Climate Effects and Efficacy of Dust and Soot in Snow

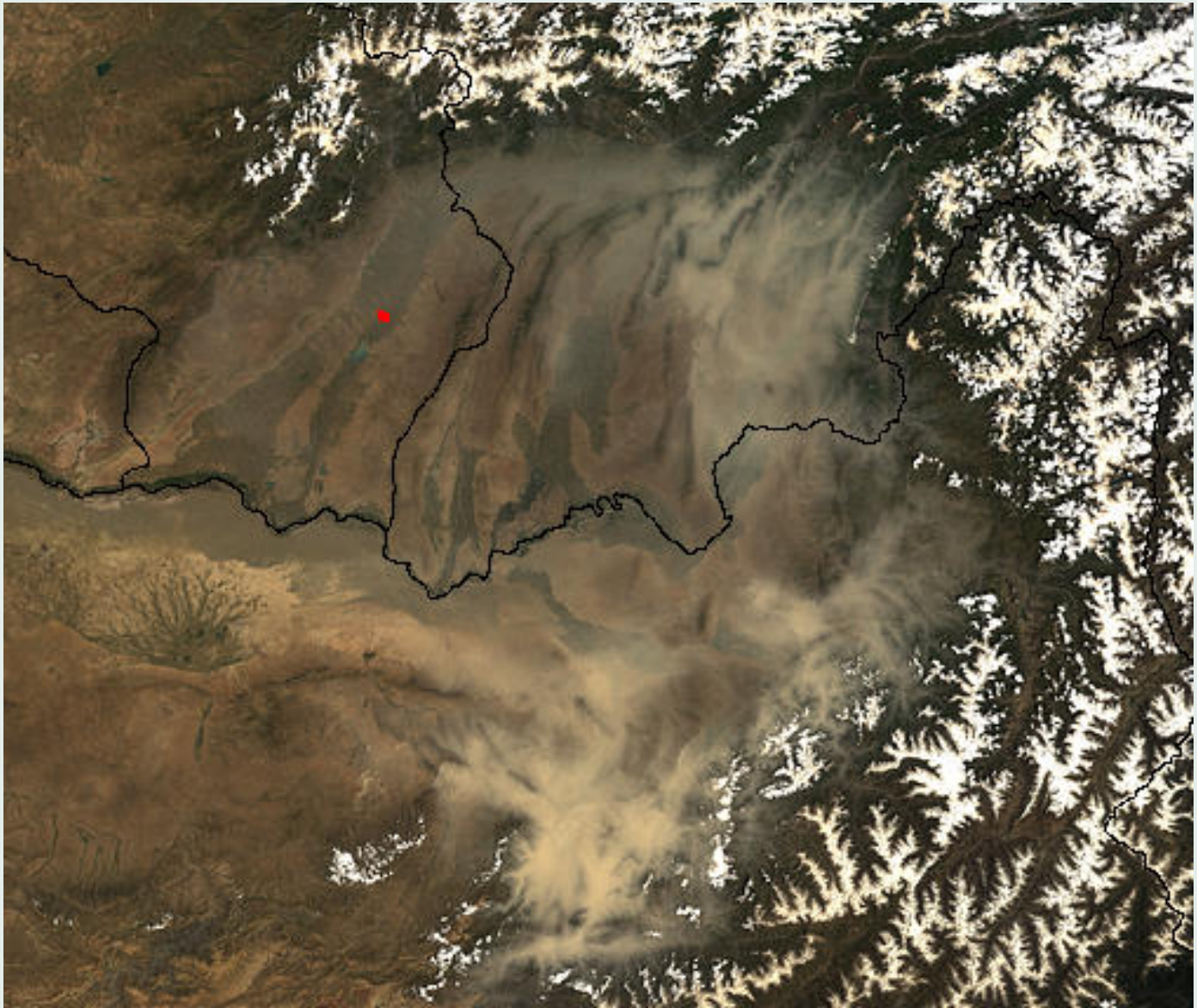
Charlie Zender, Mark Flanner, and Jim Randerson
Department of Earth System Science, University of California, Irvine

Natalie Mahowald, Phil Rasch and Masaru Yoshioka
Climate and Global Dynamics Division, NCAR, Boulder, CO

Tom Painter
National Snow and Ice Data Center, Boulder, CO

Contributions from:
M. Andreae (MPI), T. Bond (UIUC), D. Bundy (NCAR), P. Khasibhatla (Duke)
C. Luo (UCI), D. Muhs (USGS), T. Roush (NASA)

Presented to: American Geophysical Union (AGU) Fall meeting, San Francisco
(Web: http://dust.ess.uci.edu/smn/smn_dst_agu_200612.pdf)



