Snow-albedo feedback triggered by carbonaceous particles

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NCAR

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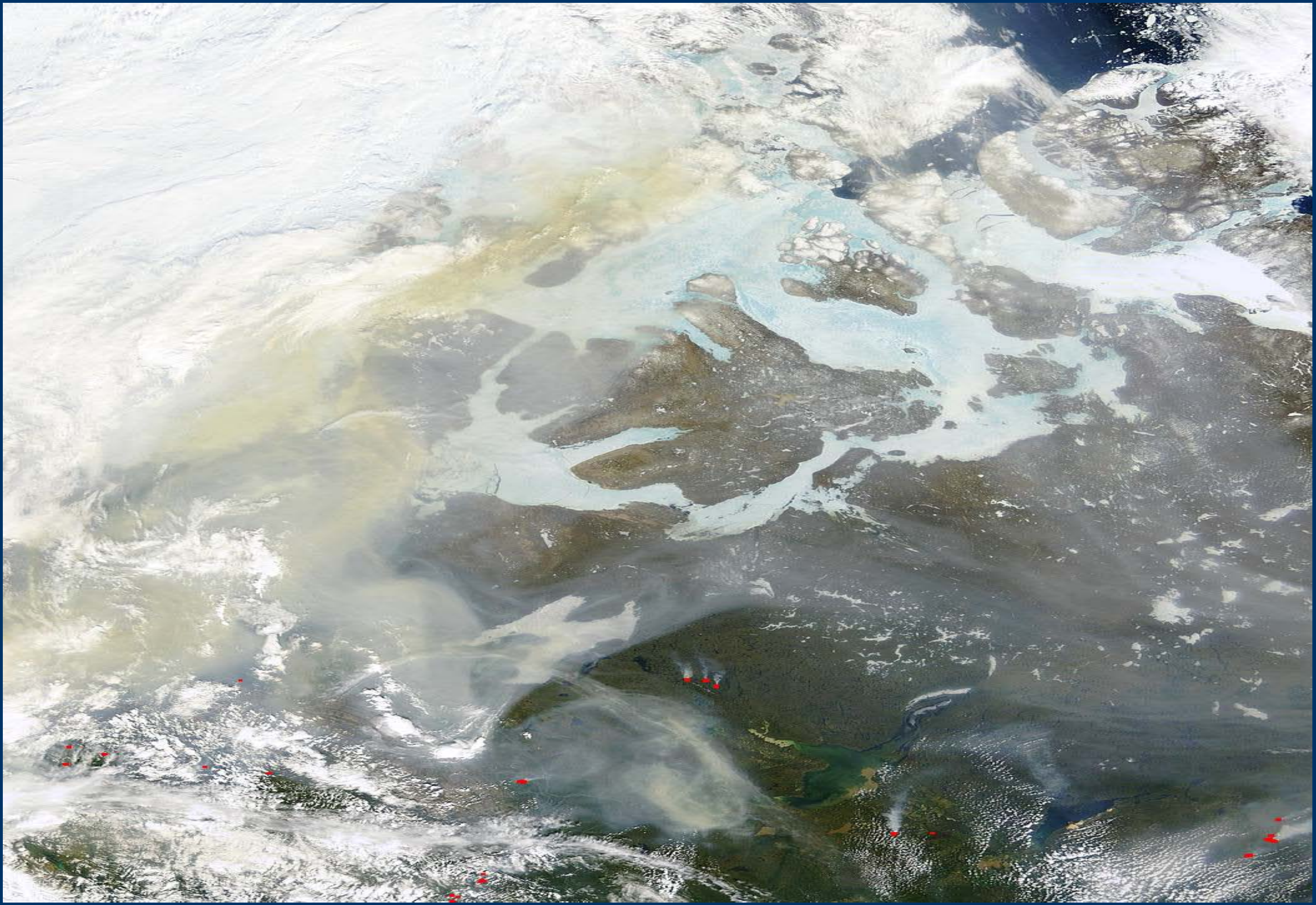
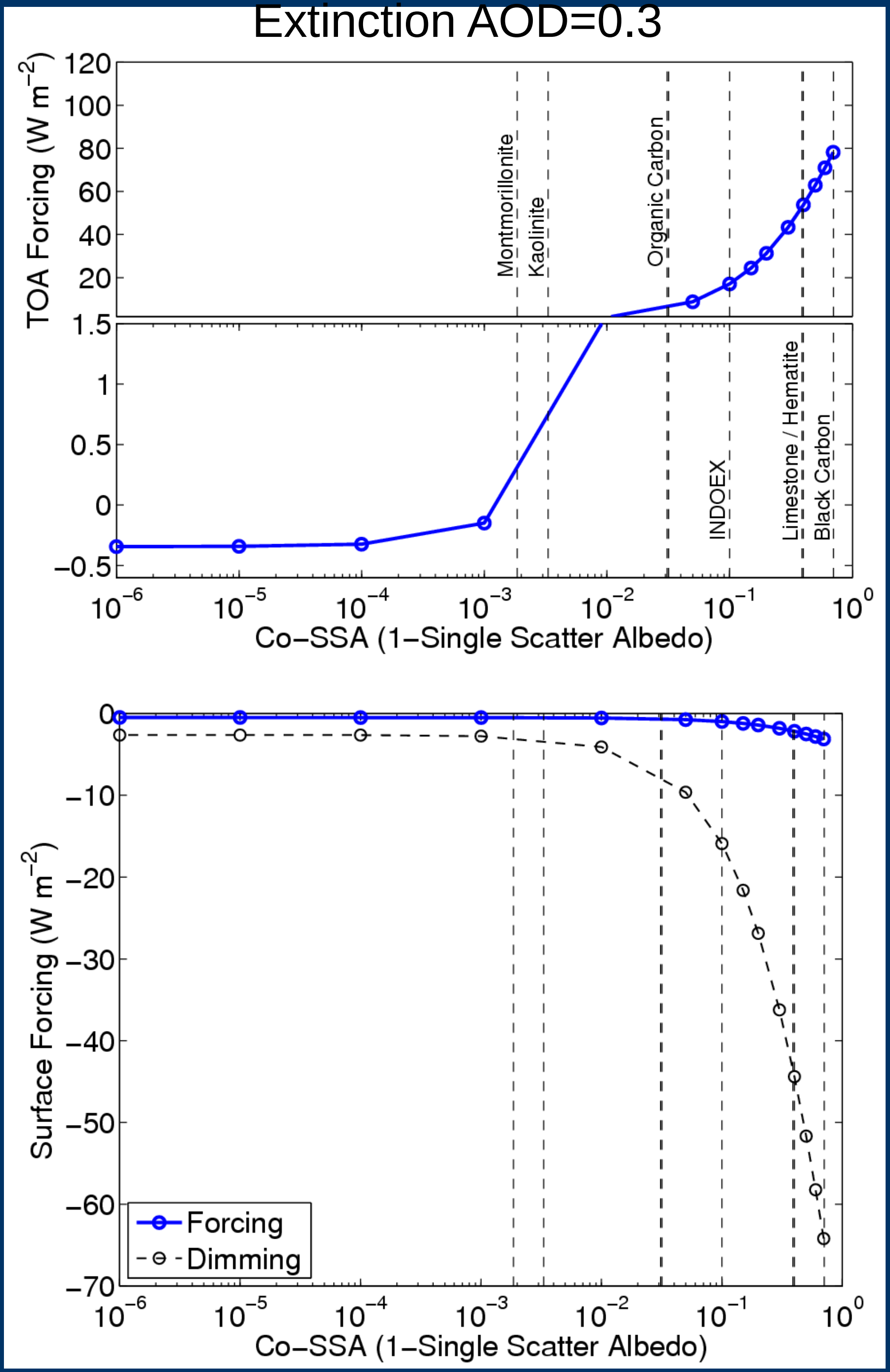
Carbonaceous particles: positive radiative forcing over snow



