Radiative forcing of black carbon and mineral dust deposited to snowpack

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University of Michigan
Atmospheric, Oceanic & Space Sciences

Outline

Snow darkening from BC and other "snowsols"

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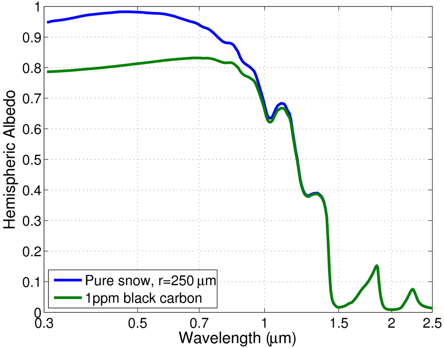

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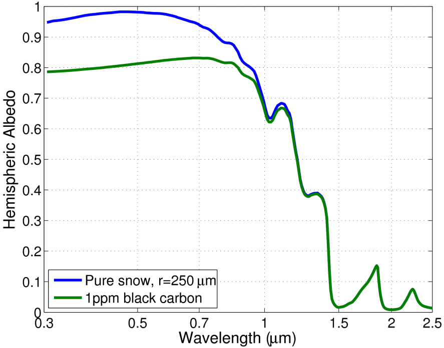

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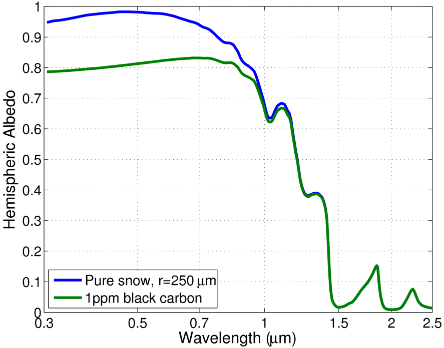

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    - A typical reflected green photon undergoes $\sim$ 1000 scattering events before emerging from the top of snowpack

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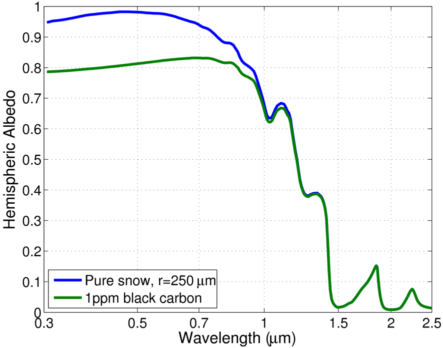

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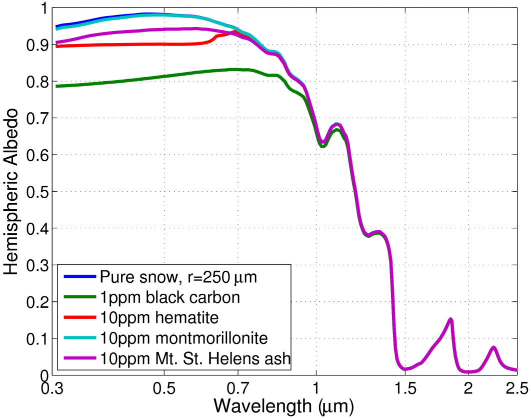
- Snow scatters visible radiation efficiently via refraction
  - A typical reflected green photon undergoes $\sim$ 1000 scattering events before emerging from the top of snowpack
- Longer persistence in near-surface snow than atmosphere.