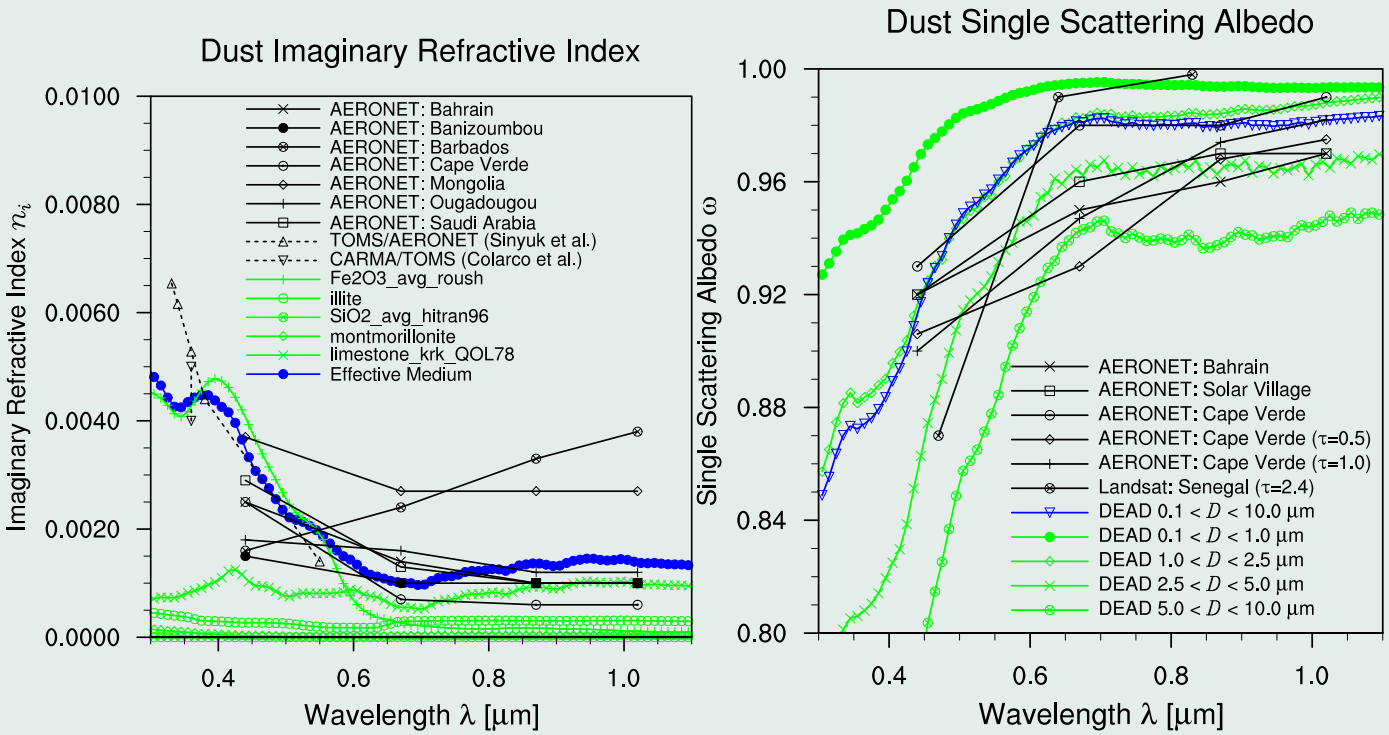


Figure 2: Imaginary refractive index and single scattering albedo for dust comprising 47% Quartz, 25% Illite, 25% Montmorillonite, 2% Limestone, 0.8% Hematite (i.e., 0.6% Fe). Retrievals from Kaufman et al. (2001), Dubovik et al. (2002), Colarco et al. (2002), and Sinyuk et al. (2003).

1. Global Dust-Soot-Snow Methods

1. Community Atmosphere Model with Slab Ocean Model (CAM/SOM)
2. Industrial Carbonaceous aerosol emissions (Bond et al., 2004)
3. Global Fire Emissions Database (GFED2) (Randerson et al., 2005; van der Werf et al., 2006)
4. BC/OC Emissions factors (Andreae and Merlet, 2001, updated)
5. BC/OC Optical properties (Chang and Charalampopoulos, 1990; Bond and Bergstrom, 2005; Bond et al., 2006)
6. Dust Entrainment and Deposition model (DEAD) (Zender et al., 2003; Mahowald et al., 2006)
7. Dust Optical Properties (Sokolik and Toon, 1999; Dubovik et al., 2002; Sinyuk et al., 2003)
8. SNow, ICe, and Aerosol Radiative model (SNICAR) (Flanner and Zender, 2005, 2006; Flanner et al., 2007)
9. Experiment(Control): Soot+Dust are (not) radiatively active in snowpack

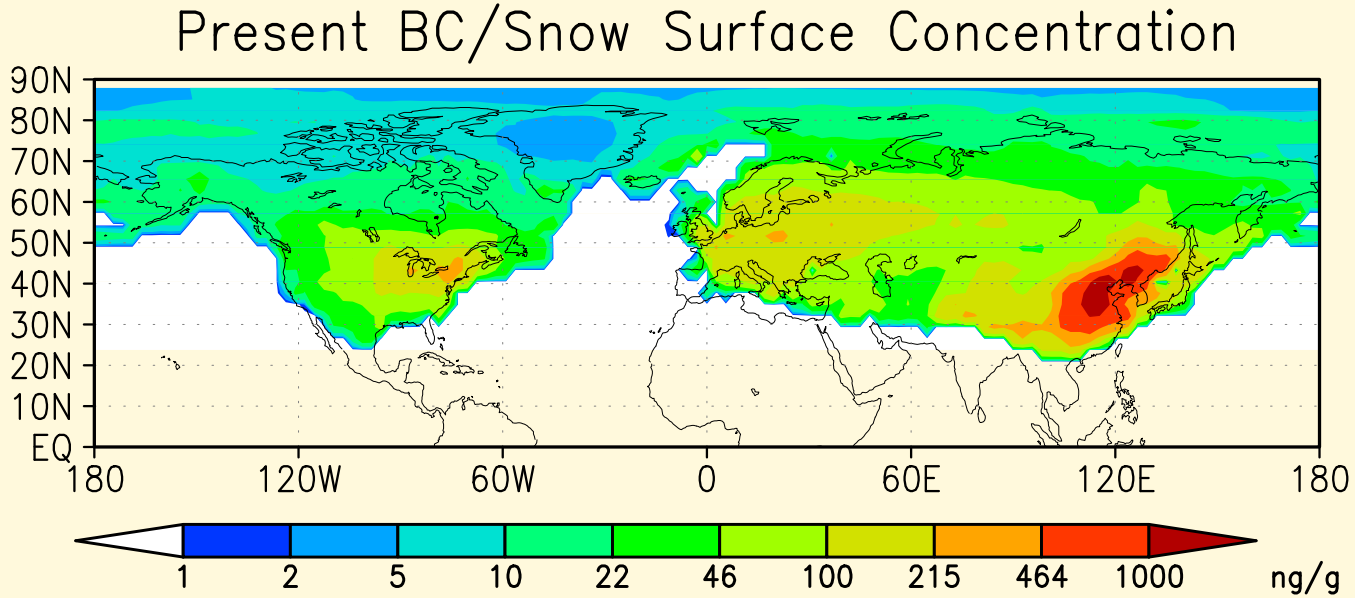


Figure 3: Present day soot concentration in snowpack, 2002 emissions. (Flanner *et al.*, 2007, *JGR*). Global mean $\sim 18\,\mathrm{ng\,g^{-1}}$.