Smoke over the Canadian Arctic

Aerosol radiative forcing over (pure) snow



- TOA forcing
  - Mixtures with SSA < 0.999 (λ=500 nm) produce a positive TOA forcing
  - Organic carbon: Positive
- Surface forcing
  - Strong "dimming" from absorbing aerosols, but small forcing because of snow's high reflectance
  - Multiple scattering between snow and aerosol layer

<u>OC/BC emission ratios:</u>

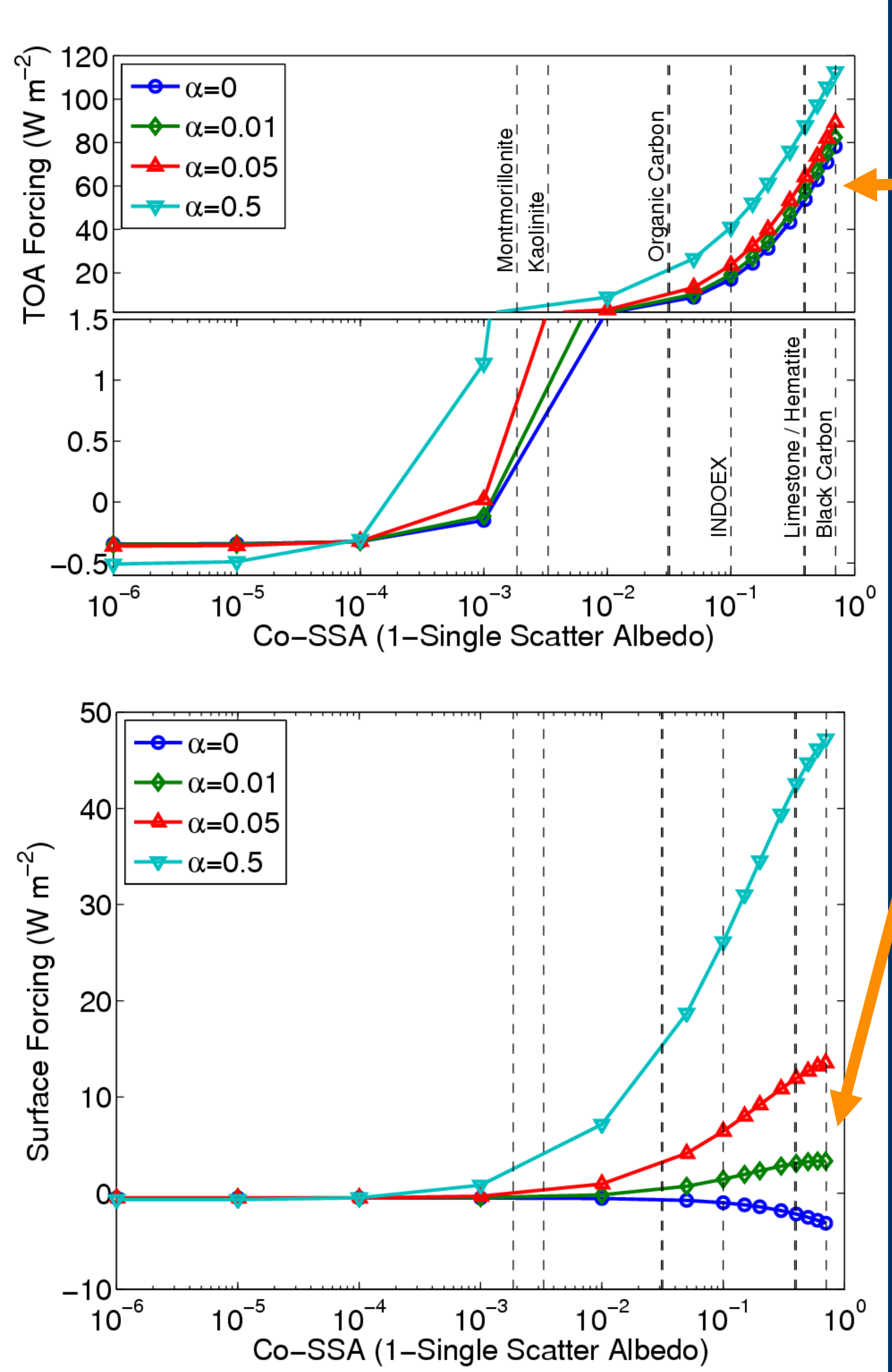
Biomass burning: ~10
Biofuel: ~6
Fossil Fuel: ~0.9

Snow albedo perturbed by black carbon

1 gram of BC

- Why do ppb levels of BC perturb albedo?
  - BC absorptivity is ~5 orders of magnitude > ice
  - Snow scatters visible radiation efficiently via refraction
    - A typical reflected green photon undergoes ~1000 scattering events before emerging from the top of the snowpack.
    - Hence, photon path-length is large, and probability of encountering the rare BC particle is reasonable

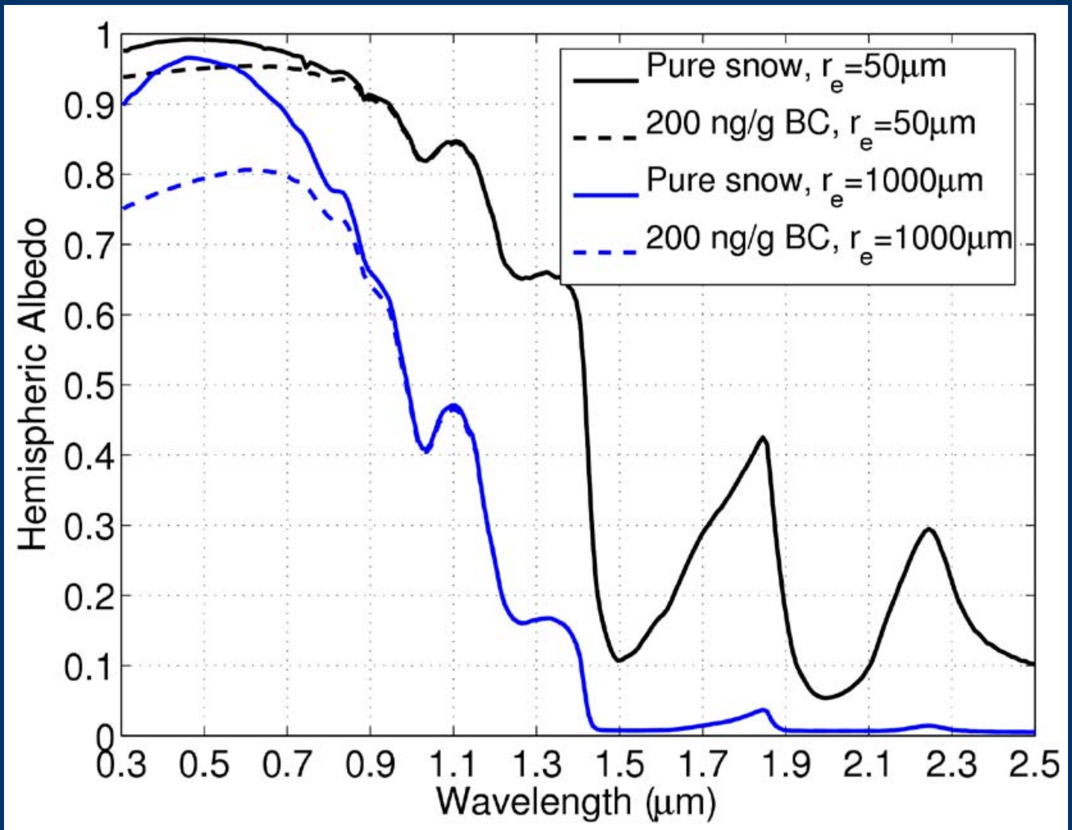
Aerosol radiative forcing over (dirty) snow