Albedo perturbation from impurities



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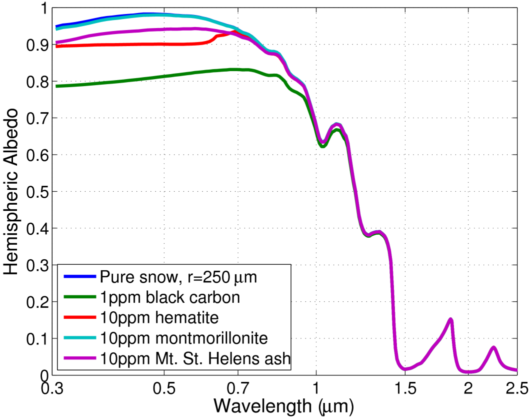
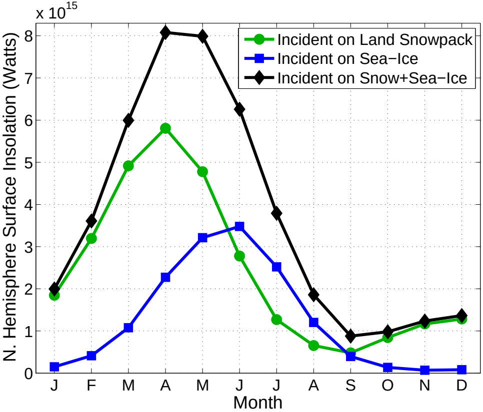


- Simulate it yourself at: http://snow.engin.umich.edu

Springtime uniqueness

$$\int_{NH} Q^{\downarrow}(r) S(r)\, dr \qquad (1)$$



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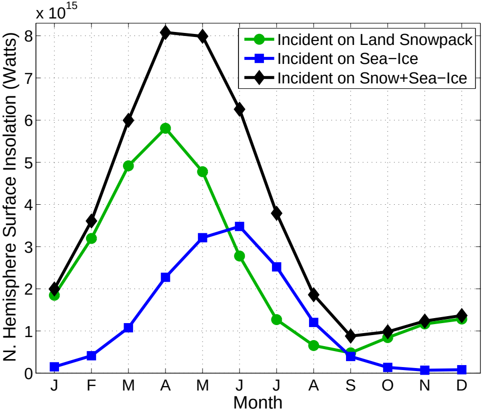

- Solar energy incident on snowpack peaks in March–May
- This is also the season of maximum albedo feedback strength: $d(\text{albedo})/dT$ (*Hall and Qu*, 2006, *Fernandes et al.*, 2009)

Global-scale studies on snow darkening

The Snow, Ice, and Aerosol Radiative (SNICAR) model, coupled with the NCAR CAM/CLM model

- 5 spectral bands
- 5 vertical snow layers
- Snow aging/microphysics model (*Flanner and Zender*, 2006)
- Particle removal with meltwater
- BC optical properties from *Bond and Bergstrom* (2006)

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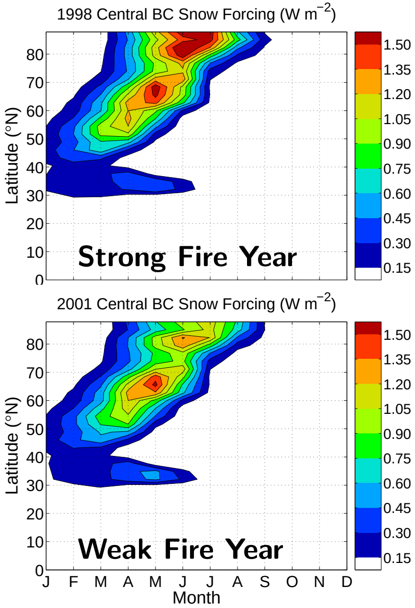
- Drive CLM-offline with aerosol deposition fields from external sources (e.g., AeroCom)

Spatial/temporal characteristics of BC/snow forcing



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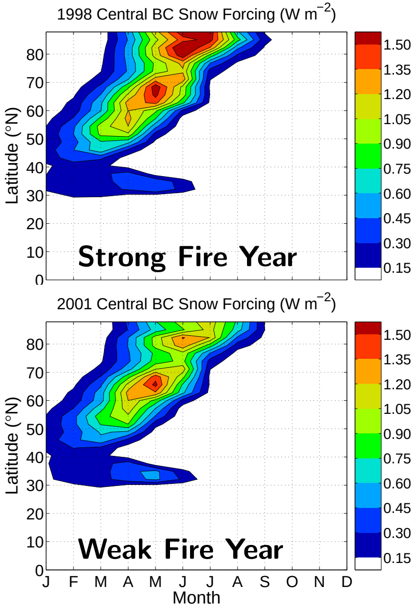