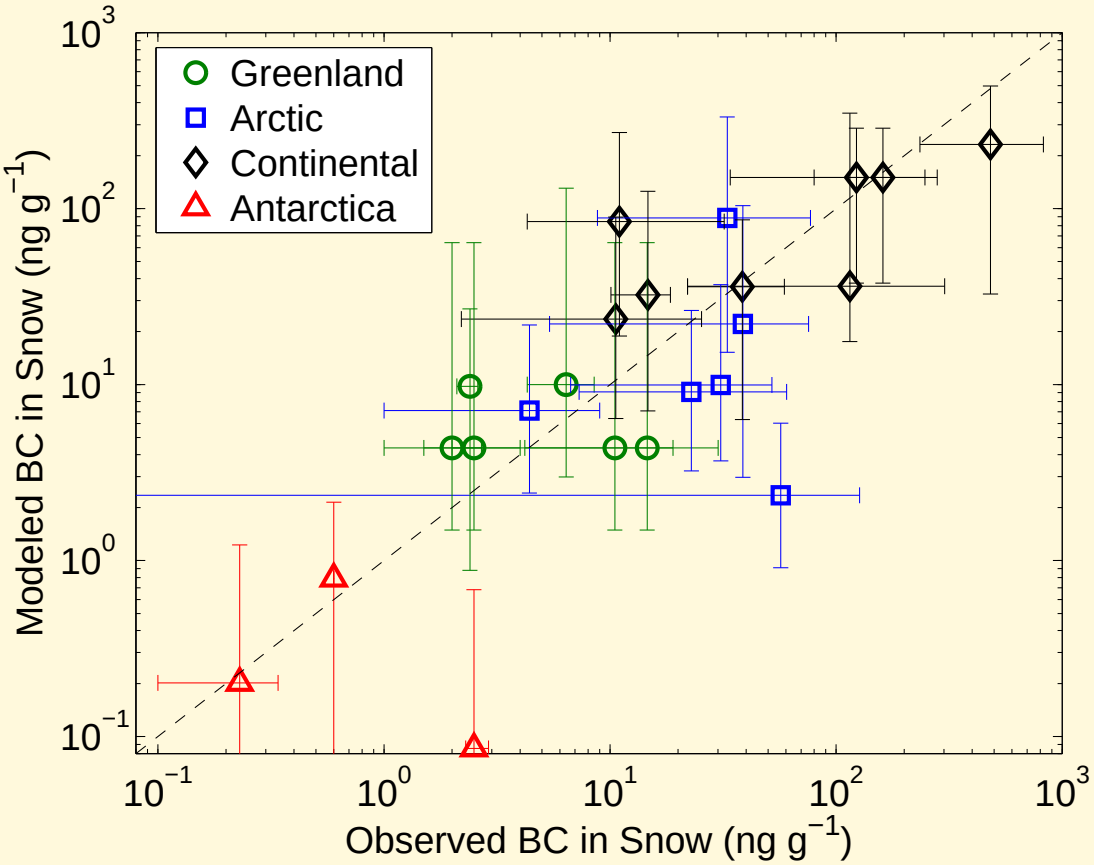


Figure 4: Observed and simulated BC concentrations (Flanner *et al.*, 2007, *JGR*).

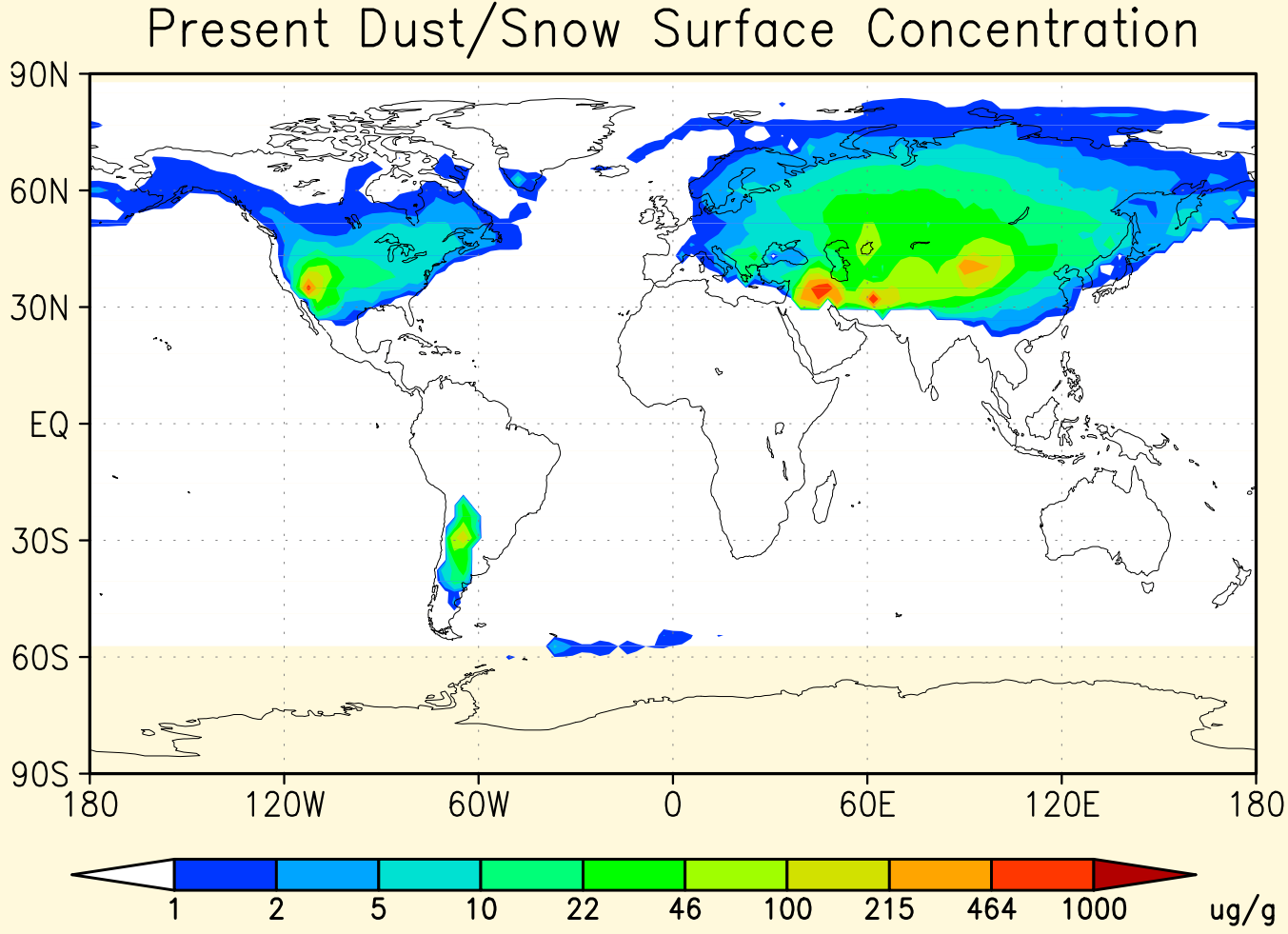


Figure 5: Present day dust concentration in snowpack. Global mean $\sim 3.2\,\mu g\,g^{-1}$.