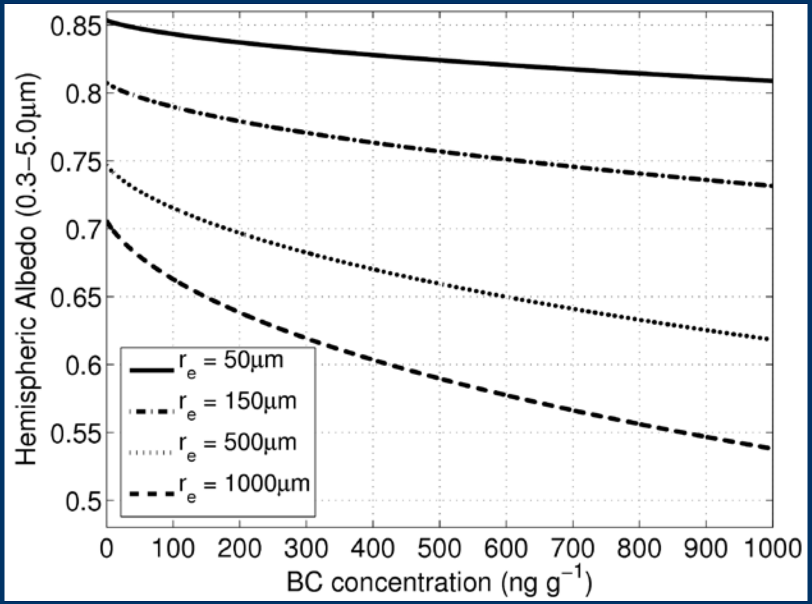


- Snow darkening:
  - Increases TOA forcing
  - Reverses the sign of net surface forcing
- Ratio of particle mixing ratio in snow to atmospheric column burden (α) is affected by many processes
  - Deposition efficiency
  - Meltwater removal from snow
  - Mean estimate is 0.05

Importance of snow grain size

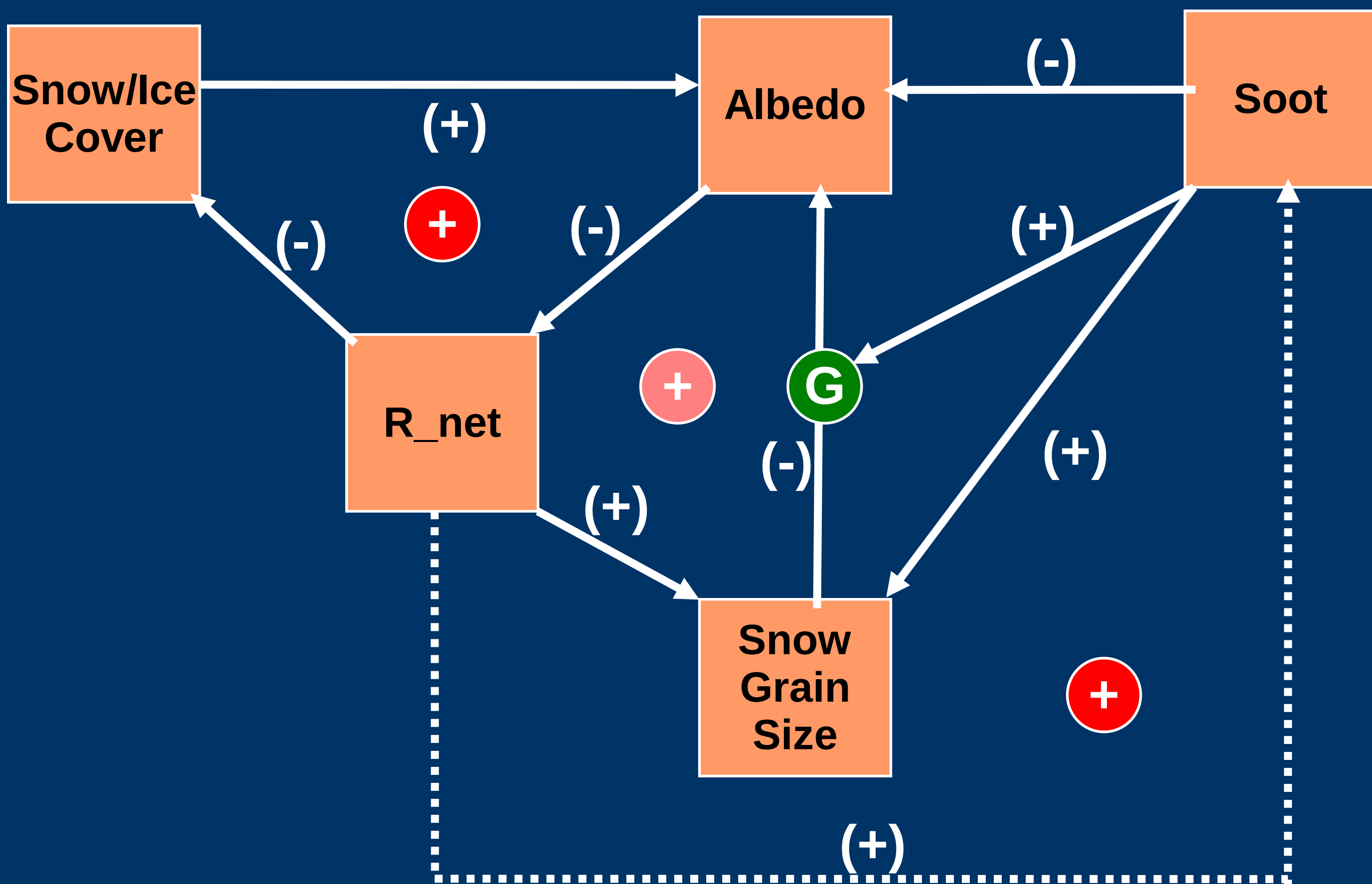
- Snow exhibits large variability in grain size
  - (30 < r_e < 2000 µm)
- Grain size determines pure snow albedo and the magnitude of perturbation by impurities





Three-fold variability in albedo reduction for a given mass of BC, depending on grain size