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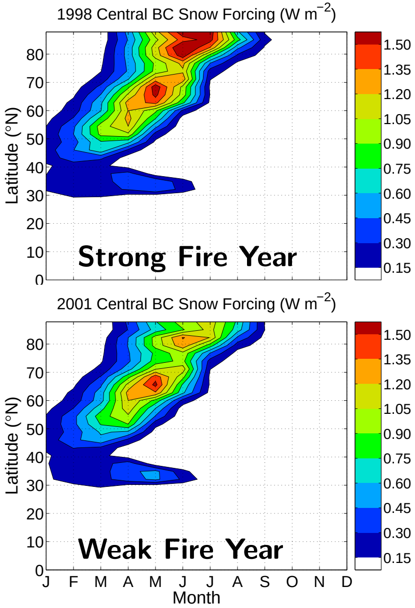

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- Global forcing is dominated by fossil fuel and biofuel sources of BC, but strong biomass burning events can dominate Arctic forcing
- Global-mean forcing (including snow and sea-ice): $\sim 0.03 - 0.06\,\mathrm{W\,m^{-2}}$ (*Koch et al, Rypdal et al, Hansen et al, Jacobson*)

Efficacy

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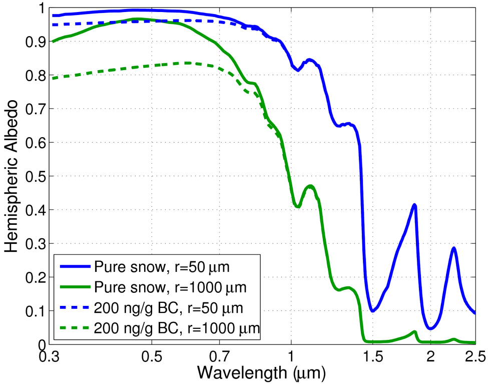
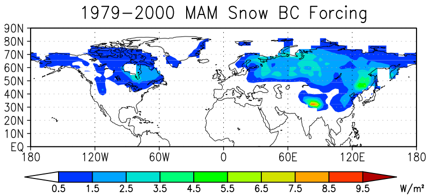
- Our equilibrium climate experiments indicate that BC/snow forcing has efficacy of 3 ± 1
- Reason 1: All of the forcing energy is deposited directly in the cryosphere, a component of the Earth System responsible for powerful albedo feedback

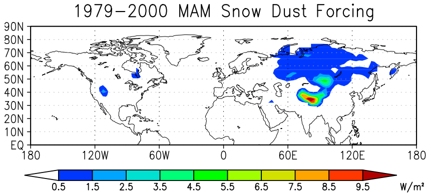
The importance of snow grain size

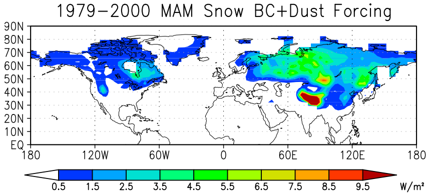
- Snow exhibits large variability in grain size ($30 < r_e < 2000\,\mu m$), $r_e \propto$ (specific surface area)$^{-1}$
- Grain size determines pure snow albedo, depth profile of absorption, and the **magnitude of perturbation by impurities**



Springtime forcing from BC and dust







- Springtime snow-averaged surface forcings (*Flanner et al.*, 2009)
  - Eurasia: $+3.9\,\mathrm{W\,m^{-2}}$ ($1.0\,\mathrm{W\,m^{-2}}$ from dust)
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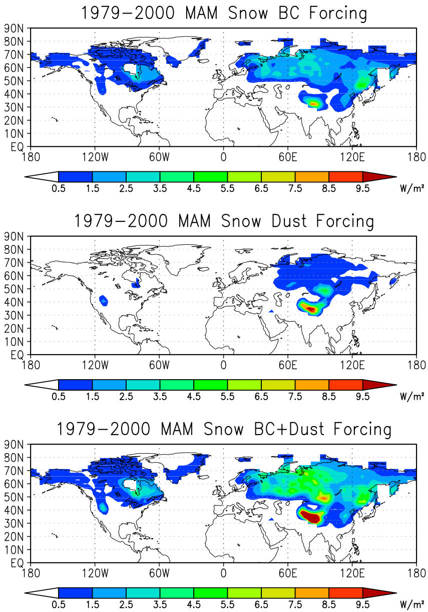

