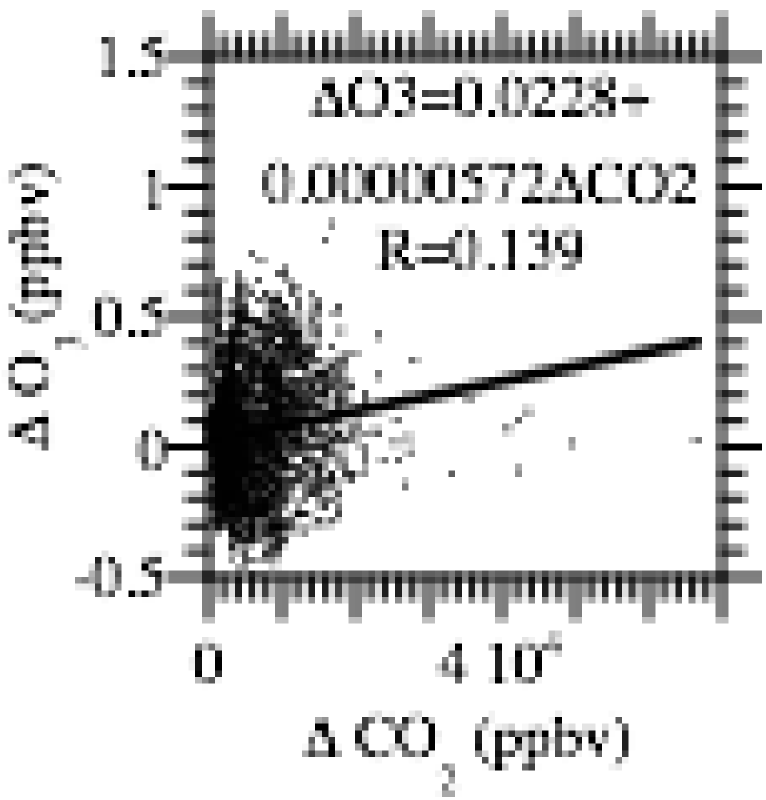
Additional O_3 deaths/yr

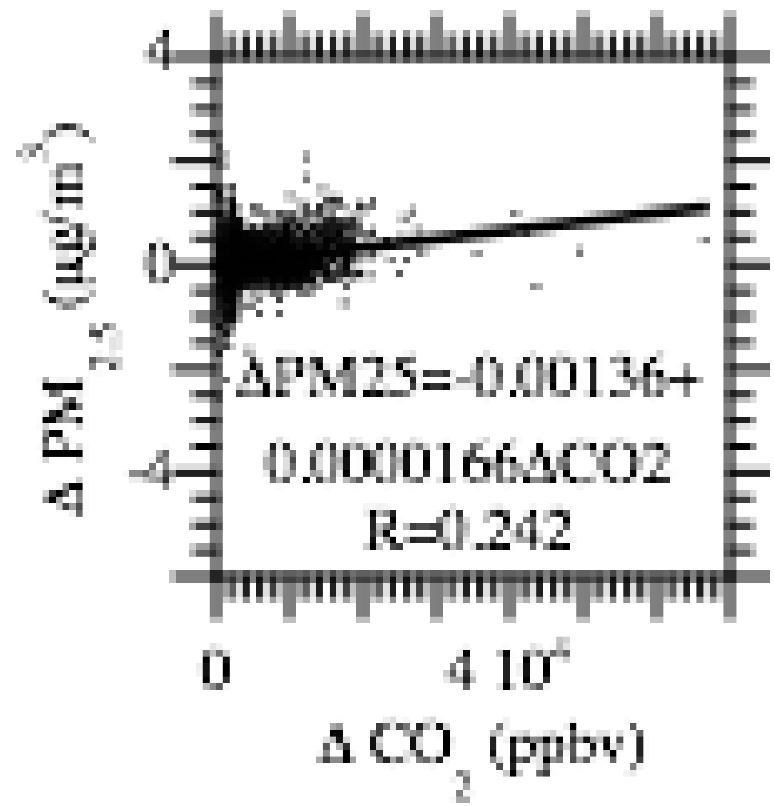


Additional $PM_{2.5}$ deaths/yr

Local CO_2 emissions increase ozone and PM deaths

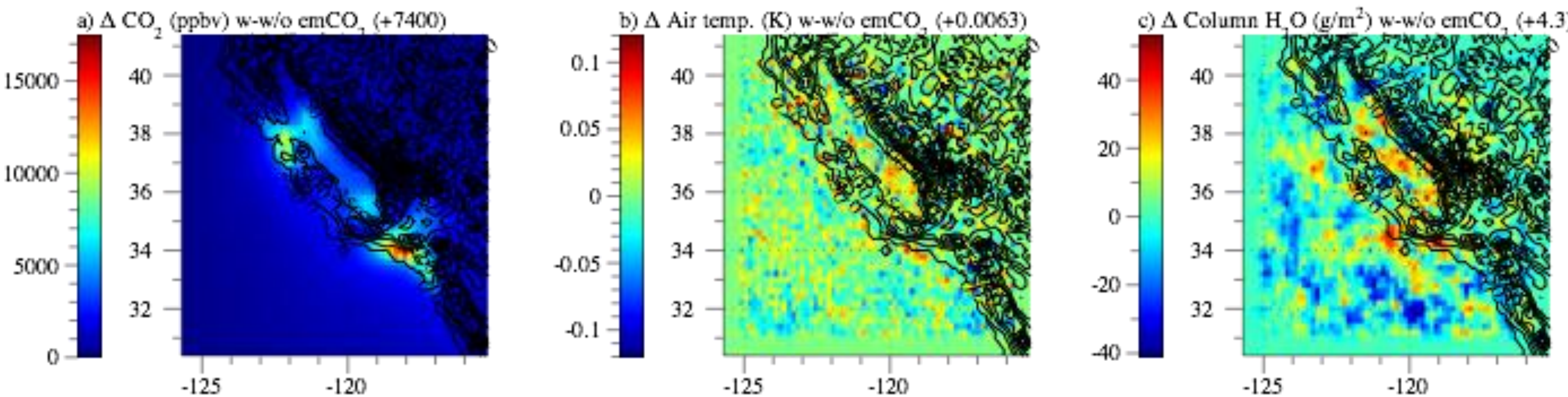
Spatial Correlation Between Increased Local CO_2 and Increased O_3 (left) & $PM_{2.5}$ (right) in Los Angeles





Changes in California Due to Local CO_2

Numbers in parentheses are population-weighted values



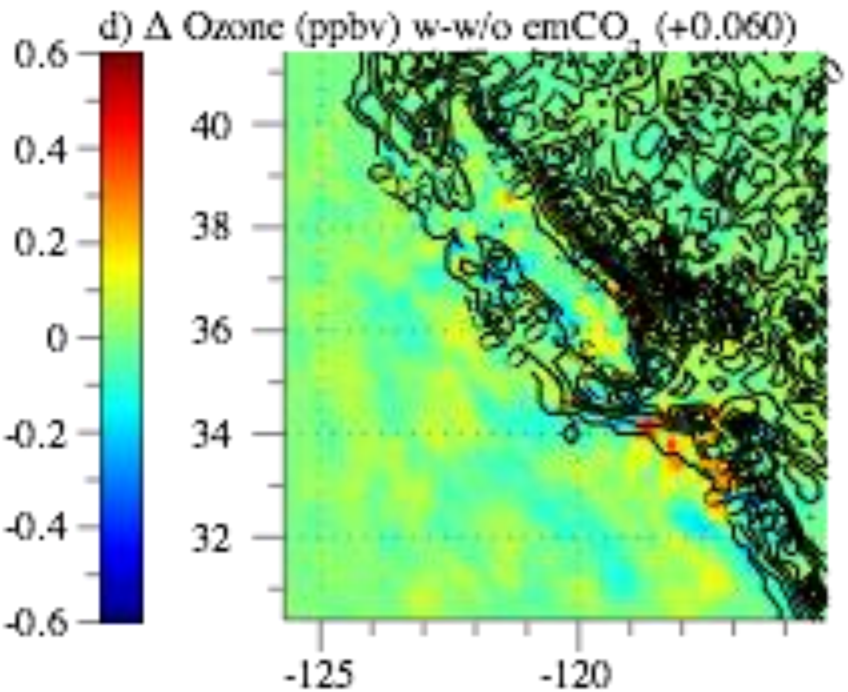
Change in column CO_2
"CO_2 Domes"