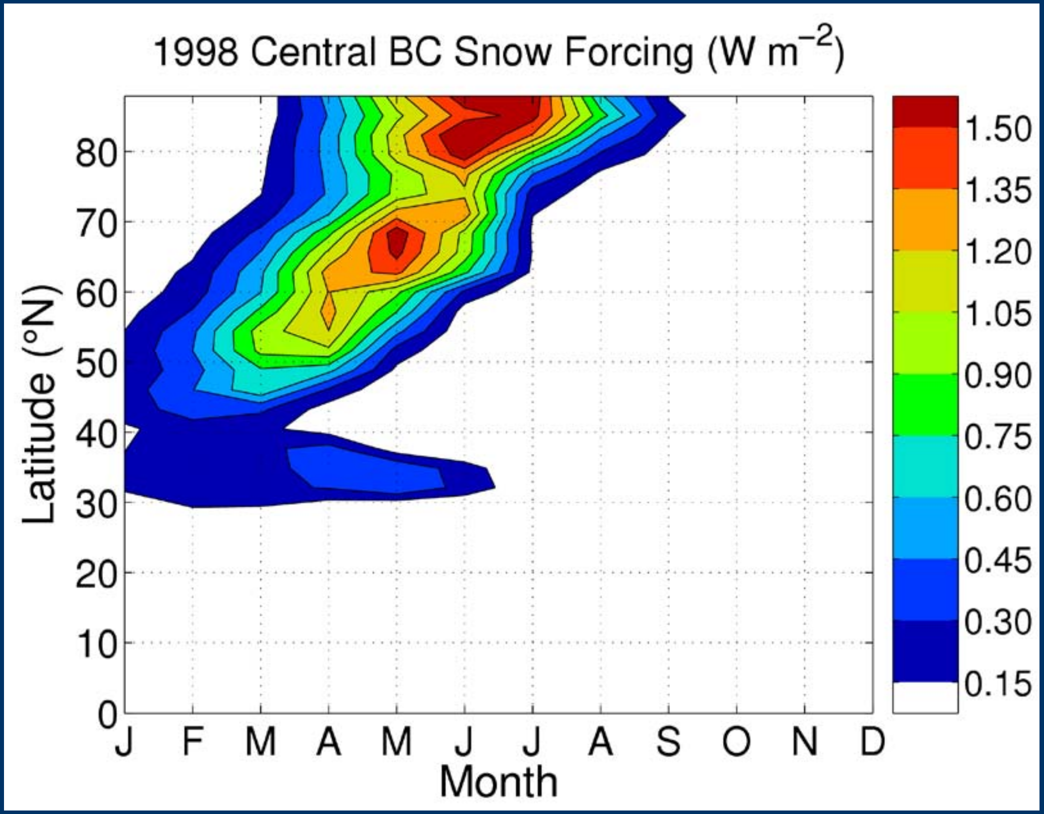
Multiple positive feedbacks caused by impurities and snow aging

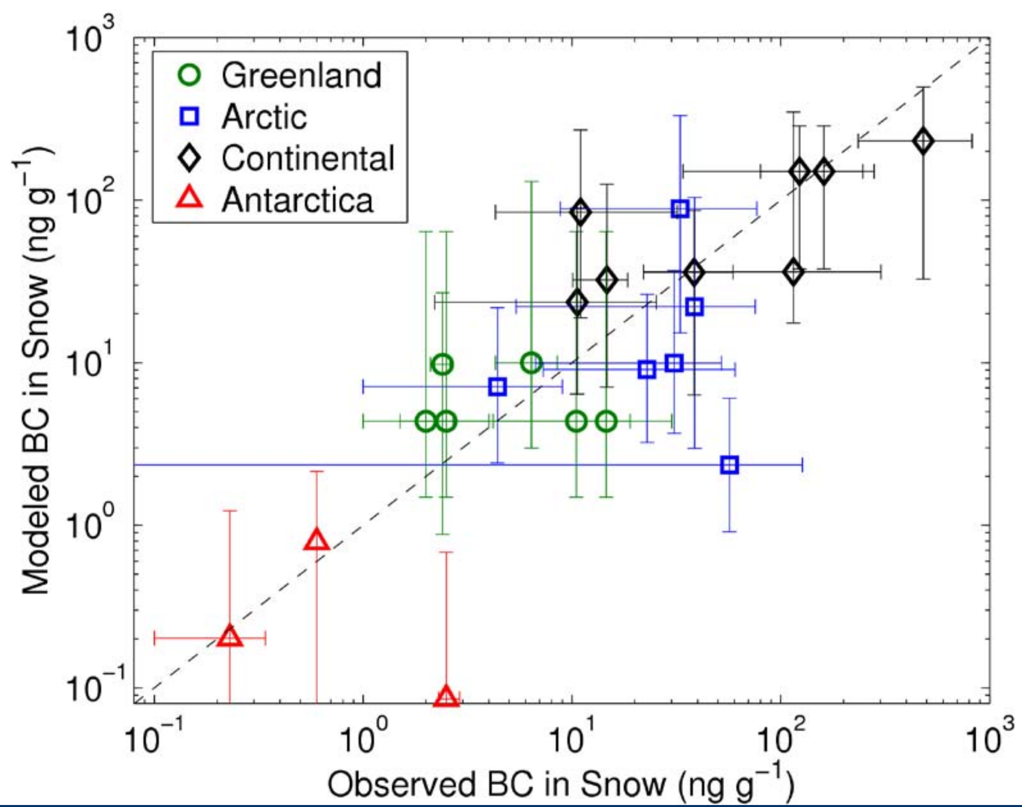


Concentration of hydrophobic and large impurities at the surface during melting

Climate sensitivity experiments

- Equilibrium climate experiments with NCAR CAM 3 model [*Collins et. al*, 2006], coupled with the SNICAR model [*Flanner et. al*, 2007], BC+OC emissions [*Bond,* 2004]
- Global, annual-mean radiative forcing from BC in snow: ~0.04-0.2 W/m^2 [*Hansen and Nazarenko*, 2004; *Jacobson*, 2004; *Flanner et. al*, 2007]





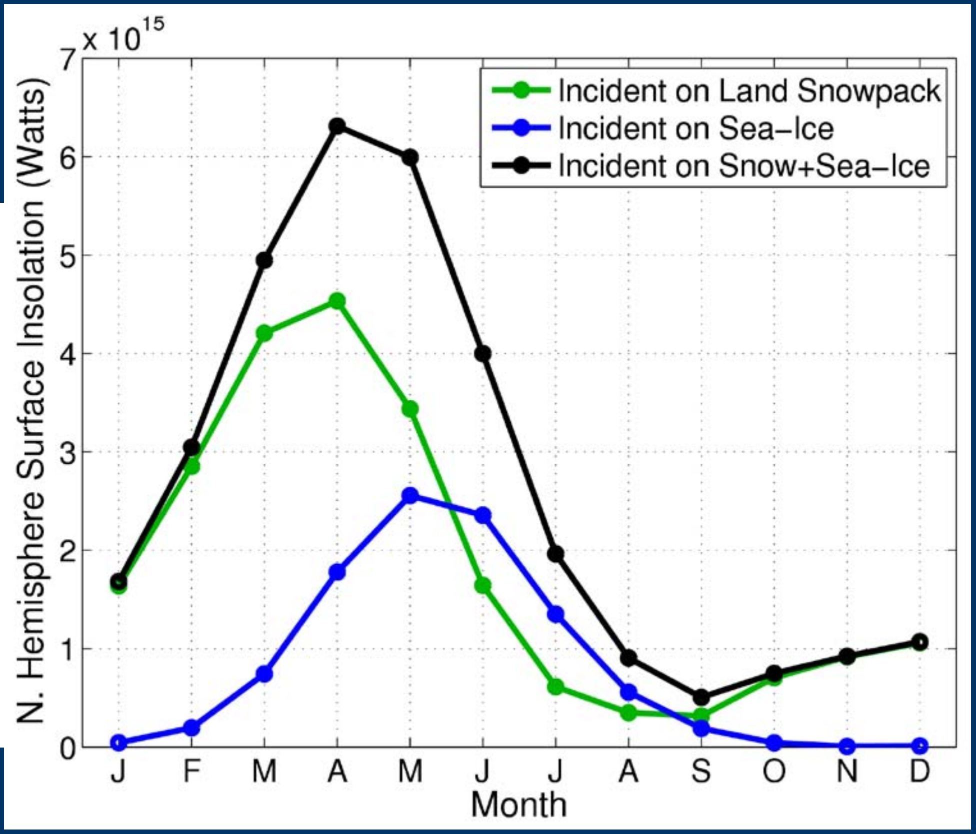
Springtime susceptibility to snow forcing

