Aerosol forcings and non-linear climate response

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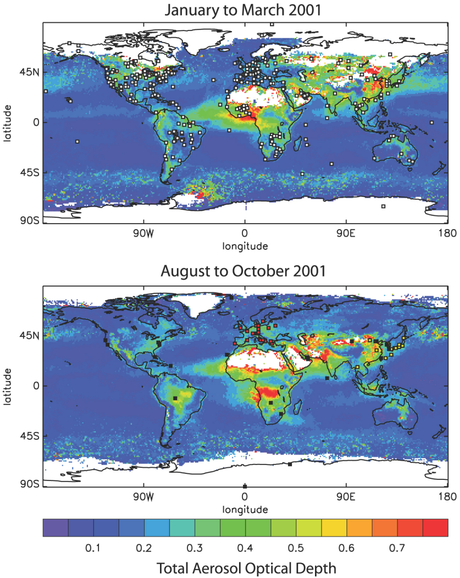
How are atmospheric aerosols produced?

- Incomplete combustion: Particle emissions of *black carbon* and *organic carbon* aerosols
- Sulfur dioxide (gas) emissions and oxidation to form *sulfate* (a salt). $SO_2 \rightarrow H_2SO_4 \rightarrow SO_4$. Sources: Sulfur-containing fuels, volcanoes, marine phytoplankton (via DMS)
- Soil disturbances that mobilize *dust*. Long-term dust changes result from changes in land-use, precipitation and soil moisture, surface winds, water coverage
- Entrainment of water droplets and evaporation to produce *sea salt*
- Emissions of ammonia and nitric acid, which form *nitrate* aerosols (in competition with sulfate)
- Emission of plant matter, fungal spores, and bacteria (*primary organic matter*)
- Gas and aqueous phase organic reactions that produce *secondary organic aerosols*

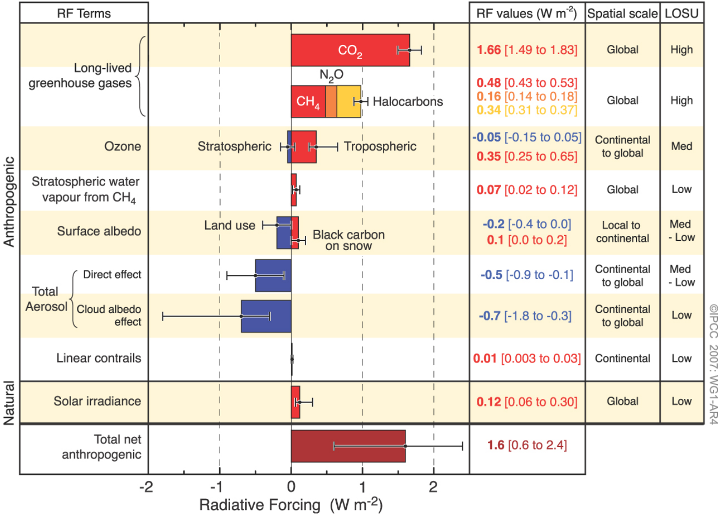
Aerosol optical depth: Large spatial heterogeneity



- Derived from MODIS
- Also note seasonal variability
- Retrievals over bright surfaces (e.g., Arctic, Sahara) are difficult

Radiative forcing (IPCC AR4)

Definition: The change in net energy flux at the tropopause, after stratospheric adjustment, caused by 1750–2005 changes in each agent

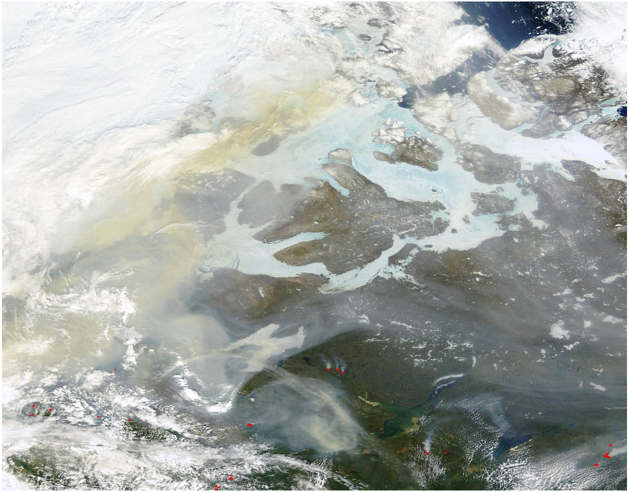


What controls direct radiative forcing of aerosols?