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- BC emissions from Asia increased from $\sim 1.6 - 2.6\,\mathrm{Tg/yr}$ during 1980–2000 (*Bond et al.*, 2007)

Sources of uncertainty

Perturbed physics experiments to characterize forcing uncertainty (*Flanner et al.*, 2007)

Table: Range in global-mean BC/snow radiative forcing resulting from reasonable ranges of the following factors: (*Flanner et al.*, 2007)

	Low	High
BC Emissions	-46%	$+100\%$
Snow Aging	-42%	$+58\%$
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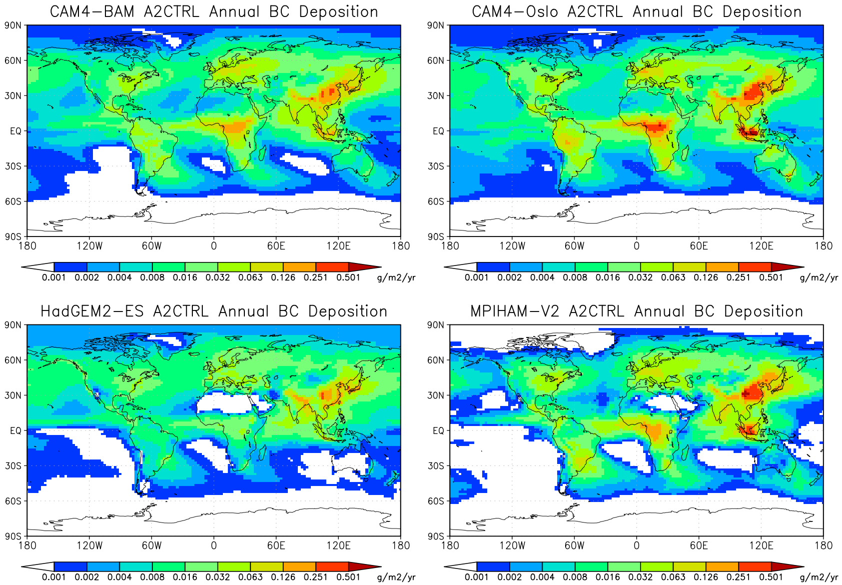
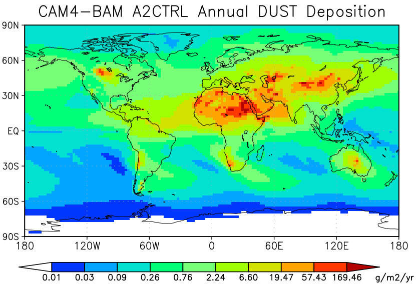
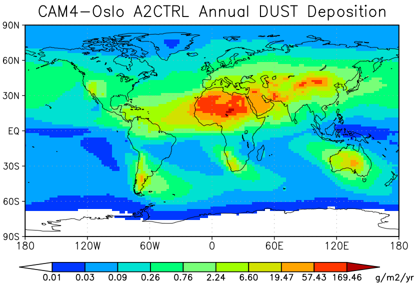
- Here, examine AeroCom:
  - Phase I "B" experiments (identical emissions)
  - Phase II "A2CTRL" experiments