- Northern hemisphere insolation incident upon snowpack peaks during March-May
  - Boreal spring is time of maximum snow-albedo feedback strength
- <u>Goal:</u> quantify relative effects on springtime climate of carbon dioxide, carbonaceous particles in atmosphere, and particles in snow

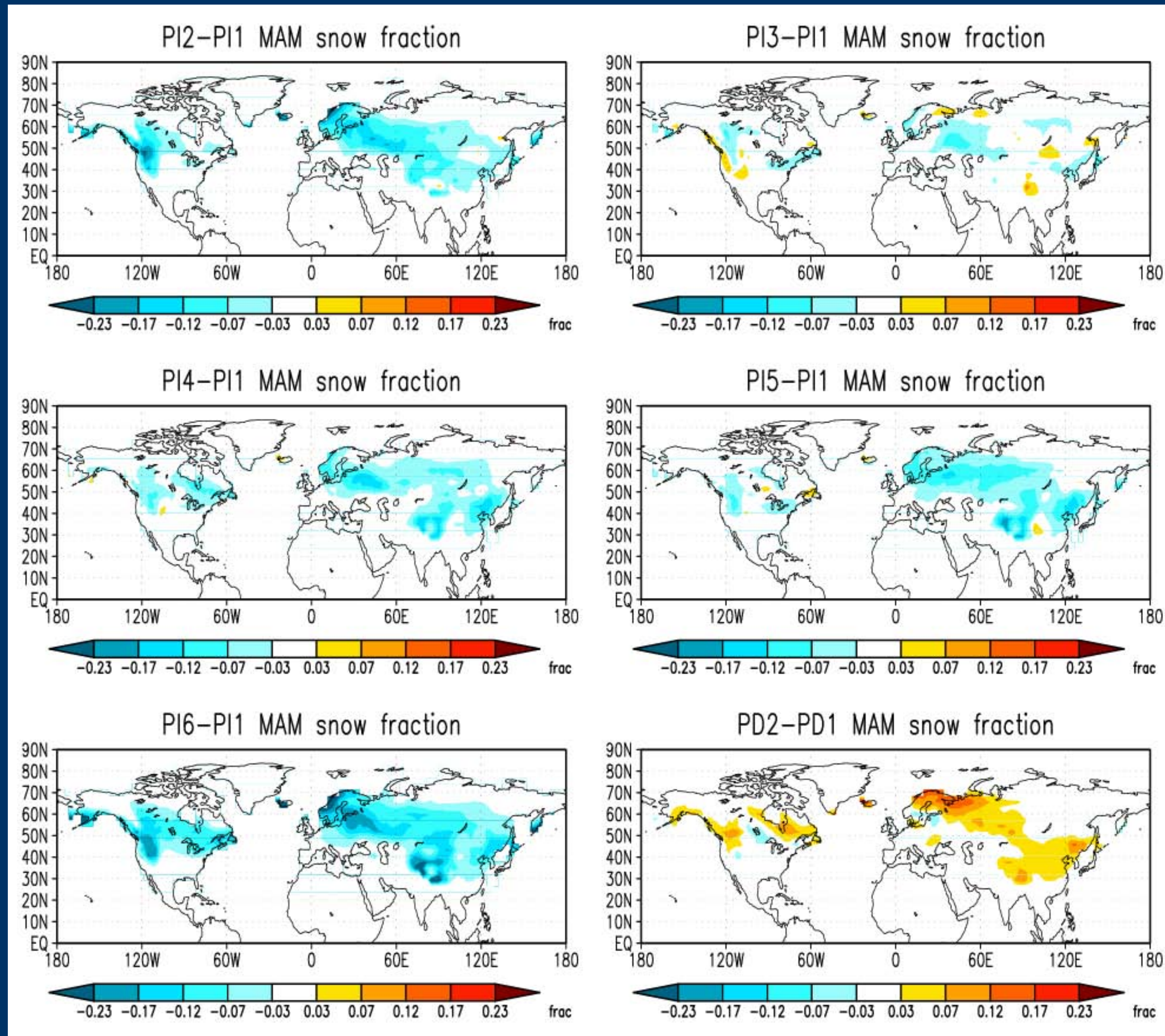
Table 1. Model Experiments

Experiment Case	CO_2 (ppm)	FF+BF BC+OM[a] active in atm?	FF+BF BC active in snow?	BB BC and dust[b] active in snow?	Ocean / sea-ice Configuration
PI1[d]	289	no	no	no	slab
PI2	380	no	no	no	slab
PI3	289	yes	no	no	slab
PI4	289	no	yes	no	slab
PI5	289	yes	yes	no	slab
PI6	380	yes	yes	no	slab
PD1[e]	380	yes	yes	yes	slab
PD2[e]	380	no	no	no	slab

[a] Fossil fuel and biofuel black carbon and organic matter
[b] Biomass burning black carbon and mineral dust
[d] "PI" experiments have pre-industrial initial conditions
[e] "PD" experiments have present-day initial conditions



Changes in spring snow cover



CO_2

BC+OC in atmosphere

BC in snow only

BC+OC in atmosphere and snow

BC+OC and CO_2

Removal of FF+BF BC+OC in present climate

- Eurasian springtime snow loss from BC+OC is comparable to that from CO_2
- Large snow losses predicted with BC in snow, but not with BC+OC exclusively in atmosphere