Increase in surface air temperature

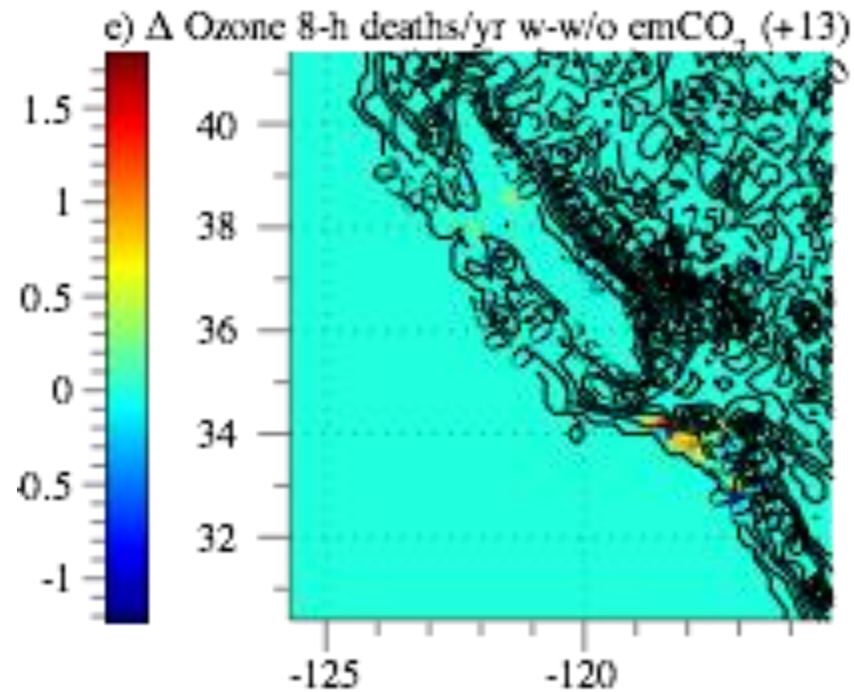
Increase in column H_2O

Local CO_2 emissions increase temperatures, water vapor

Additional O_3 deaths/yr From CO_2 Domes



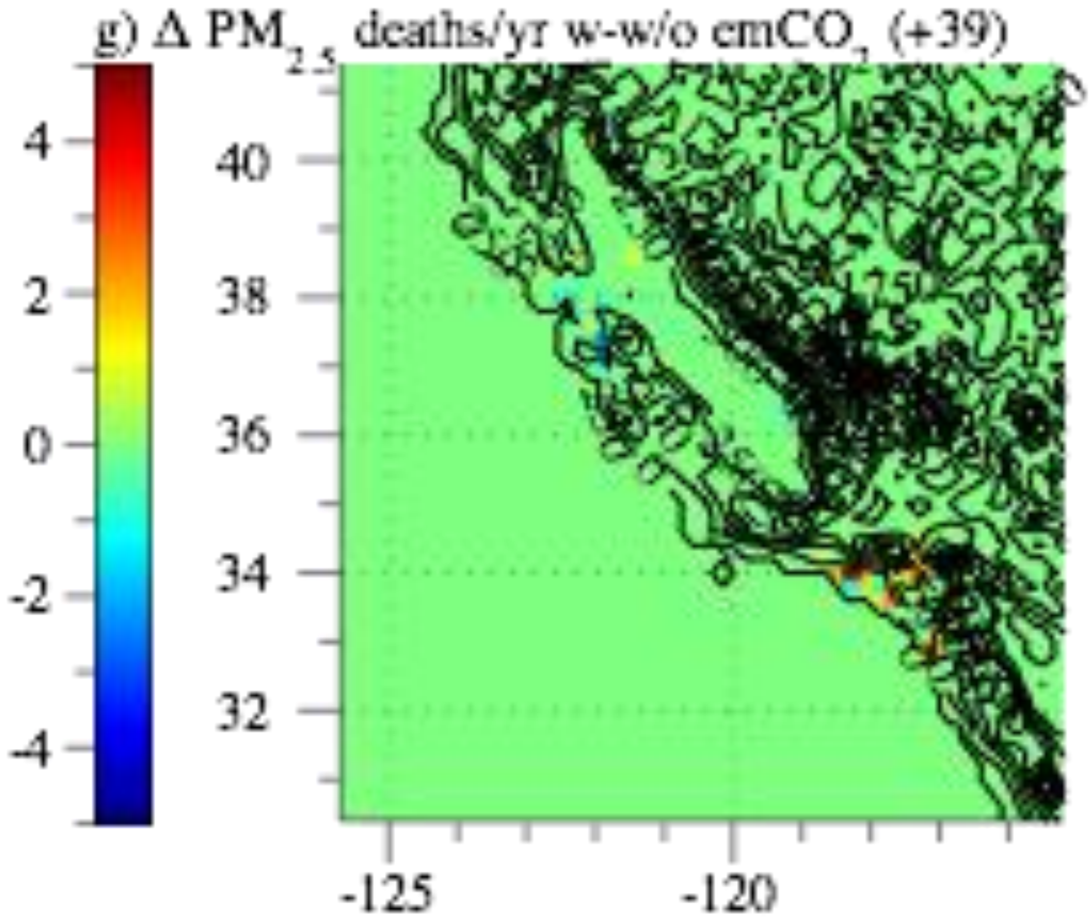
Increase in surface O_3



Additional O_3 deaths/yr

Local CO_2 emissions increase O_3 and O_3 deaths

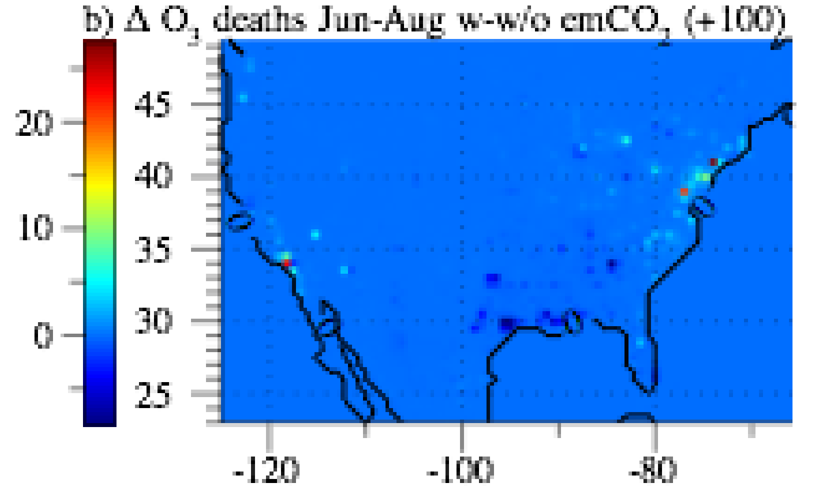
Additional PM deaths/yr From CO_2 Domes



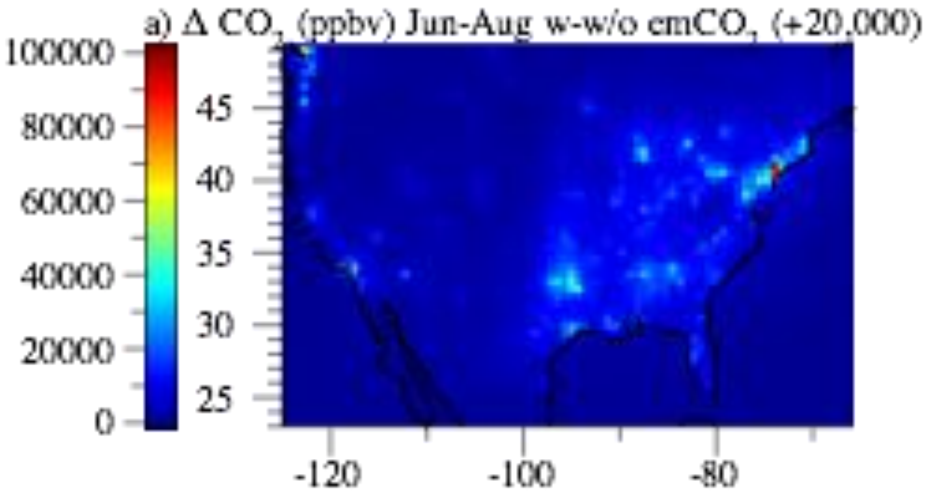
Local CO_2 emissions increase $PM_{2.5}$ deaths

1-Year Death Inc. Due to CO_2 Domes

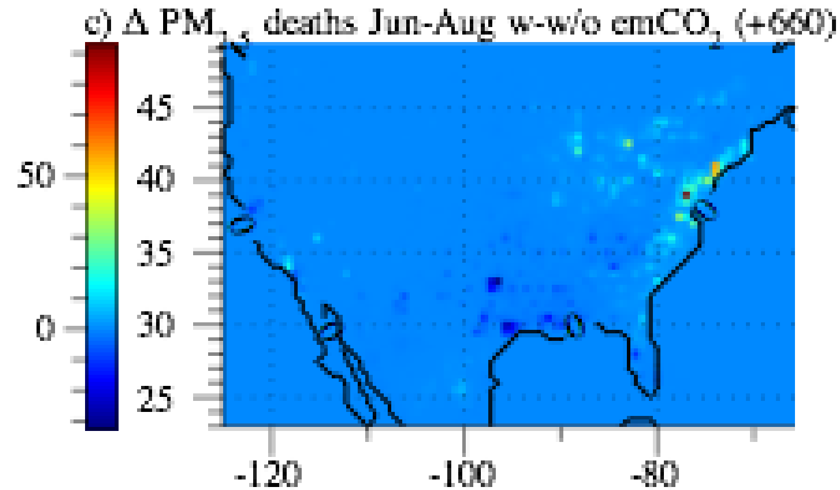
Additional ozone deaths/yr



Increase in CO2 from local emissions



Additional PM deaths/yr