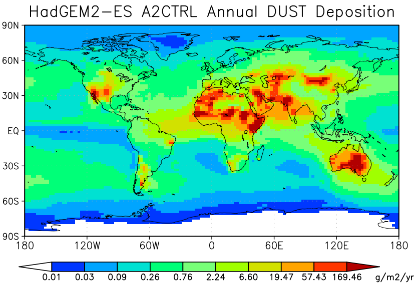
BC Deposition in A2CTRL

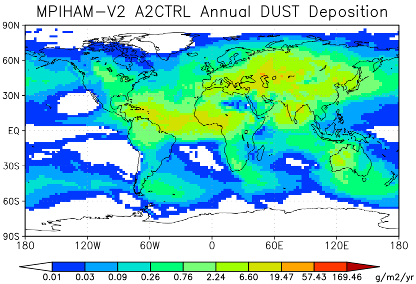


Dust Deposition in A2CTRL









Phase I (B) Global forcing

Table: Global annual-mean radiative forcing of BC and mineral dust in land-based snowpack [$W\,m^{-2}$]

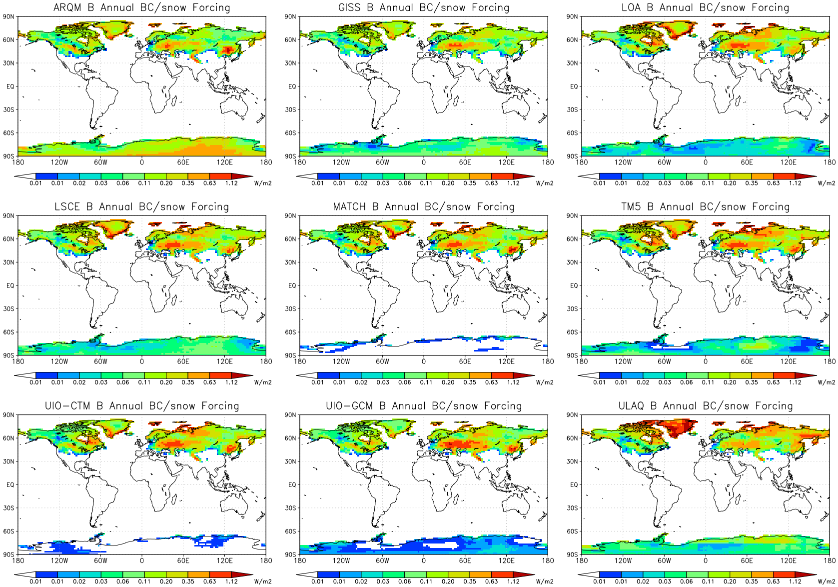
Model	BC	Mineral dust
ARQM	0.022	0.010
GISS	0.015	0.007
LOA	0.023	0.006
LSCE	0.023	0.007
MATCH	0.022	0.008
TM5	0.025	0.005
UIO-CTM	0.021	0.007
UIO-GCM	0.021	N/A
ULAQ	0.027	0.006
UMI	0.021	0.008
Mean	**0.022**	**0.007**
σ	14%	30%

Phase II (A2CTRL) Global forcing

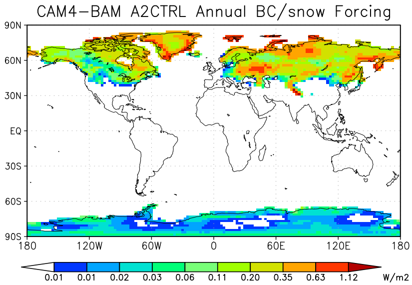
Table: Global annual-mean radiative forcing of BC and mineral dust in land-based snowpack [$W\,m^{-2}$]

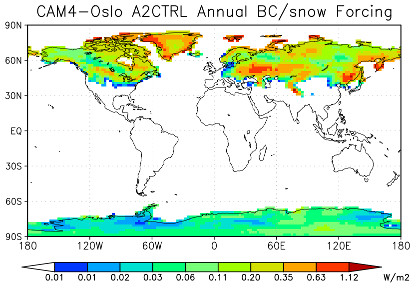
Model	BC	Mineral dust
CAM4-BAM	0.023	**0.026**
CAM4-Oslo	0.023	0.006
CAM-Oslo	0.023	0.006
HadGEM2-ES	0.027	0.002
MPIHAM-V2	0.022	0.011
Mean	**0.024**	**0.010**
σ	8%	90%