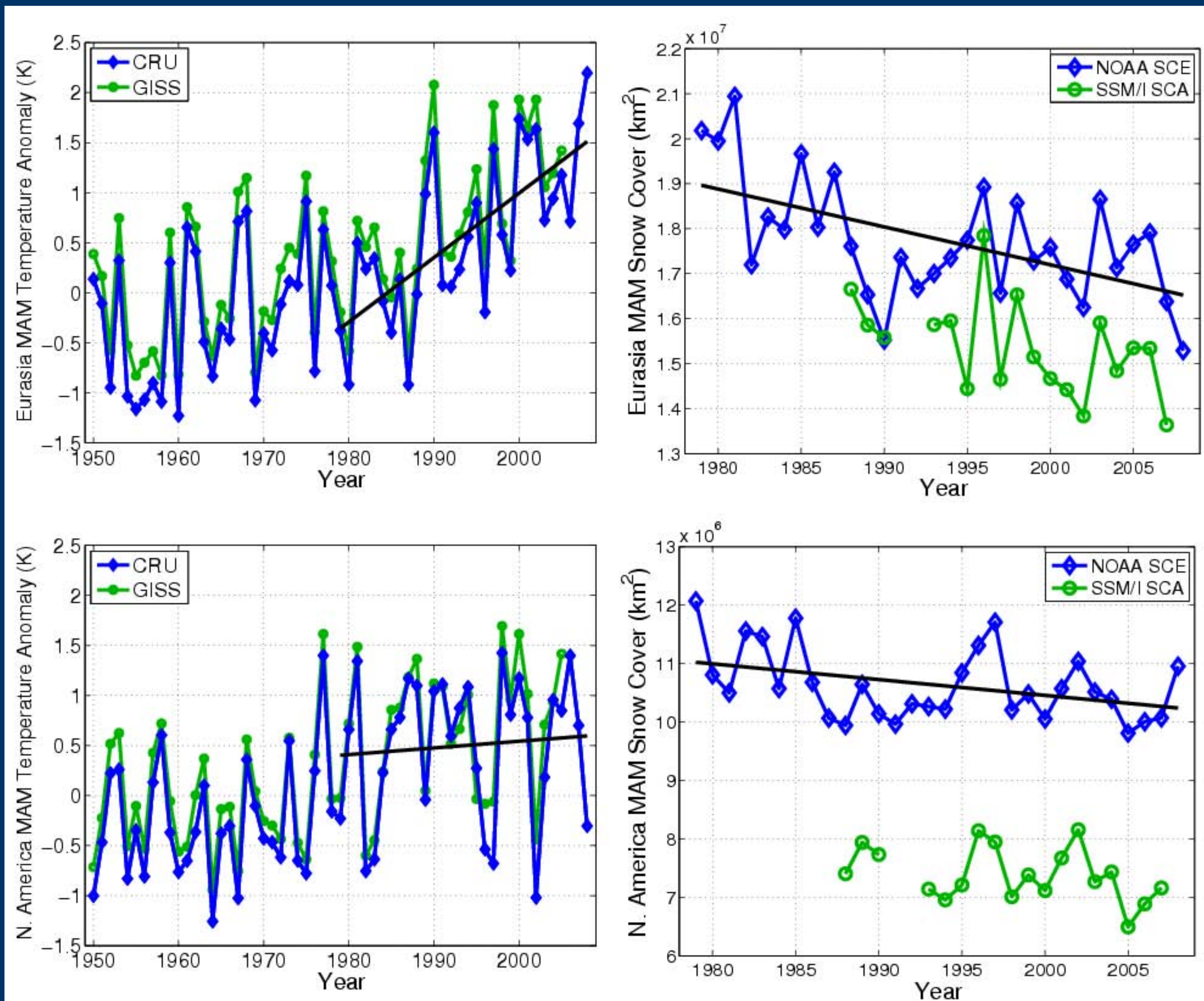
Observed springtime climate trends

Temperature

Snow cover

Eurasia

North America

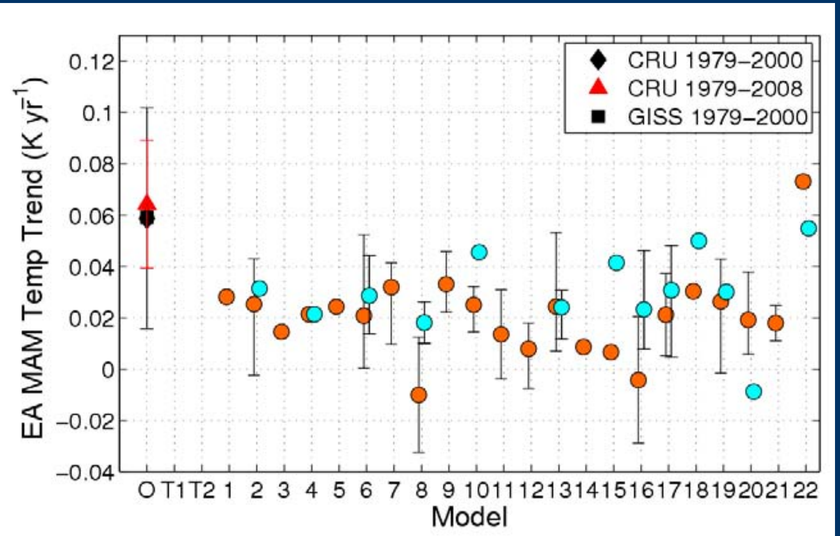


- 1979-2008 warming rate over springtime Eurasia is +0.6°C / decade, whereas N. America trend is not significant
- Spring snow cover losses:
  - Eurasia: 14%
  - North America: 7%