Local CO_2 emissions increase $PM_{2.5}$ and O_3 deaths

Summary

Locally-emitted CO_2 produces CO_2 domes, which increase local ozone and $PM_{2.5}$ premature deaths in California by ~50-100/yr. Thus, reducing locally-emitted CO_2 may reduce local air pollution and mortality. If correct, this result contradicts the basis for all previous local air pollution regulation worldwide, which has ignored CO_2, thus it provides the basis for controlling CO_2 due to its local health impacts.

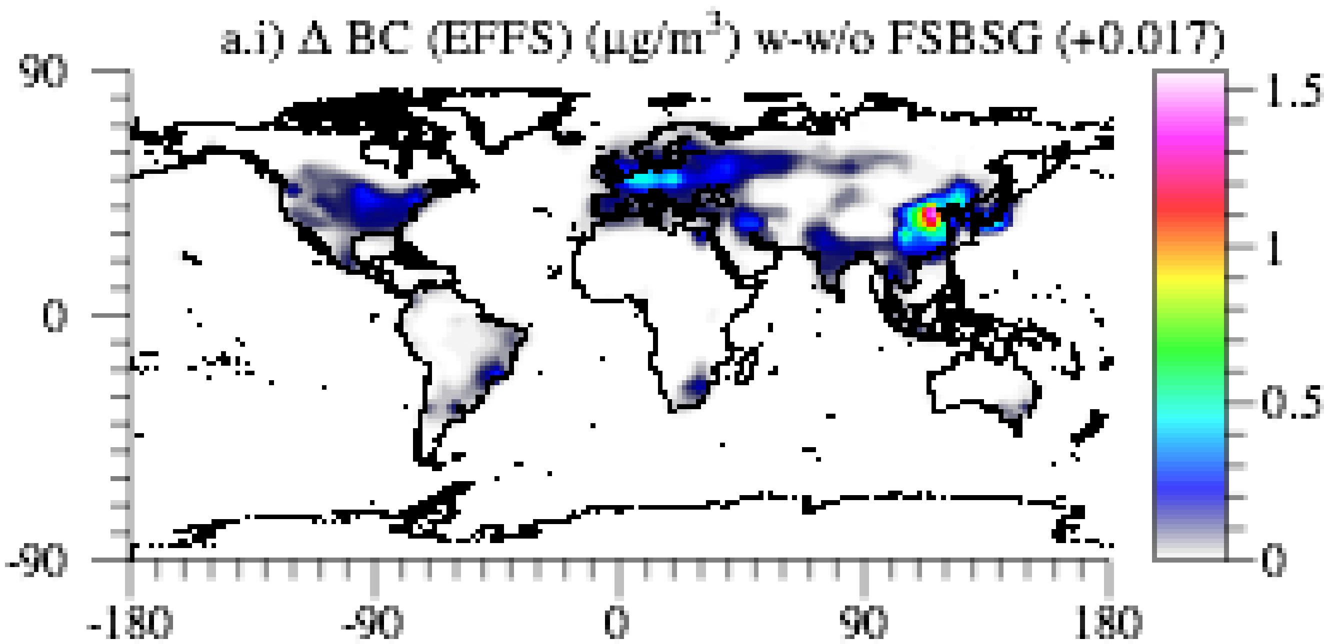
The result also implies that the main assumption behind “cap and trade” that CO_2 impacts are the same regardless of where CO_2 is emitted, is incorrect.