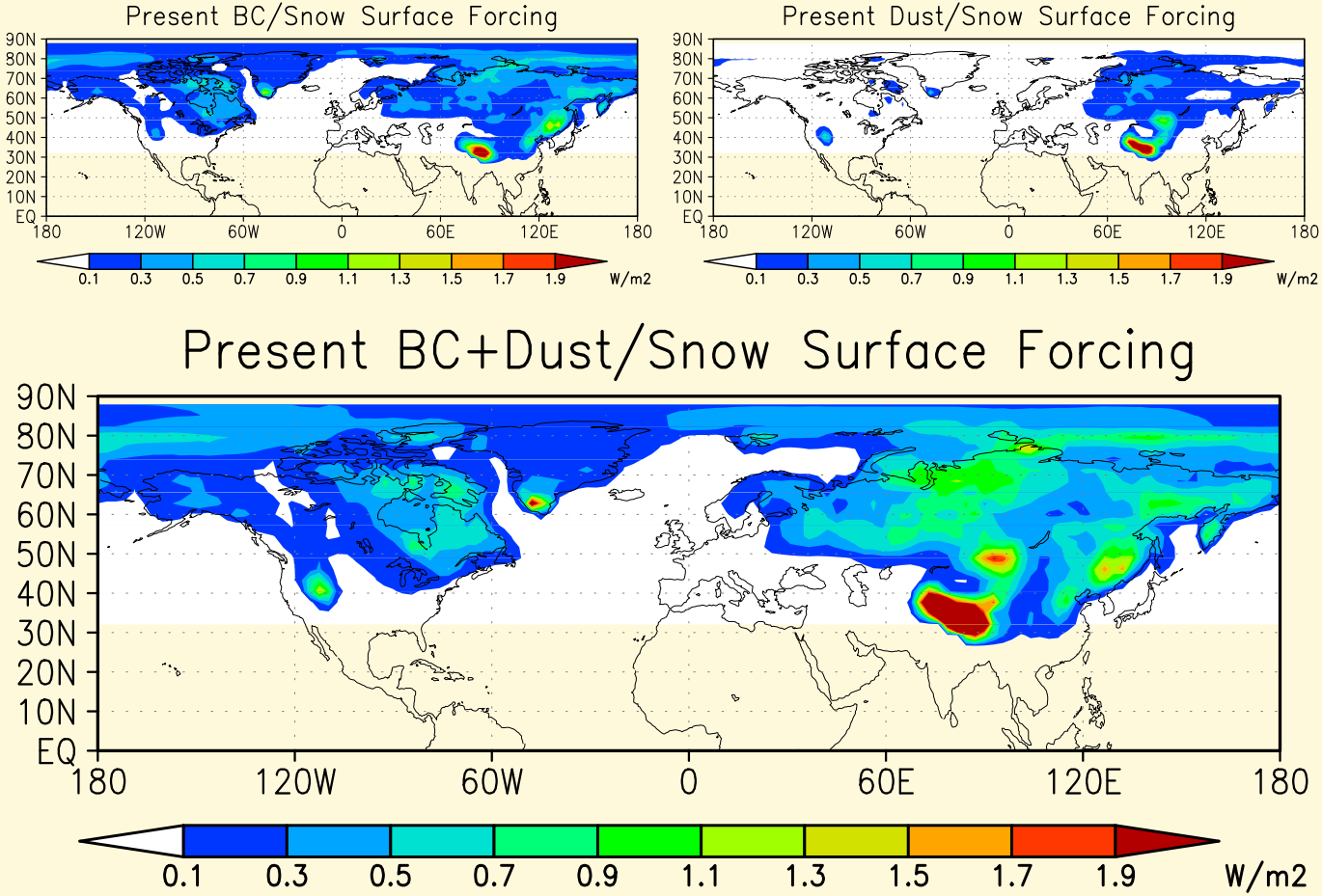
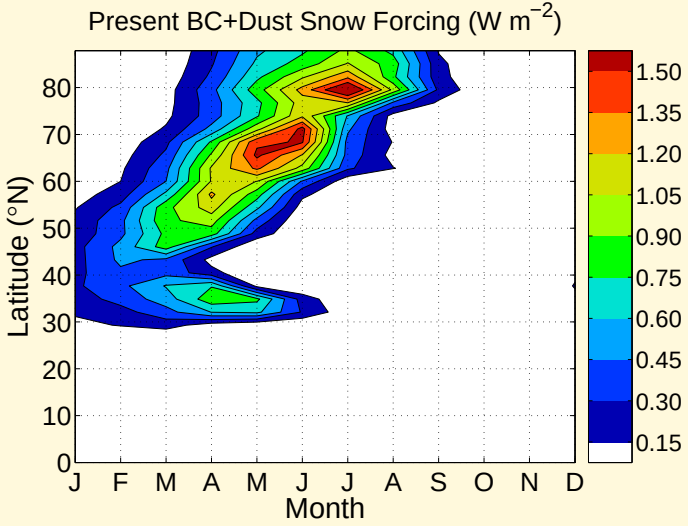
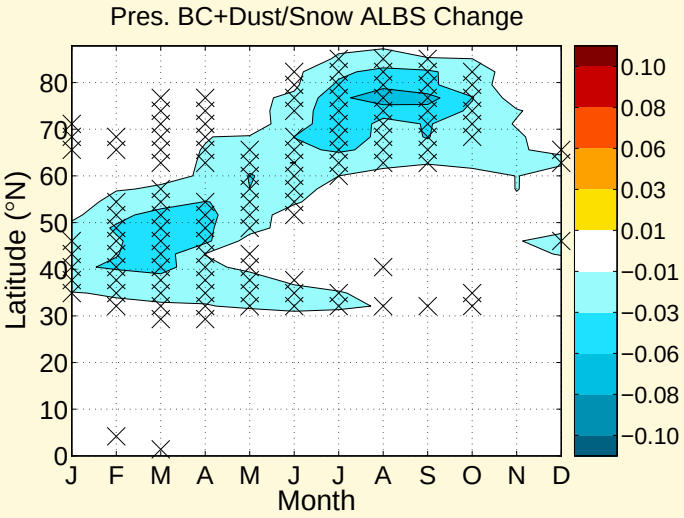
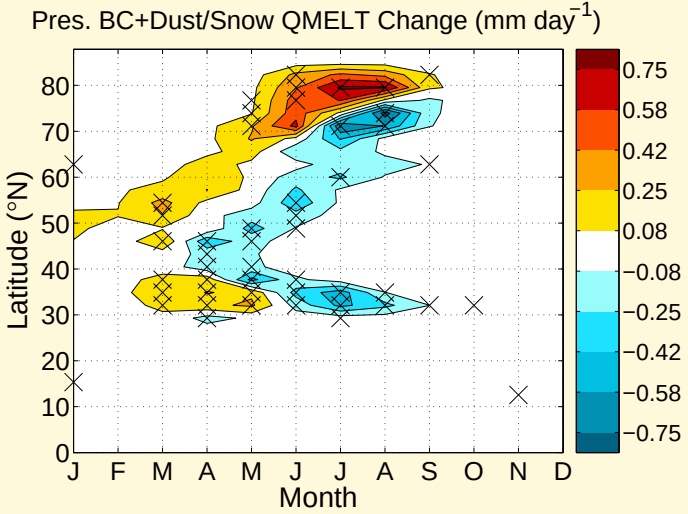
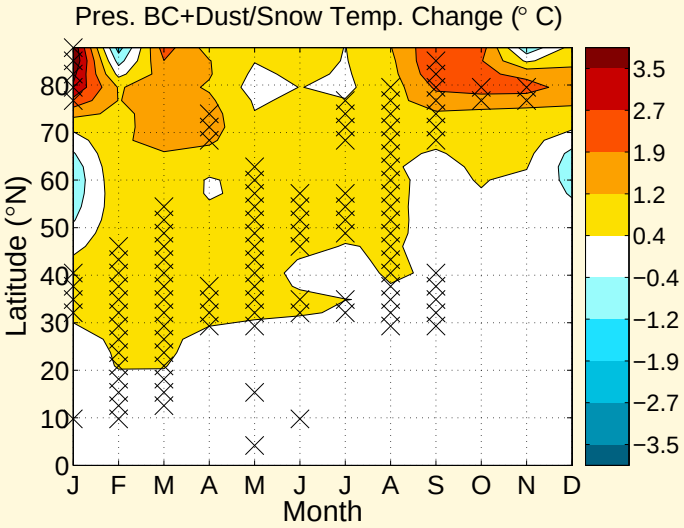