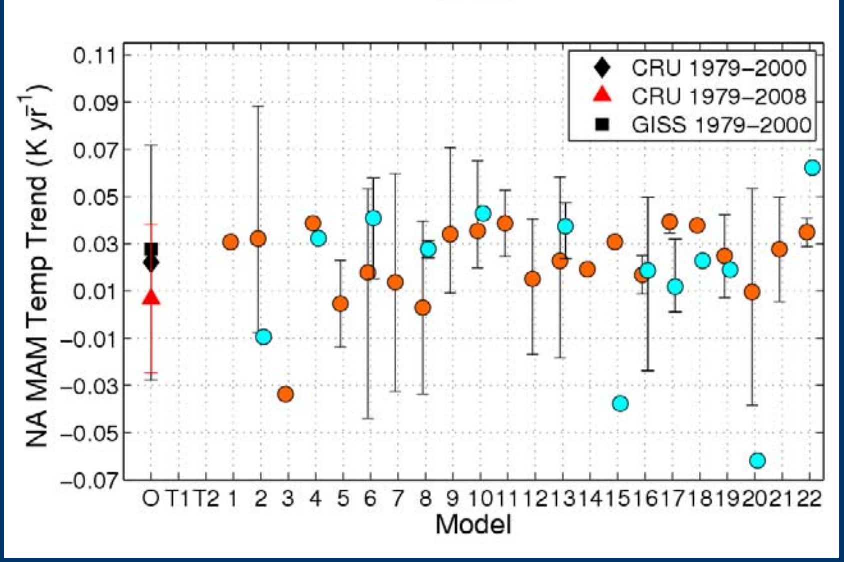
1979-2000 IPCC springtime hindcasts

Temperature trends

Eurasia

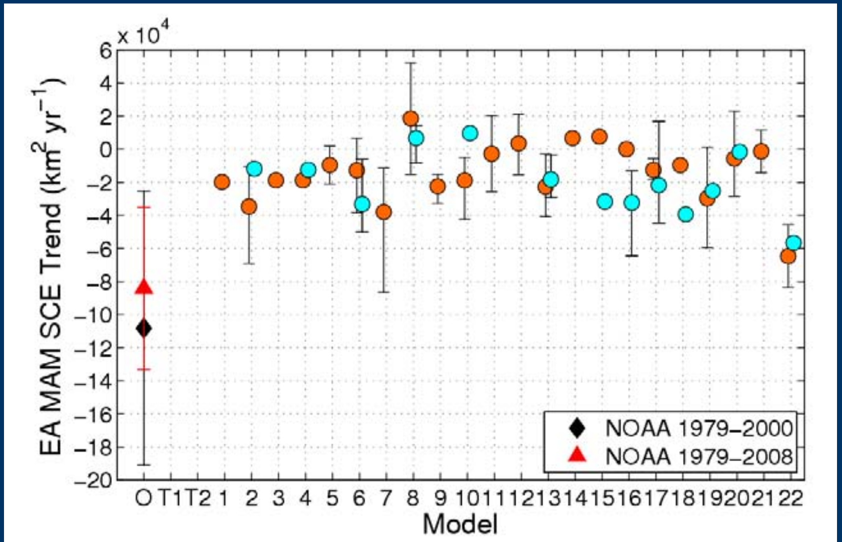


North America

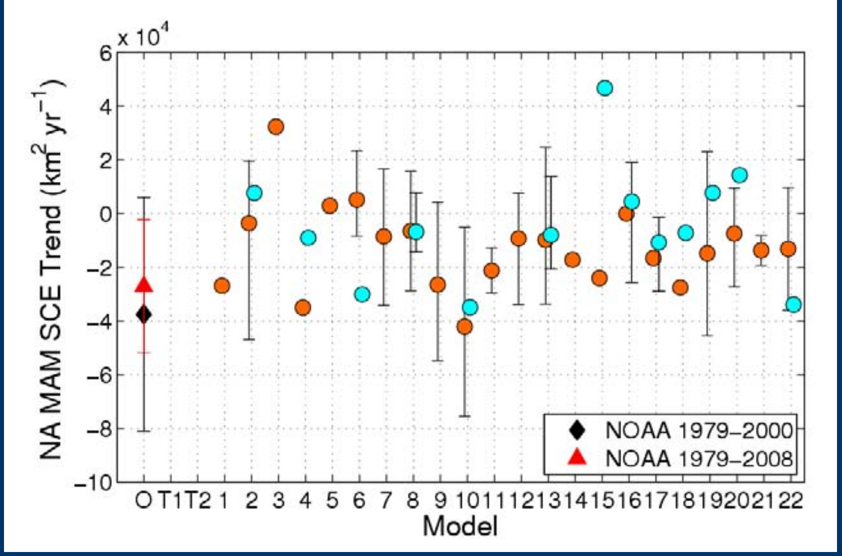


Snow cover trends

Eurasia



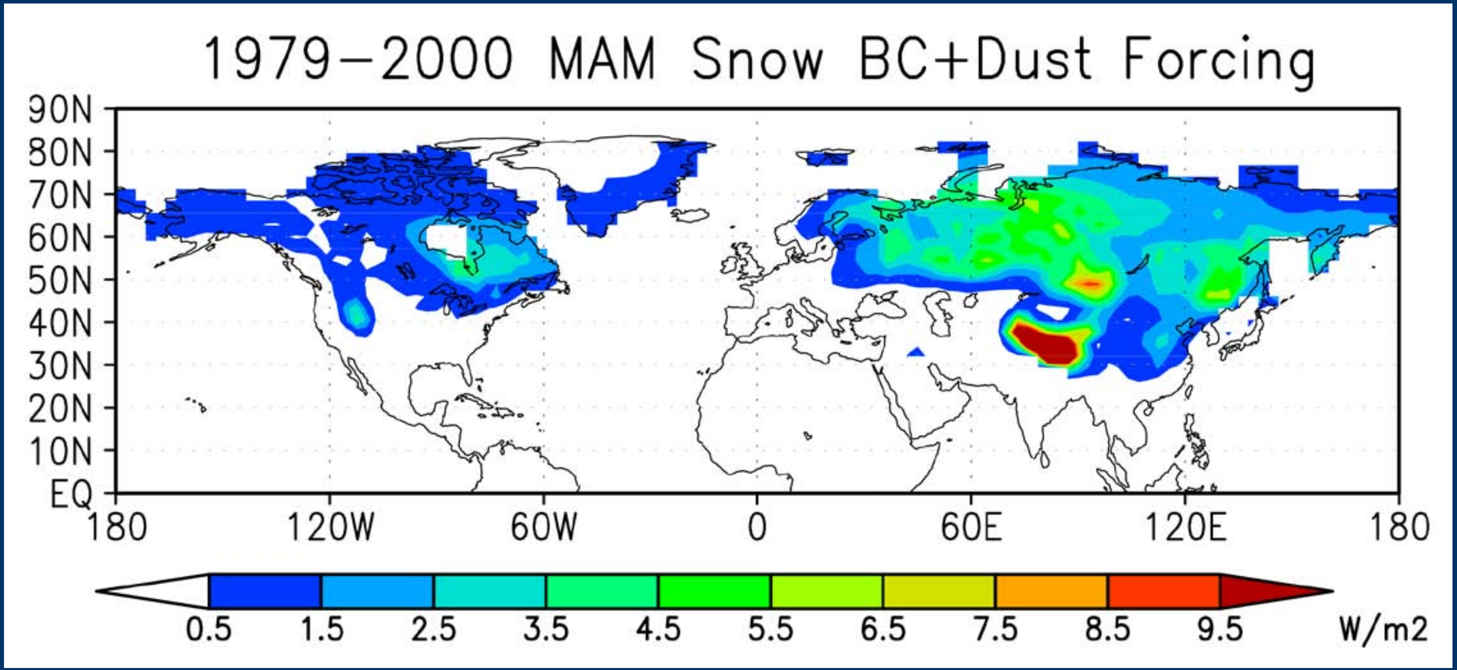
North America



Orange: IPCC AR4 coupled atmosphere-ocean simulations
Light blue: IPCC AR4 forced-SST (AMIP) simulations

Springtime snow forcing from BC and dust

- Spring snow-averaged surface forcing from BC+dust:
  - Eurasia: 3.9 W/m^2
  - North America: 1.2 W/m^2
  - Not included in IPCC simulations
- BC emissions from Asia increased from ~1.6-2.6 Tg/yr during 1980-2000 [*Bond et al.*, 2007]