Papers:

http://www.stanford.edu/group/efmh/jacobson/Ve.html

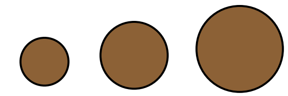
http://www.stanford.edu/group/efmh/jacobson/urbanCO2domes.html

Simulation-Averaged Emitted FF-soot BC

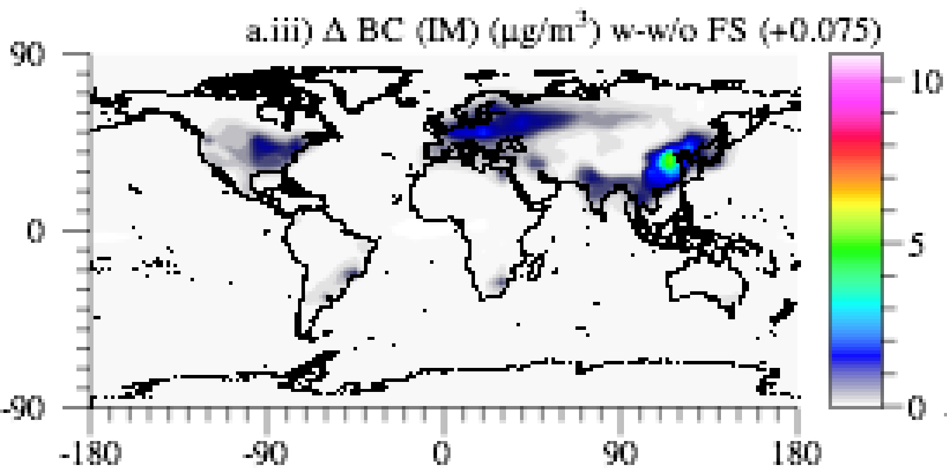


BC from FF soot is about half that of BC from FF+BF soot

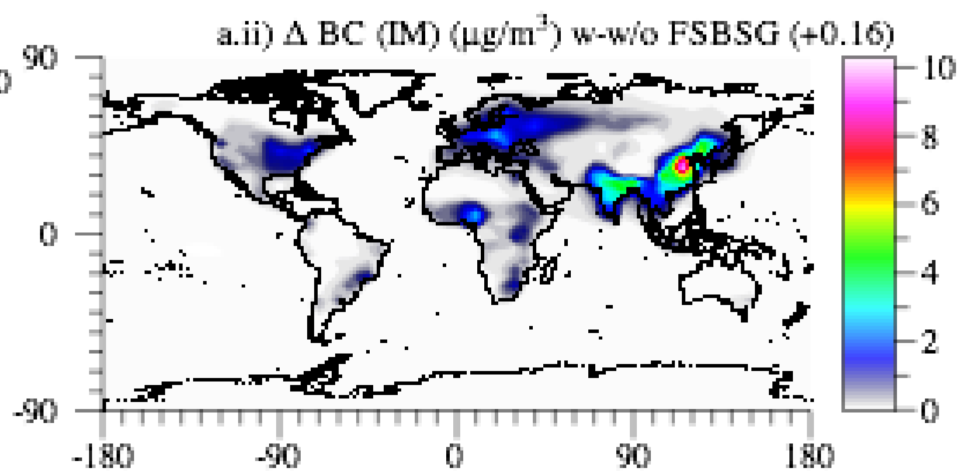
Internally-Mixed BC From the FF Soot Simulation and from FF+BF Soot Simulation



Internally-Mixed FF BC

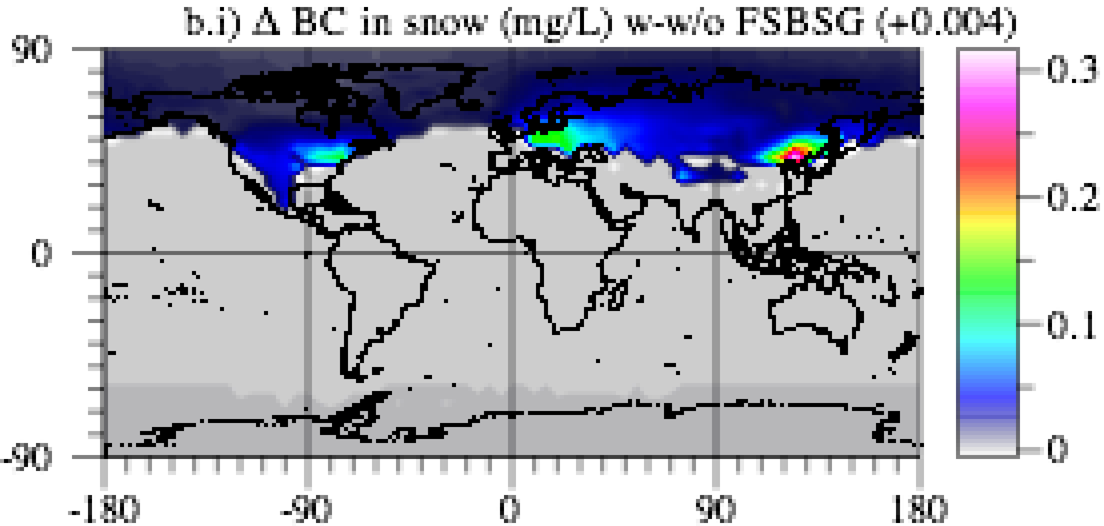


Internally-Mixed FF+BS BC



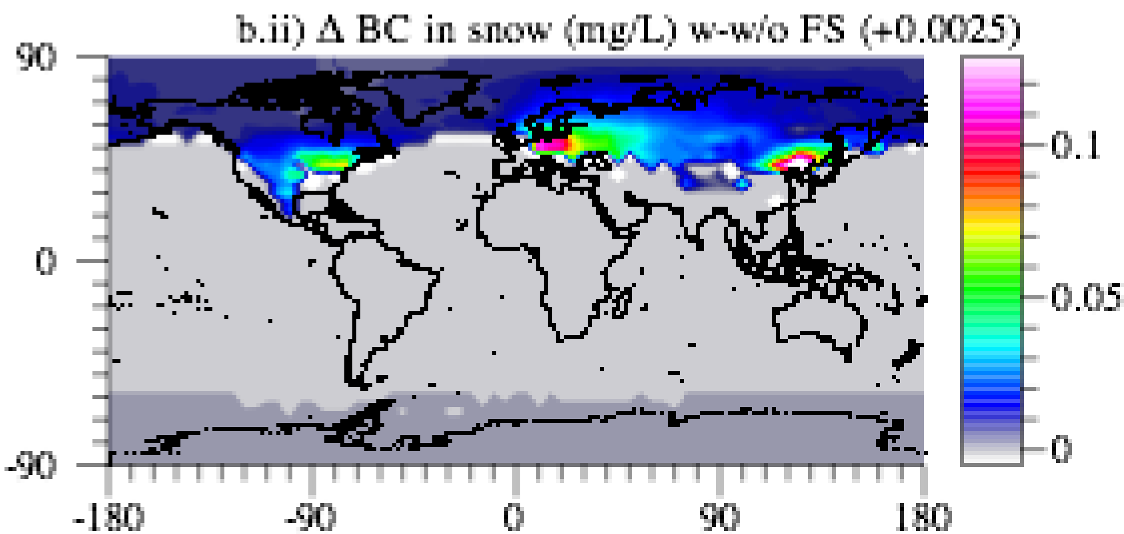
BC from FF soot is about half that of BC from FF+BF soot