Figure 6: Present day global surface forcing by soot and dust in snowpack. Global mean $\sim 0.064\,\mathrm{W\,m^{-2}}$.


Present BC+Dust Snow Forcing (W m^{-2})
Latitude (°N)
Month
J F M A M J J A S O N D
0 10 20 30 40 50 60 70 80
1.50 1.35 1.20 1.05 0.90 0.75 0.60 0.45 0.30 0.15


Pres. BC+Dust/Snow ALBS Change
Latitude (°N)
Month
J F M A M J J A S O N D
0 10 20 30 40 50 60 70 80
0.10 0.08 0.06 0.03 0.01 −0.01 −0.03 −0.06 −0.08 −0.10


Pres. BC+Dust/Snow QMELT Change (mm day^{-1})
Latitude (°N)
Month
J F M A M J J A S O N D
0 10 20 30 40 50 60 70 80
0.75 0.58 0.42 0.25 0.08 −0.08 −0.25 −0.42 −0.58 −0.75


Pres. BC+Dust/Snow Temp. Change (° C)
Latitude (°N)
Month
J F M A M J J A S O N D
0 10 20 30 40 50 60 70 80
3.5 2.7 1.9 1.2 0.4 −0.4 −1.2 −1.9 −2.7 −3.5

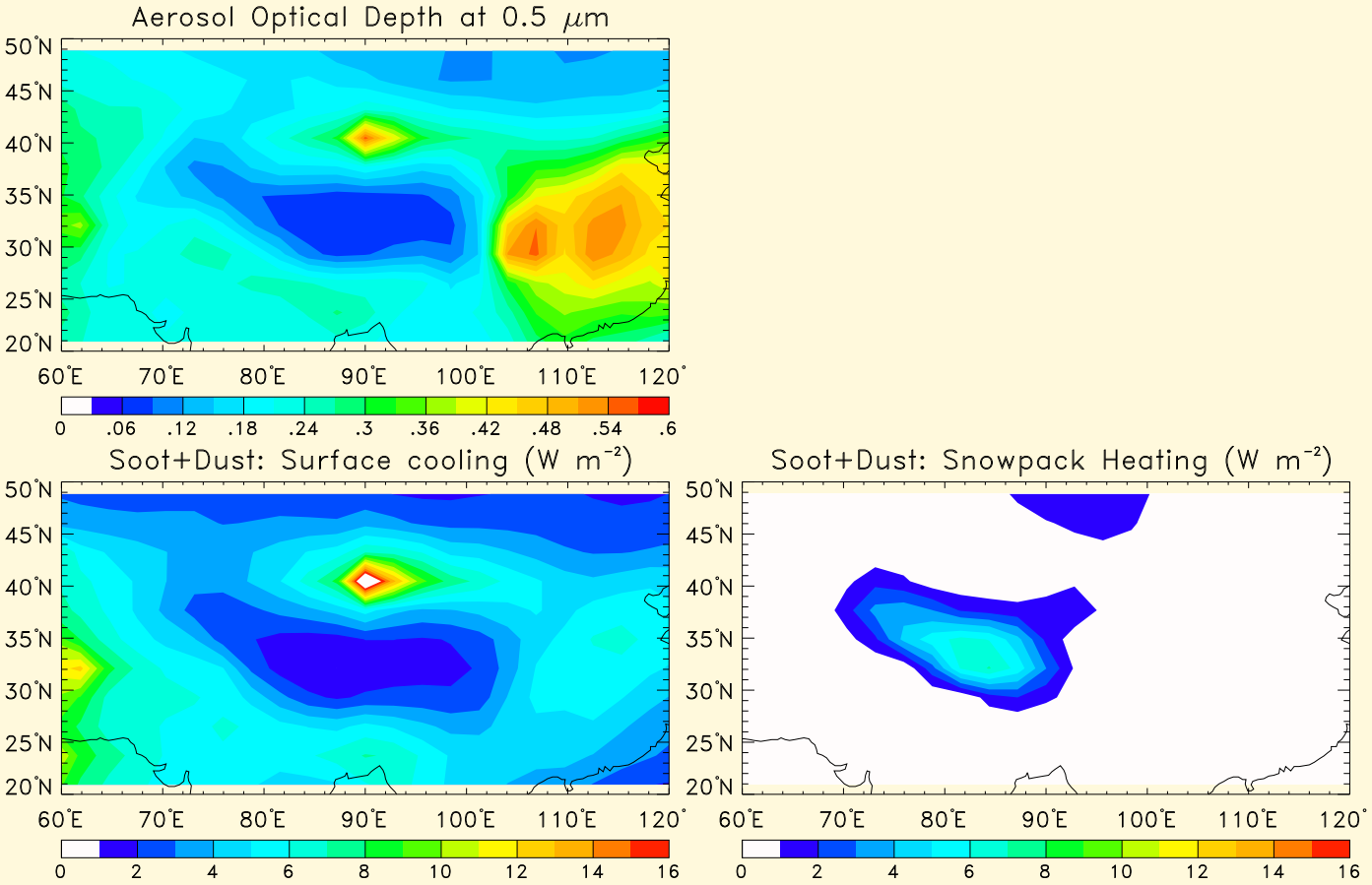


Figure 8: Forcing by aerosol impurities in snowpack exceeds forcing by atmospheric aerosol (and GHGs) in the Tibetan Plateau region.

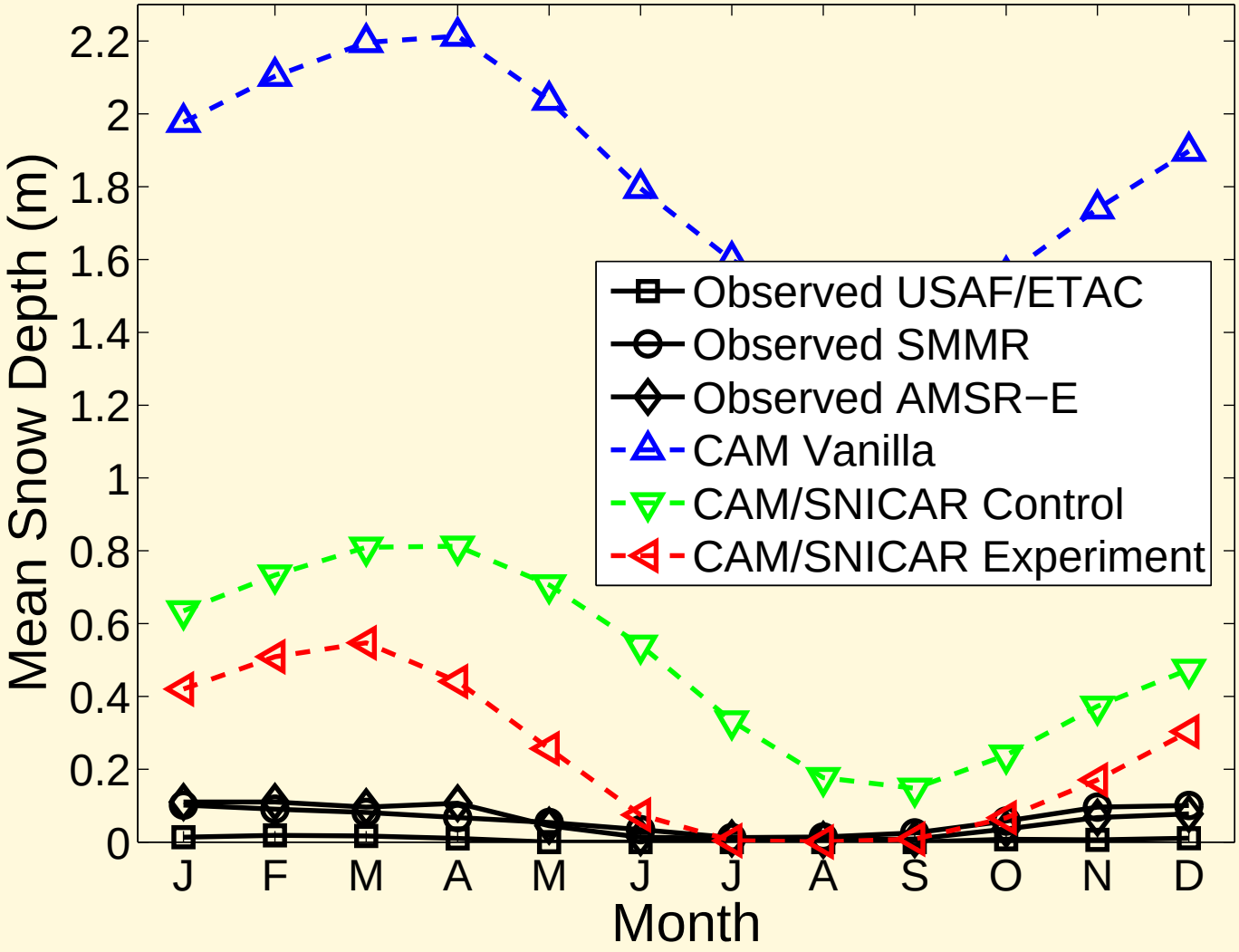


Figure 9: Observed and simulated Tibetan Plateau snow depth.