- Aerosol amount
- Aerosol absorptivity (single-scatter albedo) and mass extinction
- Amount of incident solar radiation
- Underlying surface reflectance, governed by clouds, snow and ice, vegetation
- Longwave emissivity (generally small, except for dust)
- (Aerosol lifecycle: Water uptake, lifetime, organic condensation, etc)

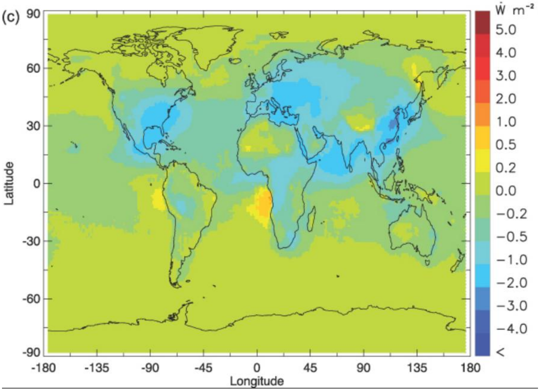
Influence of surface albedo on aerosol forcing

High reflectance, positive aerosol RF



Smoke over the Canadian Arctic (*NASA*)

Spatial variability in direct aerosol forcing



- Multi-model mean anthropogenic aerosol forcing from AeroCom (IPCC AR4)
- Influences of surface albedo and aerosol optical properties are evident

Aerosol contributions to radiative forcing

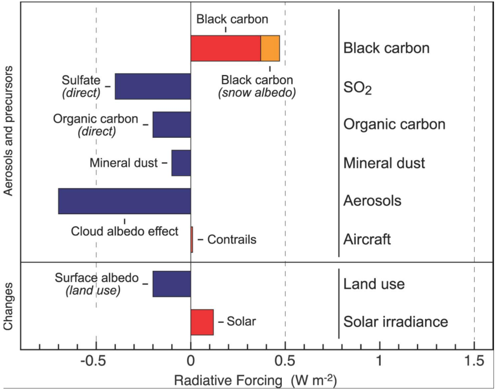


Figure: IPCC AR4, figure 2-21

- Strong interest in black carbon because it warms, and therefore carries climate mitigation potential through emissions **reductions**

Time horizons and GWP: Short-lived forcing

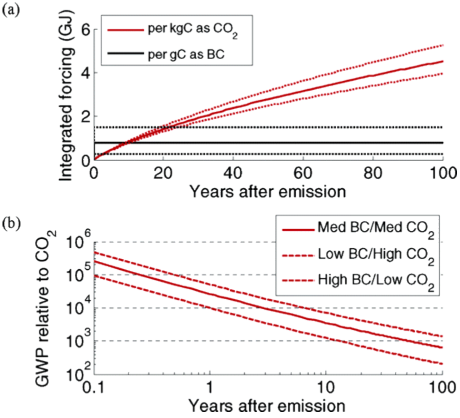


Figure: Bond and Sun, 2005

Strong, short-lived forcing from BC:

- Residence time is ∼1 week
- GWP_{100yrs} of BC is still ∼600 times greater than CO_2

$$AGWP_x = \int_0^{\tau} a_x\, c_x(t)\, dt \qquad (1)$$

$$GWP_x^{\tau} = \frac{AGWP_x}{AGWP_{CO_2}} \qquad (2)$$

Regional contributions to regional forcing

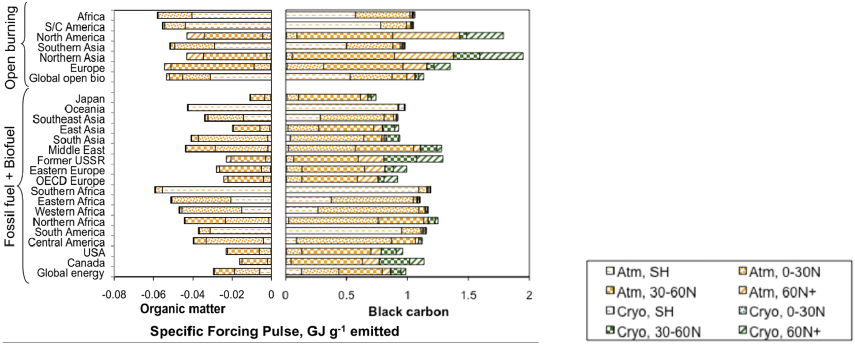


Figure: Bond et al (2011)

- Mitigation potential prompts interest in understanding source contributions to regional radiative forcing. Where can we get largest "bang for buck"?
- We can address this with source-tagged emissions simulations

Sources of Arctic BC+OC radiative forcing

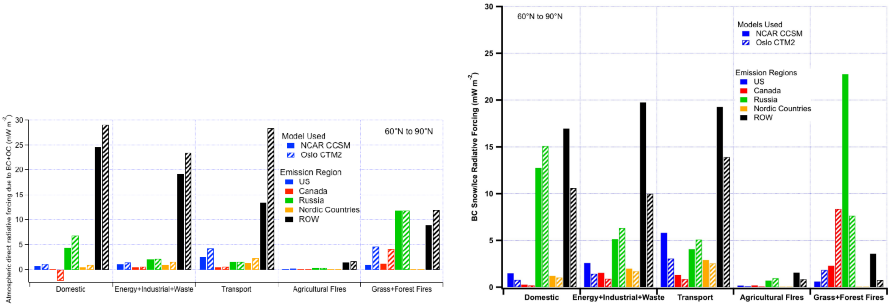


Figure: AMAP BC report (2011). Left: Atmosphere. Right: Snow/Ice Forcing.