BC in Snow Due to FF+BF Soot + BF gases and FF Soot Alone



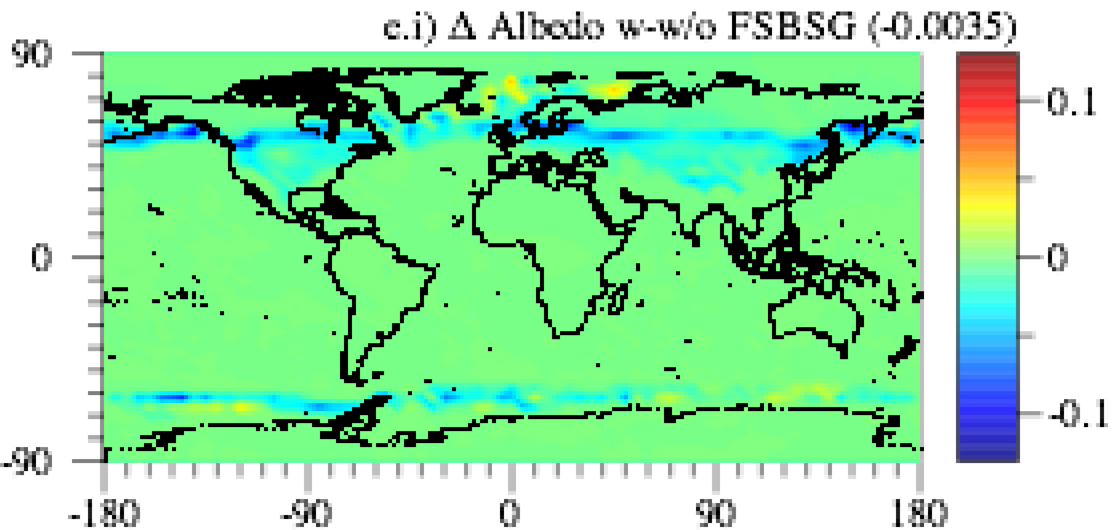
FF soot

FF+BF soot + BF gases

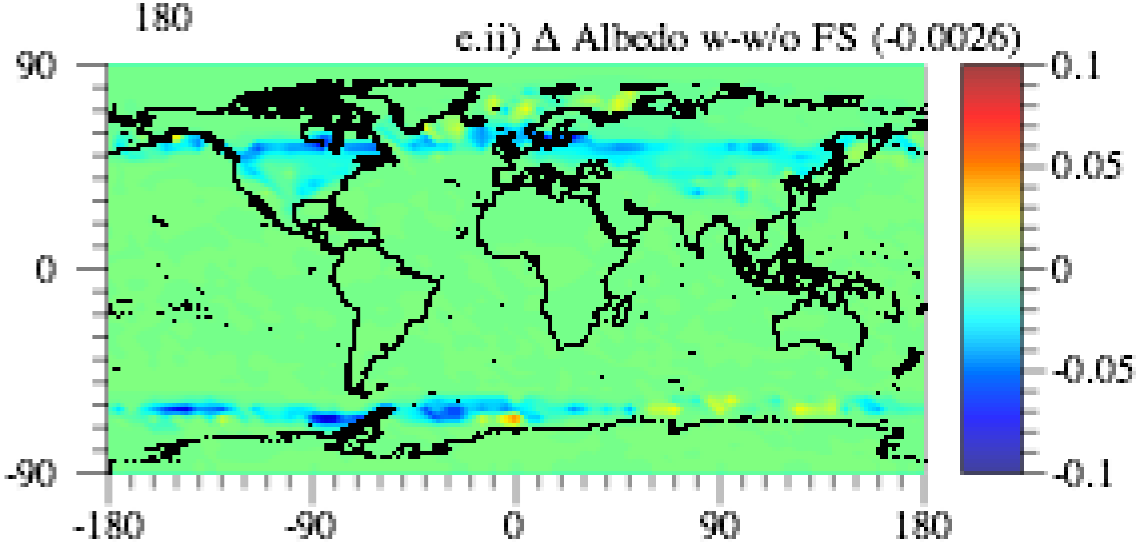


Both FF+BF soot and FF soot increase BC in snow

Surface Albedo Changes Due to FF+BF Soot + BF gases and to FF Soot Alone



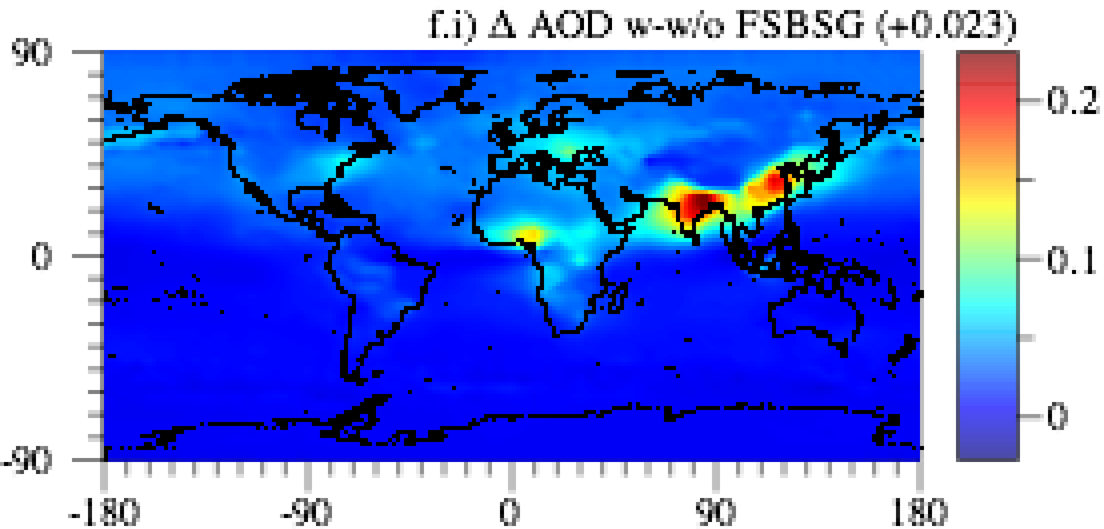
FF+BF soot + BF gases



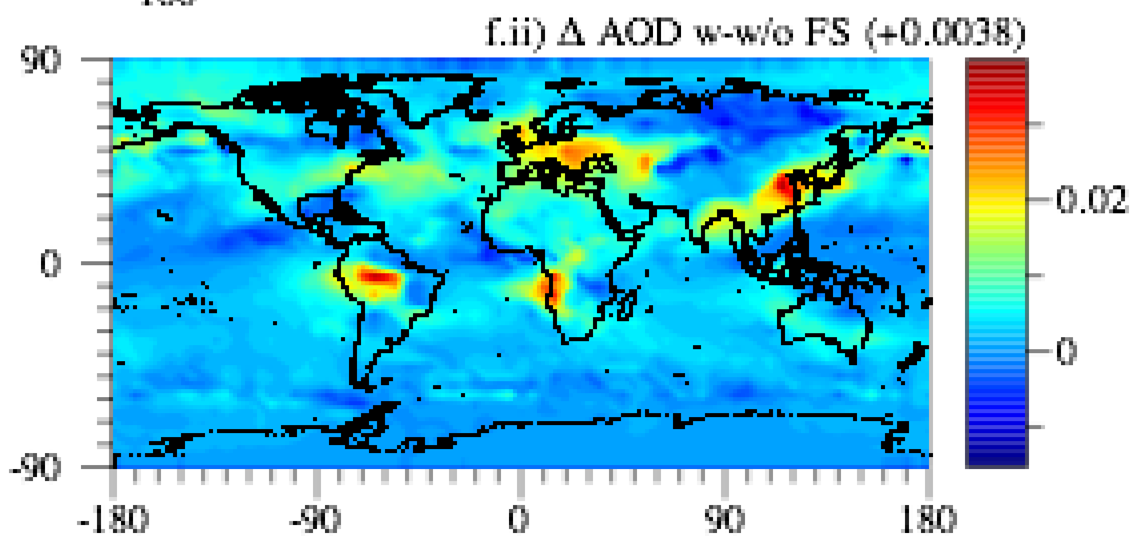
FF soot

Most albedo loss due to FF+BF soot +BF gases is due to FF soot