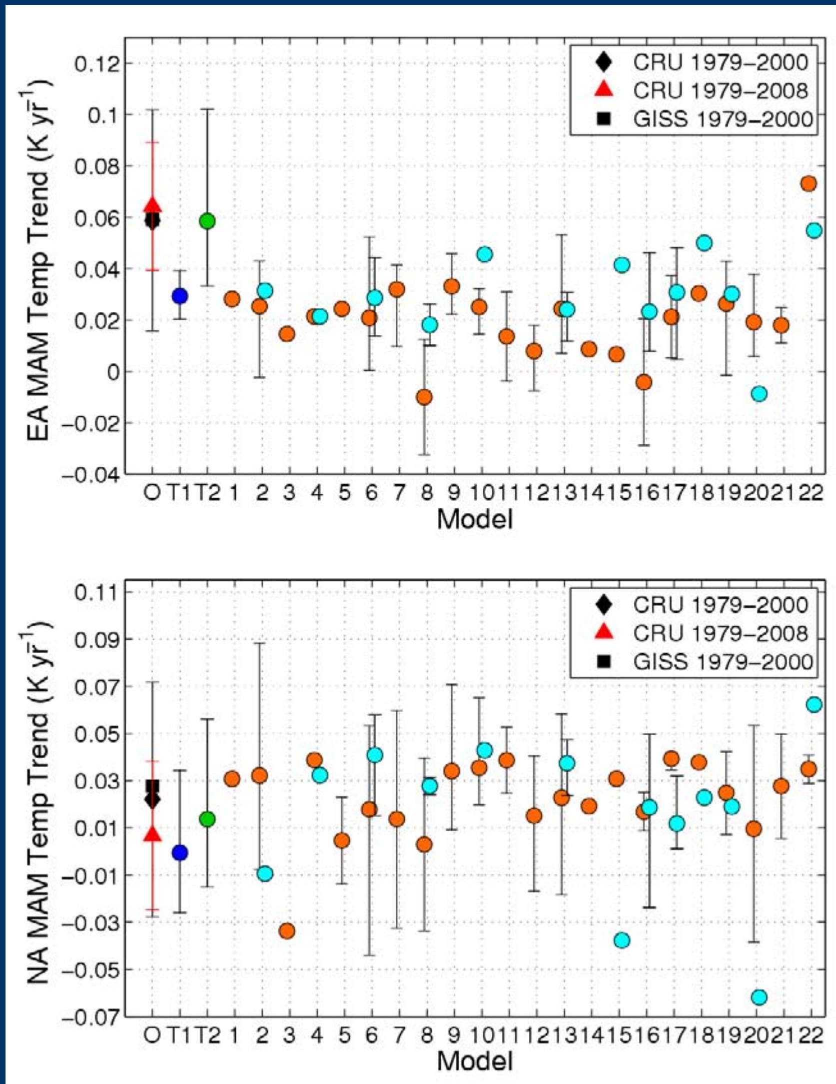
NCAR CAM model coupled with SNICAR

1979-2000 IPCC springtime hindcasts

Temperature trends

Eurasia

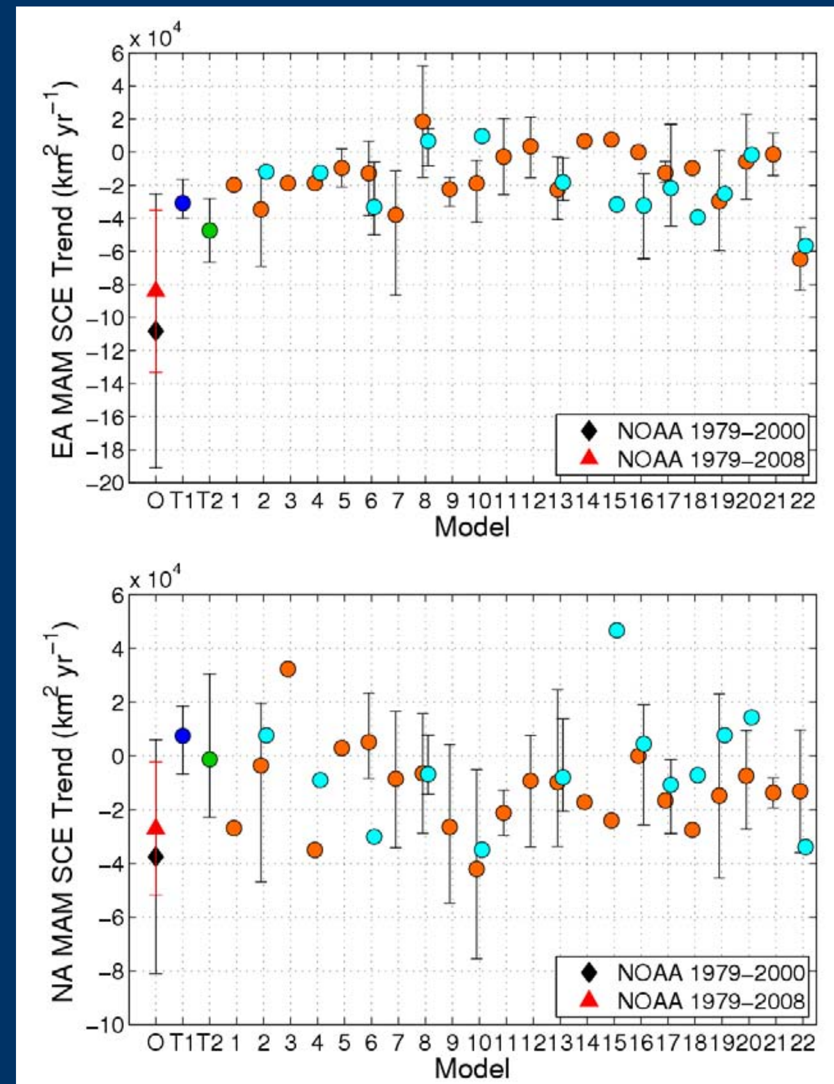
North America



Snow cover trends

Eurasia

North America

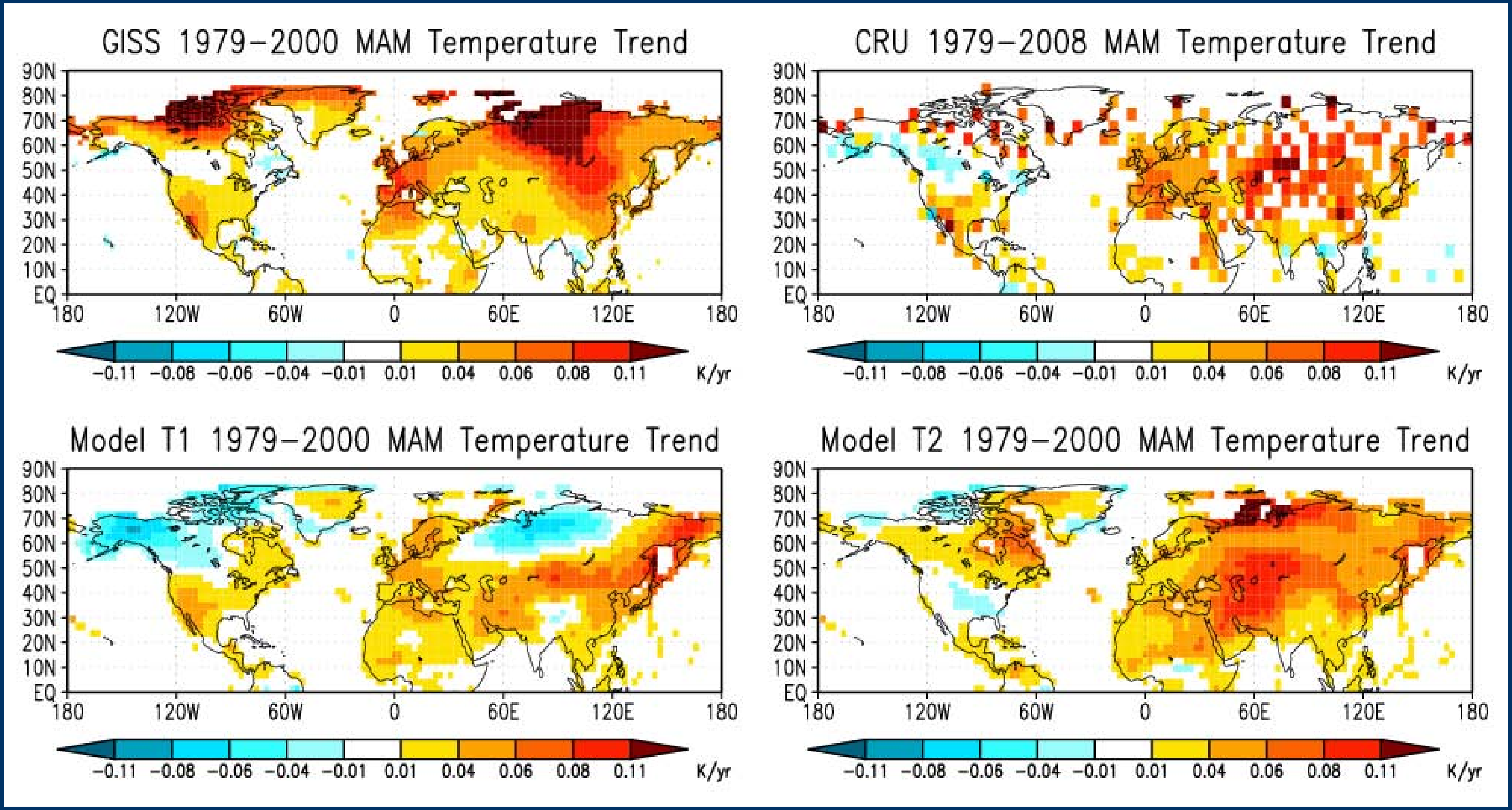


Orange:	IPCC AR4 coupled atmosphere-ocean simulations
Light blue:	IPCC AR4 forced-SST (AMIP) simulations
Dark blue:	CAM/SNICAR without snow darkening
Green:	CAM/SNICAR with snow darkening

Spatial pattern of warming trends

Observations

Without Darkening



With Darkening

Conclusions

- TOA forcing from any mixture of BC and OC is positive over snow
- Forcing from snow darkening exceeds that from "dimming", yielding net positive surface forcing from carbonaceous particles over snow
- Equilibrium climate experiments: Similar reduction in Eurasian springtime snow cover from BC+OC as from CO_2
  - Snow darkening is dominant cause
- Springtime Eurasia has warmed much more rapidly than North America during last 30 years
  - 21 of 22 IPCC AR4 models underpredict Eurasian springtime warming
  - Snow darkening from BC and dust exerts 3-fold greater forcing on Eurasian snow than North American snow
    - Improves temperature trend
    - Snow cover trend is still underpredicted
- Aerosol forcing will become more negative as snow cover depletes