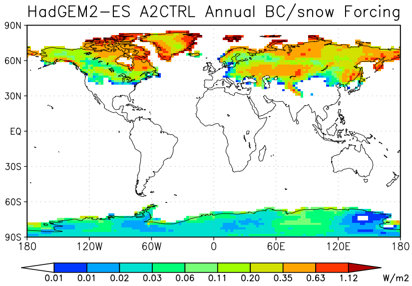
BC/Snow Forcing in Phase I B

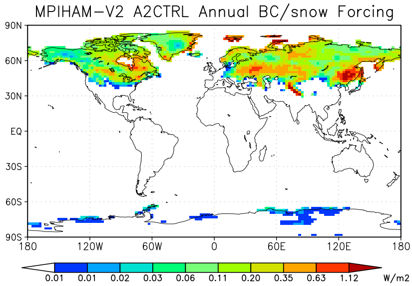


BC/Snow Forcing in A2CTRL

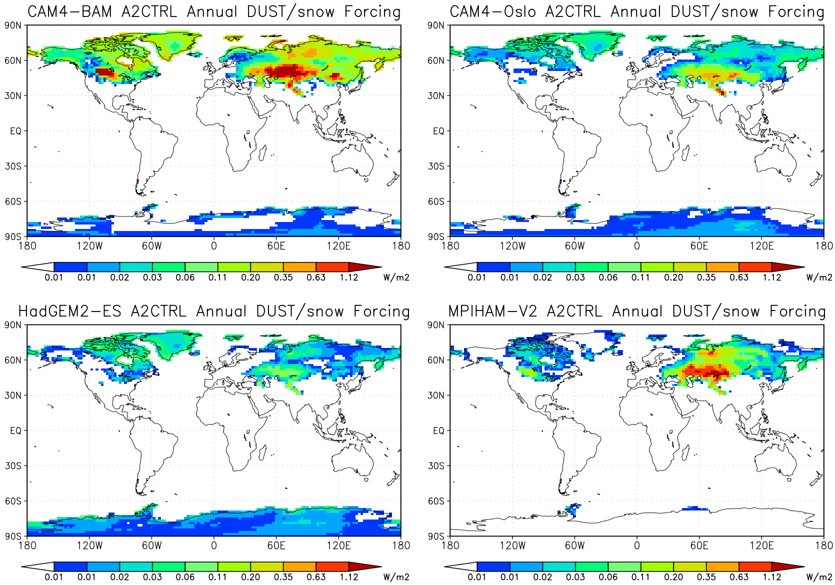








Dust/Snow Forcing in A2CTRL



Seasonal Cycle of BC/Snow Forcing

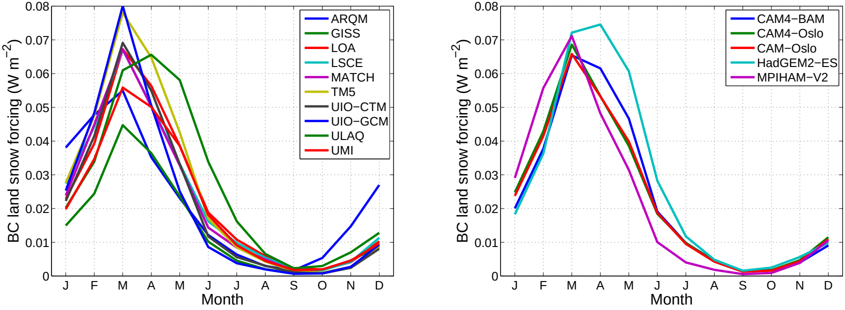


Figure: Phase I B Phase II A2CTRL

- Peak forcing in March or April

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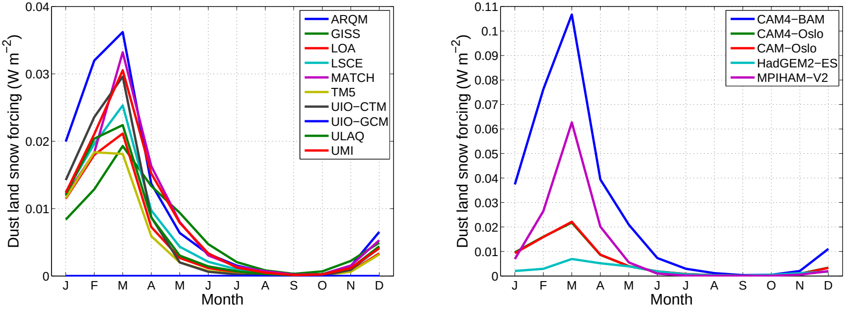