AOD Changes Due to FF+BF Soot + BF gases and to FF Soot Alone



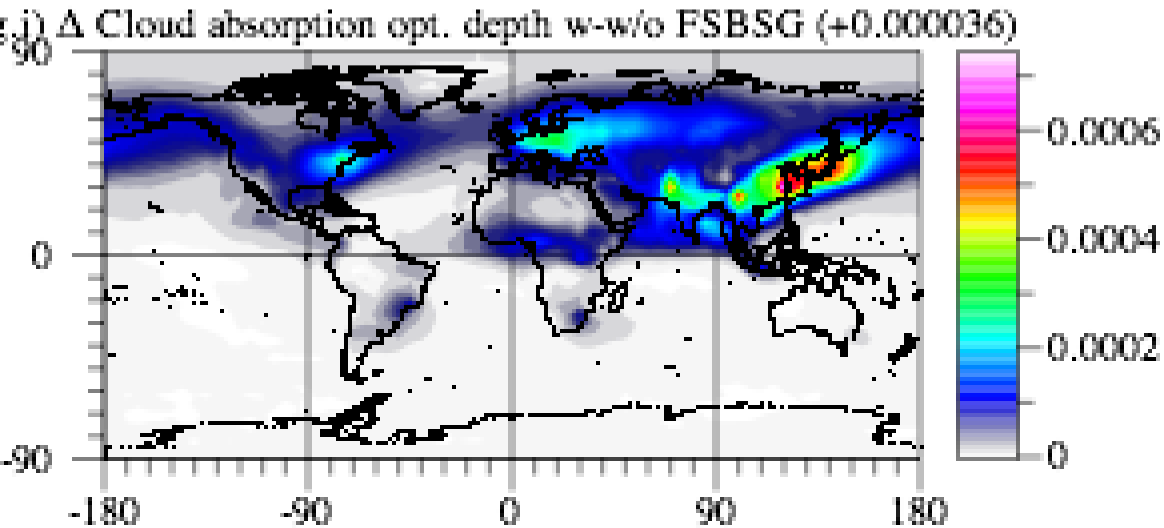
AOD change due to FF+BF soot + BF gases



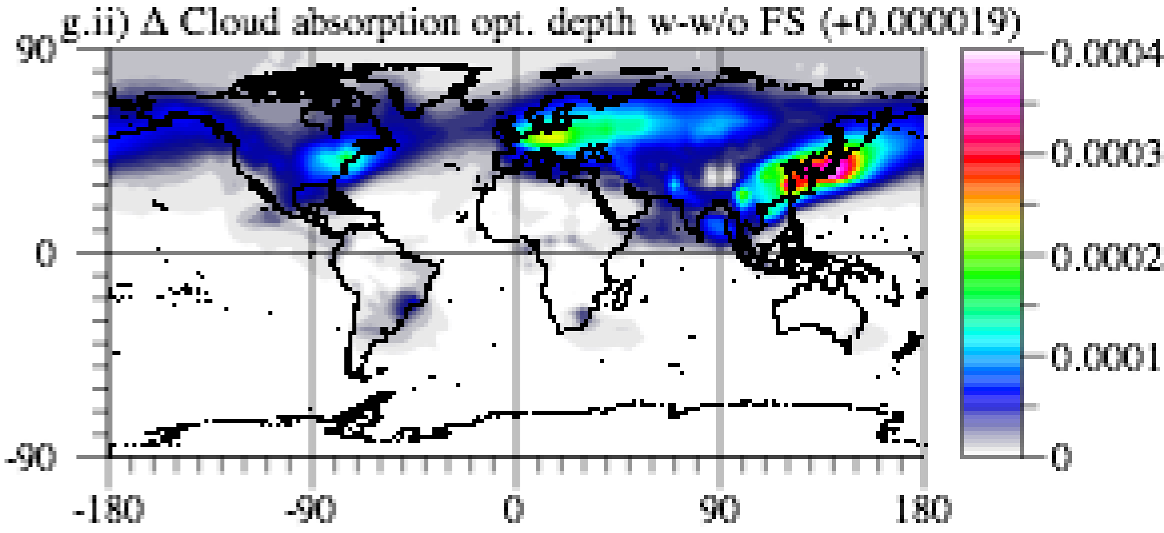
AOD change due To FF soot

FF+BF soot +BF gases increased AOD more than did FF soot

Cloud Absorption Due to BC Inclusions in Clouds



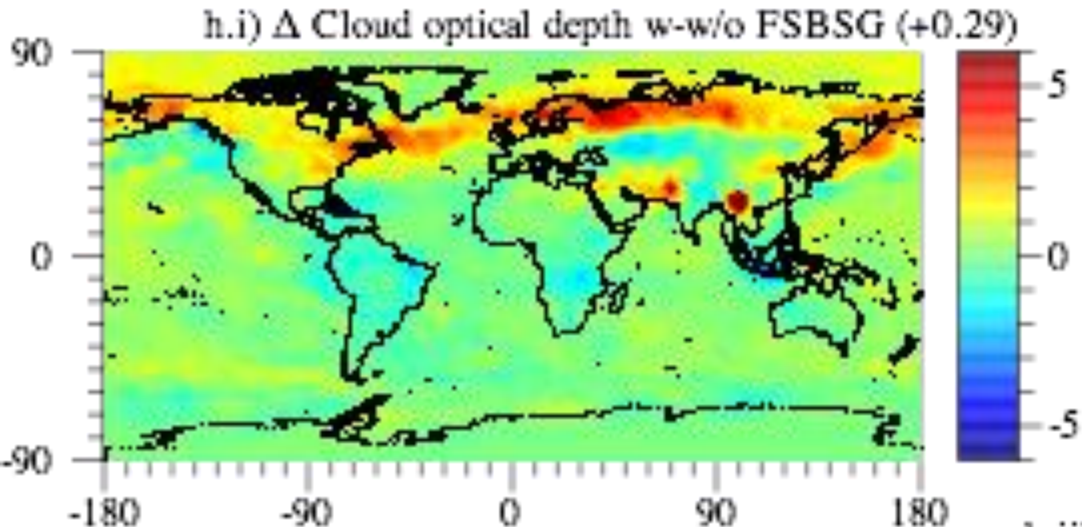
Cloud absorption OD change due to FF+BF soot + BF gases



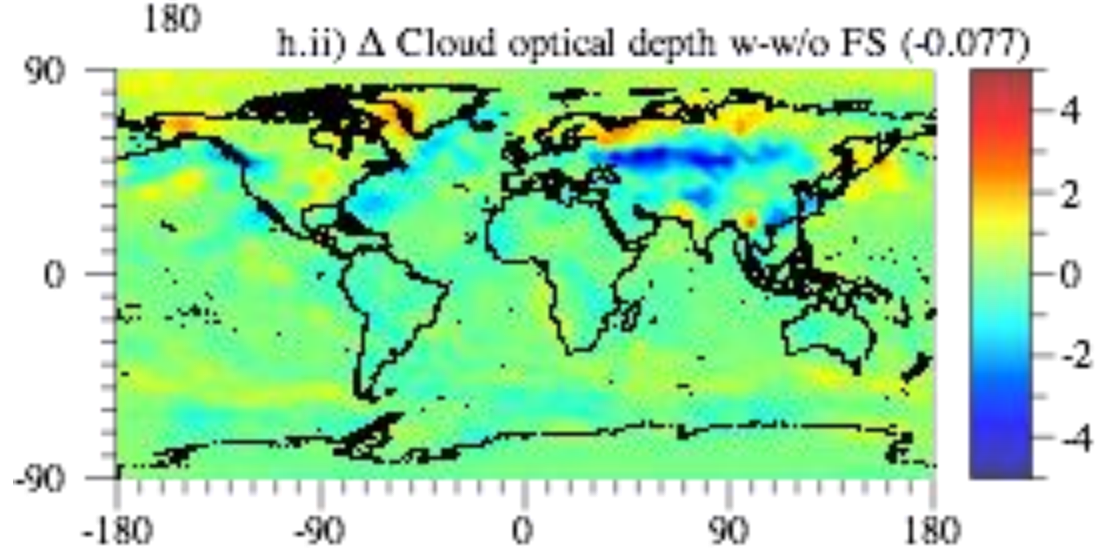
Cloud absorption OD change due to FF soot