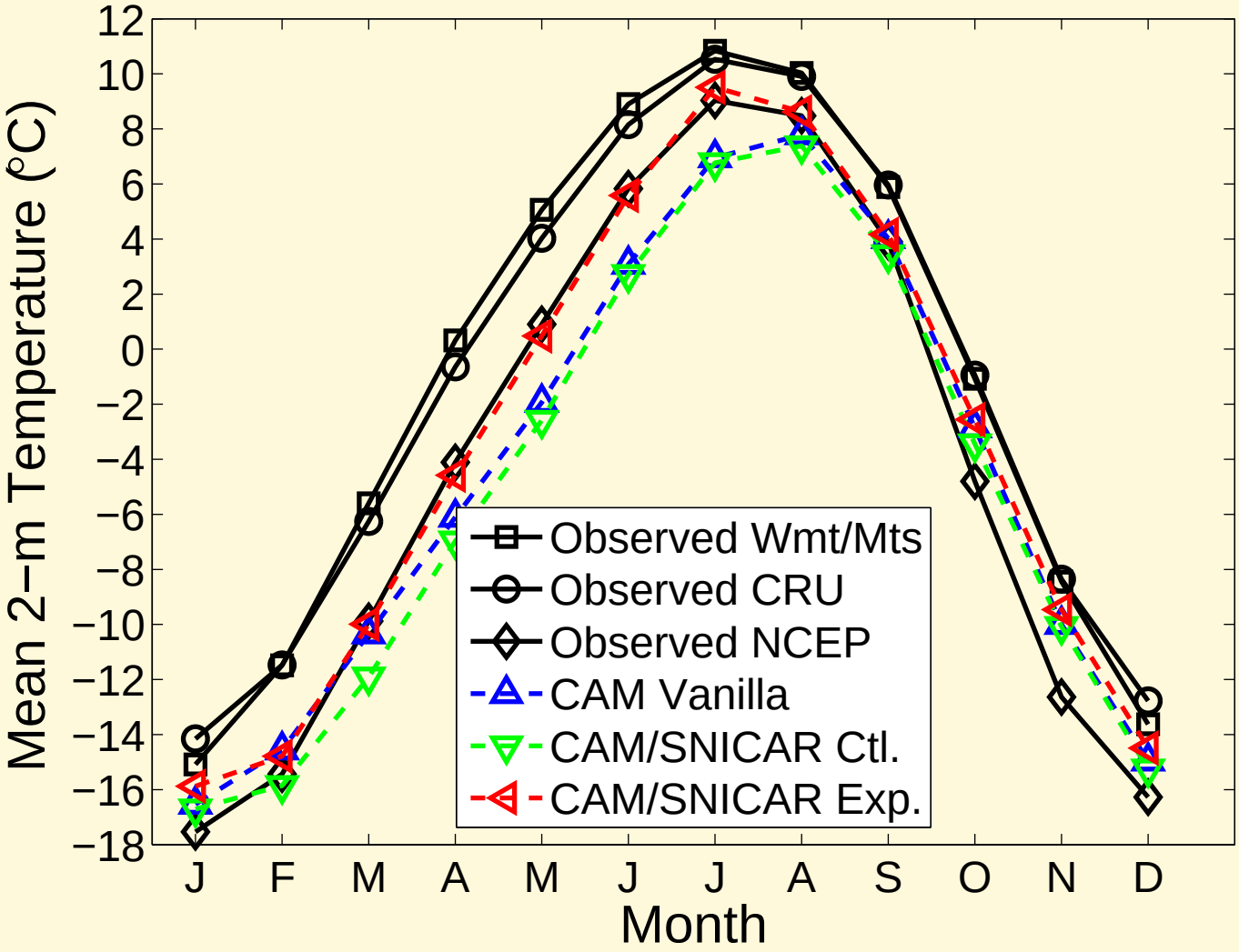


Figure 10: Observed and simulated Tibetan Plateau 2 m air temperature.

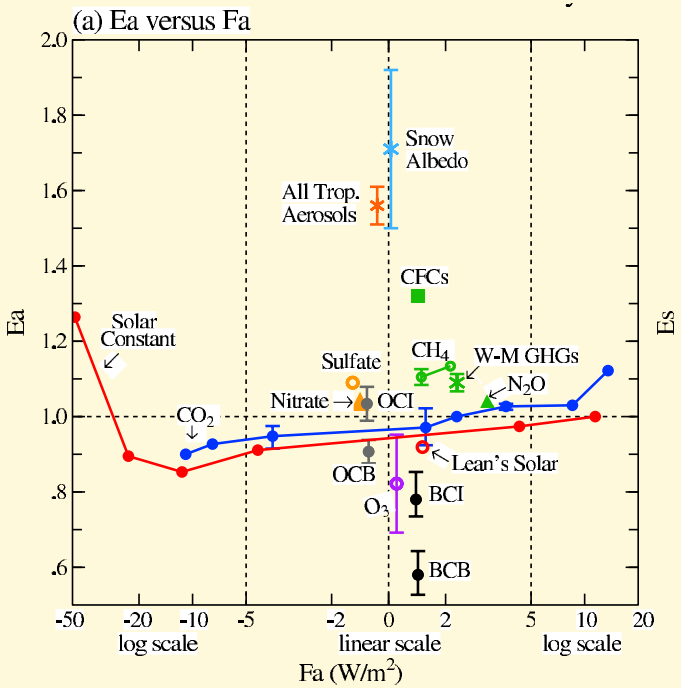


Figure 11: Hansen et al. (2005) forcing efficacies.

Efficacy $E_{\rm a}$: Response relative to response to equivalent $\mathrm{CO_2}$ forcing

$$
\begin{aligned}
E_{\rm a} &\equiv \frac{\lambda(\text{dirty snow})}{\lambda(\Delta \mathrm{CO_2})} \\
&= \frac{(\Delta T_{\rm s}/\Delta F_{\rm R}^{\rm Trp})_{\text{dirty snow}}}{(2.47\,\mathrm{K})/(3.58\,\mathrm{W\,m^{-2}})} \\
&= \frac{(\Delta T_{\rm s}/\Delta F_{\rm R}^{\rm Trp})_{\text{dirty snow}}}{0.69\,\mathrm{K\,(W\,m^{-2})^{-1}}}
\end{aligned}
$$

2. Conclusions: Climate Effects and Efficacy of Dirty Snow

Global results:

- Dirty snowpack forcing is $\sim 70/30\%$ soot/dust globally
- Dust efficacy $\sim$ soot efficacy $E_{\mathrm{a}} \sim 3$–4
- Dirty snow warms climate 0.10–0.20 K ($\sim$60% by anthropogenic soot)
- Significant climate affects on NH albedo, melt seasonality, T

Dirty snow has the greatest influence on the Tibetan Plateau:

- Pristine skies yet strong aerosol forcing via snowpack impurities
- Reduced snowpack 50% in seasonal snow areas due to snow-albedo feedback, snow grain size-temperature feedback
- Dirty snow warms TP ~ 2 K, remediates model biases

Overall:

- With forcing efficacy $E_{\mathrm{a}} \sim 3$–4, Dirty snow is the most efficient climate forcing agent known. Reducing soot emissions may be an optimal strategy to mitigate cryospheric warming.