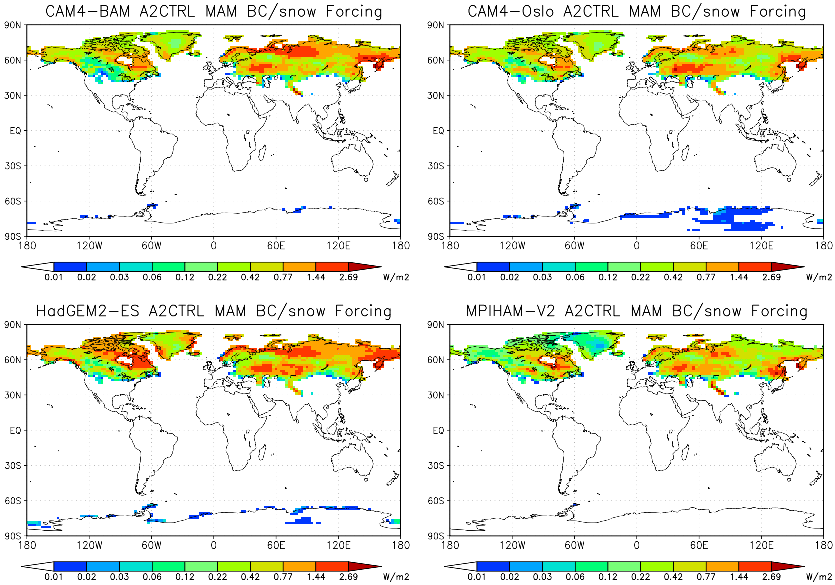


Figure: Phase I B Phase II A2CTRL

Spring BC/Snow Forcing in A2CTRL



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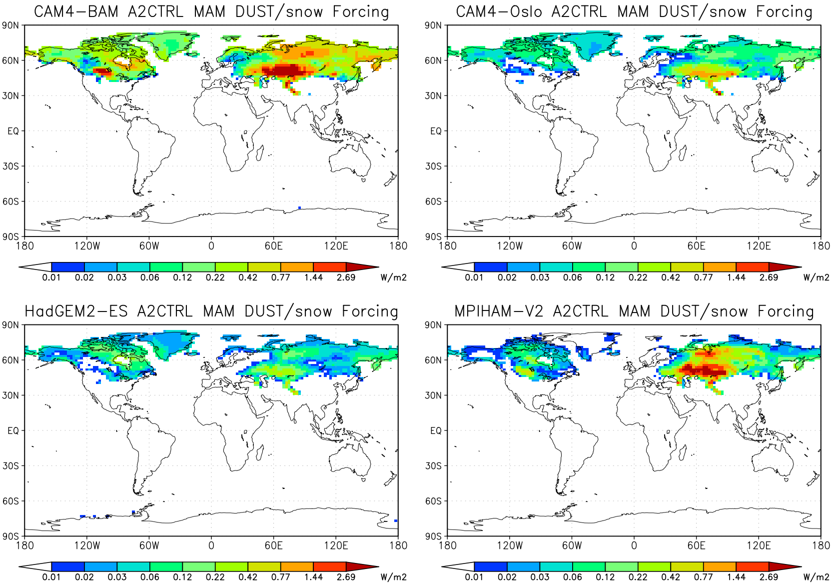

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- Include sea-ice forcing (which requires a different model)
- Quantify pre-industrial snow forcing from AeroCom experiments

Questions?

- Thanks to Michael, Philip, Stefan, and Mian.