→FF+BF soot +BF gases increased cloud absorption more than FF soot

Cloud OD Changes Due to FF+BF Soot + BF gases and to FF Soot Alone



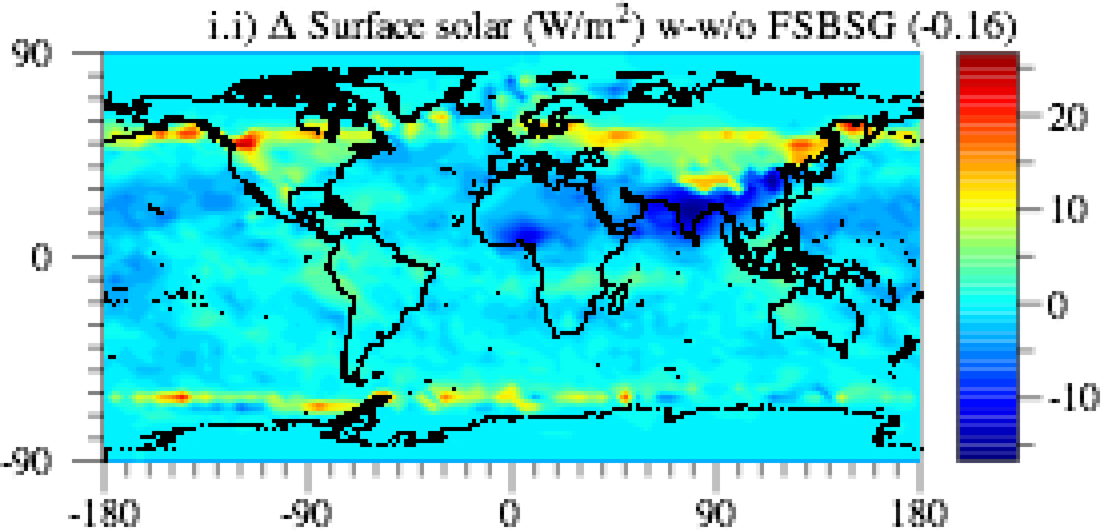
Cloud OD change due to FF+BF soot + BF gases



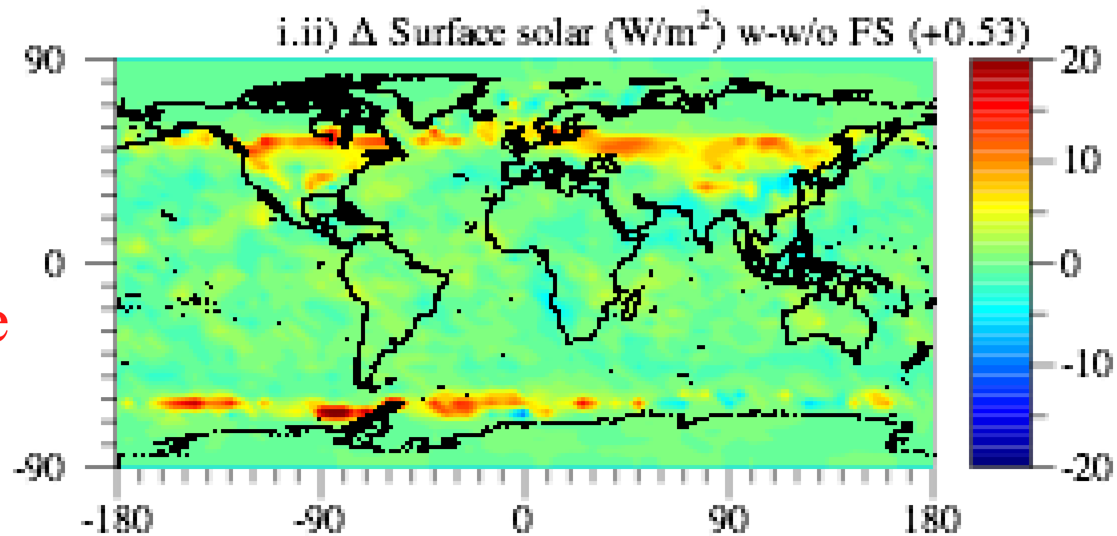
Cloud OD change due to FF soot

FF+BF soot +BF gases increased COD; FF soot decreased COD

Surface Solar Changes Due to FF+BF Soot + BF gases and to FF Soot Alone



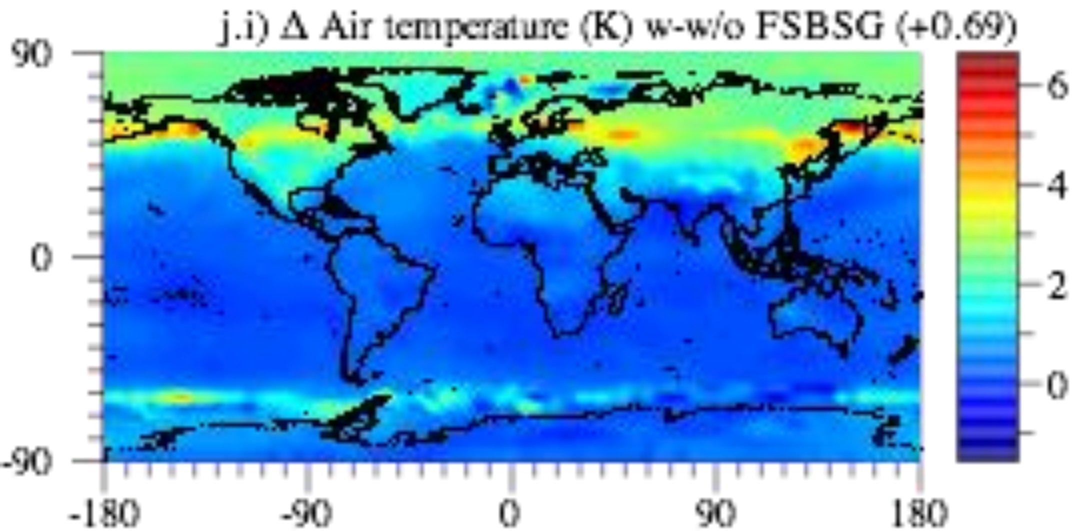
Surface solar change due to FF+BF soot + BF gases