3. References

References

Andreae, M. O. and P. Merlet, 2001: Emission of trace gases and aerosols from biomass burning. *Global Biogeochem. Cycles*, **15**(4), 955–966, doi:10.1029/2000GB001382.

Bond, T. C. and R. W. Bergstrom, 2005: Light absorption by carbonaceous particles: An investigative review. *Aerosol Sci. Technol.*, **40**(1), 27–67, doi:10.1080/02786820500421521.

Bond, T. C., G. Habib and R. W. Bergstrom, 2006: Limitations in the enhancement of visible light absorption due to mixing state. *Submitted to J. Geophys. Res.*

Bond, T. C., D. G. Streets, K. F. Yarber, S. M. Nelson, J.-H. Woo and Z. Klimont, 2004: A technology-based global inventory of black and organic carbon emissions from combustion. *J. Geophys. Res.*, **109**(D14203), doi:10.1029/2003JD003697.

Chang, H. and T. T. Charalampopoulos, 1990: Determination of the wavelength dependence of refractive indices of flame soot. *Proc. Roy. Soc. London A, Math. and Phys. Sci.*, **430**(1880), 577–591.

Colarco, P. R., O. B. Toon, O. Torres and P. J. Rasch, 2002: Determining the UV imaginary index of refraction of Saharan dust particles from Total Ozone Mapping Spectrometer data using a three-dimensional model of dust transport. *J. Geophys. Res.*, **107**(D16), doi:10.1029/2001JD000903.

Dubovik, O., B. Holben, T. F. Eck, A. Smirnov, Y. J. Kaufman, M. D. King, D. Tanré and I. Slutsker, 2002: Variability of absorption and optical properties of key aerosol types observed in worldwide locations. *J. Atmos. Sci.*, **59**(3), 590–608.

Flanner, M. G. and C. S. Zender, 2005: Snowpack radiative heating: Influence on Tibetan Plateau climate. *Geophys. Res. Lett.*, **32**(6), L06501, doi:10.1029/2004GL022076.

Flanner, M. G. and C. S. Zender, 2006: Linking snowpack micro-

physics and albedo evolution. *J. Geophys. Res.*, **111**(D12), D12208, doi:10.1029/2004GL022076.

Flanner, M. G., C. S. Zender, J. T. Randerson and P. J. Rasch, 2007: Present-day climate forcing and response from black carbon in snow. *J. Geophys. Res.*, **112**, D11202, doi:10.1029/2006JD008003, Available from `http://dust.ess.uci.edu/ppr/ppr_FZR07.pdf`.

Hansen, J., M. Sato, R. Ruedy, L. Nazarenko, A. Lacis, G. A. Schmidt, G. Russell, I. Aleinov, M. Bauer, S. Bauer, N. Bell, B. Cairns, V. Canuto, M. Chandler, Y. Cheng, A. D. Genio, G. Faluvegi, E. Fleming, A. Friend, T. Hall, C. Jackman, M. Kelley, N. Kiang, D. Koch, J. Lean, J. Lerner, K. Lo, S. Menon, R. Miller, P. Minnis, T. Novakov, V. Oinas, J. Perlwitz, J. Perlwitz, D. Rind, A. Romanou, D. Shindell, P. Stone, S. Sun, N. Tausnev, D. Thresher, B. Wielicki, T. Wong, M. Yao and S. Zhang, 2005: Efficacy of climate forcings. *J. Geophys. Res.*, **110**(D18104), doi:10.1029/2005JD005776.

Kaufman, Y. J., D. Tanré, O. Dubovik, A. Karnieli and L. A. Remer, 2001:

Absorption of sunlight by dust as inferred from satellite and ground-based remote sensing. *Geophys. Res. Lett.*, **28**, 1479–1482.

Mahowald, N. M., M. Yoshioka, W. D. Collins, A. J. Conley, D. W. Fillmore and D. B. Coleman, 2006: Climate response and radiative forcing from mineral aerosols during the last glacial maximum, pre-industrial, current, and doubled-carbon dioxed climates. *Submitted to Geophys. Res. Lett.*

Randerson, J. T., G. R. van der Werf, G. J. Collatz, L. Giglio, C. J. Still, P. Kasibhatla, J. B. Miller, J. W. C. White, R. S. DeFries and E. S. Kasischke, 2005: Fire emissions from C_3 and C_4 vegetation and their influence on interannual variability of atmospheric CO_2 and $\delta^{13}CO_2$. *Global Biogeochem. Cycles*, **19**, GB2019, doi:10.1029/2004GB002366.

Sinyuk, A., O. Torres and O. Dubovik, 2003: Combined use of satellite and surface observations to infer the imaginary part of refractive index of Saharan dust. *Geophys. Res. Lett.*, **30**(2), 1081, doi:10.1029/2002GL016189.

Sokolik, I. N. and O. B. Toon, 1999: Incorporation of mineralogical compo-

sition into models of the radiative properties of mineral aerosol from UV to IR wavelengths. *J. Geophys. Res.*, **104**(D8), 9423–9444.

van der Werf, G. R., J. T. Randerson, L. Giglio, G. J. Collatz, P. S. Kasibhatla and A. F. Arellano, Jr., 2006: Interannual variability of global biomass burning emissions from 1997 to 2004. *Atmos. Chem. Phys.*, **6**, 3423–3441.

Zender, C. S., H. Bian and D. Newman, 2003: Mineral Dust Entrainment And Deposition (DEAD) model: Description and 1990s dust climatology. *J. Geophys. Res.*, **108**(D14), 4416, doi:10.1029/2002JD002775.