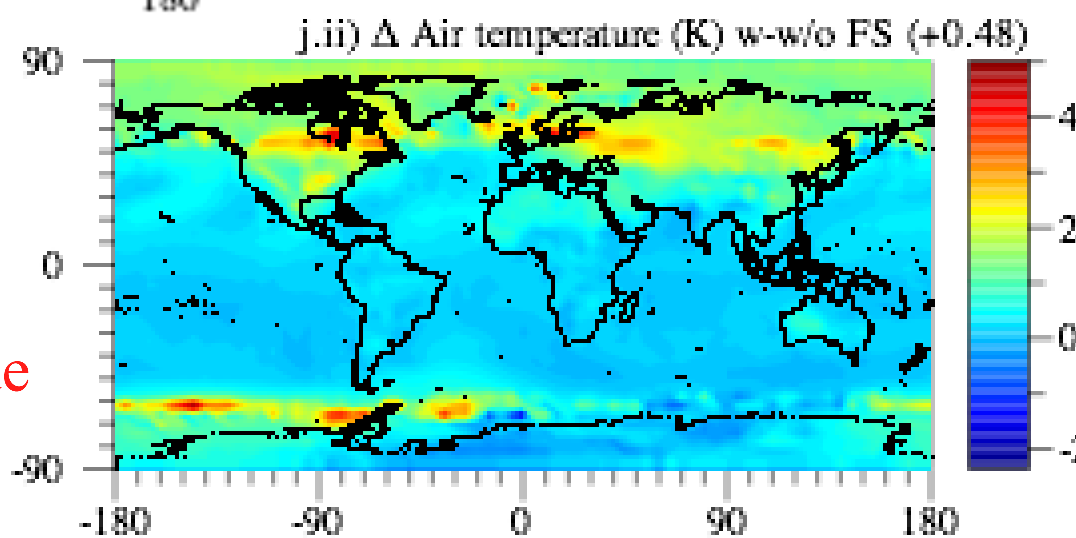
Surface solar change due to FF soot

→FF+BF soot +BF gases decreased surface solar; FF soot increased it

Temperature Changes Due to FF+BF Soot + BF gases and to FF Soot Alone



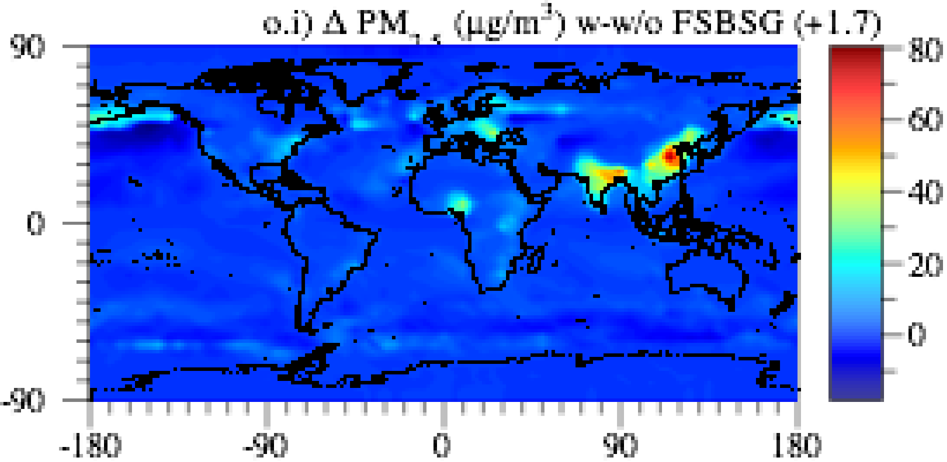
Air temperature change due to FF+BF soot + BF gases

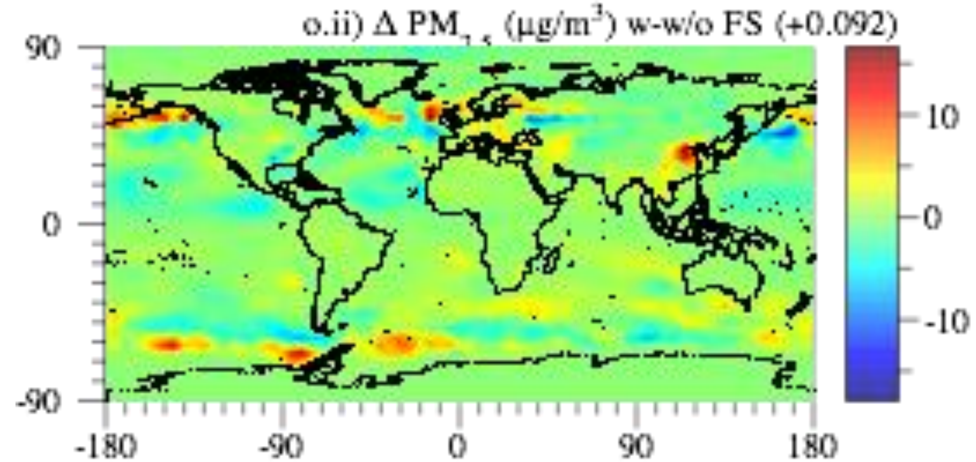


Air temperature change due to FF soot

Most temperature inc. due to FF+BF soot +BF gases is due to FF soot

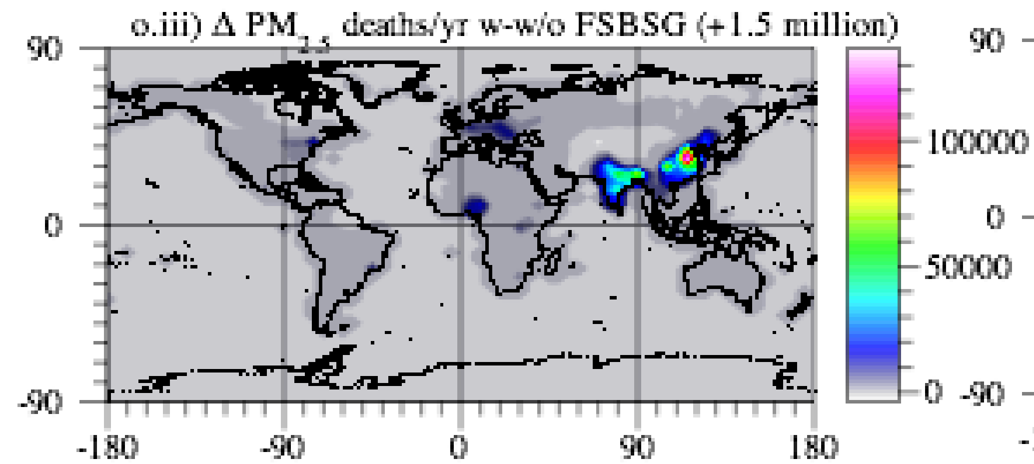
Changes in PM and Resulting Deaths due to FF+BF soot + BF gases and to FF soot

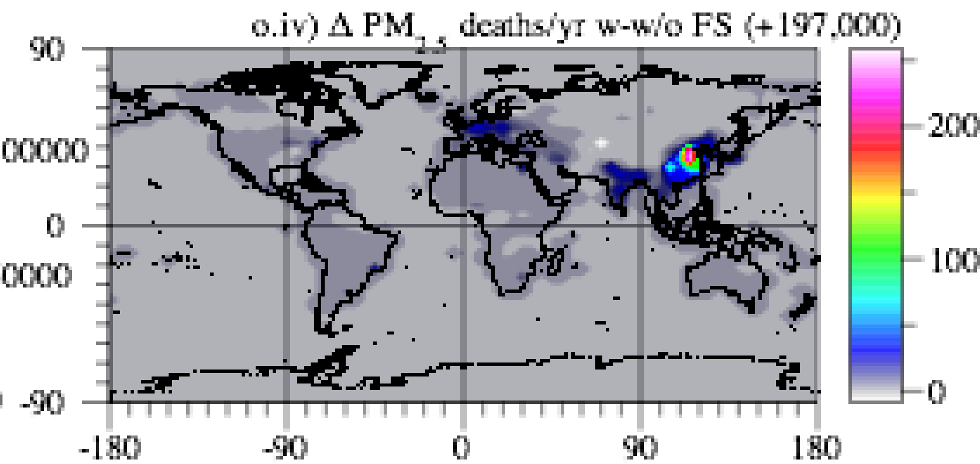




FF+BF soot + BF gases

FF soot





Deaths due to BF soot+gases ~7 times those due to FF soot