- ROW sources dominate Arctic atmosphere burden
- Russian, Canadian contributions dominated by Grass+Forest Fire
- Russian sources more likely to deposit within Arctic
- Results sensitive to simulation of polar dome and deposition

Mass-normalized Arctic BC+OC radiative forcing

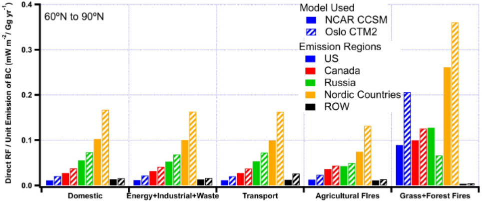


Figure 8-6: Normalized direct RF by BC north of 60°N for the two models.

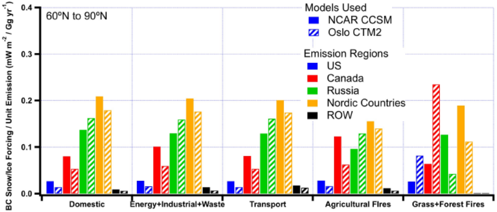


Figure 8-7: BC Snow/Ice RF north of 60°N for both models. The RF is normalized to the BC emissions.

- Unit emissions from Nordic countries exert largest Arctic forcing

Aerosol influences on the energy budget

- All atmospheric aerosols cause *surface dimming* (reduced downwelling surface insolation), and therefore negative *surface forcing*
- Aerosols can heat the atmosphere through solar and net longwave absorption. After the climate responds, this heating can outweigh the negative surface forcing, causing net warming of surface air.
- Snow-deposited aerosols darken the surface, counteracting negative surface forcing from atmospheric constituents
- Top-of-atmosphere forcing is generally, but not always, a decent predictor of the equilibrium global surface temperature change.
- Focus here on black carbon. Consequences of mitigation actions depend on changes in all co-emitted species.

Are all forcings created equal?

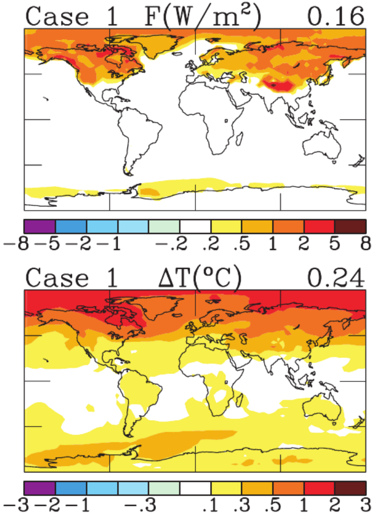


Table 2. Specified snow and ice albedo changes

Experiment	Arctic, %	NH land, %	Antarctica, %	Rest of SH, %
Case 1	2.5 (vis λ)	5 (vis λ)	0	1 (vis λ)
Case 2	2.5 (vis λ)	5 (vis λ)	0	0
Case 3	0	5 (all λ)	0	0
Case 4	2.5 (all λ)	0	0	0

- *Hansen and Nazarenko* (2004), "Soot climate forcing via snow and ice albedo", PNAS
- Study demonstrated that Earth's climate may be quite sensitive to slight changes in snow reflectance (producing small radiative forcing)
- Justification for 5% change in snow albedo?

Snow darkening from black carbon (and ash)

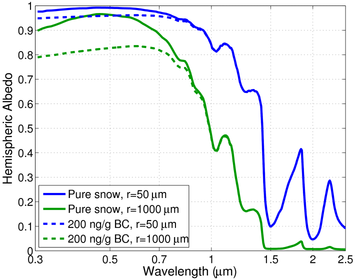
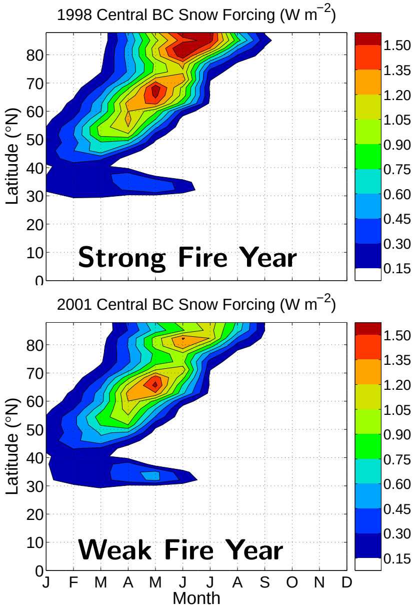


Figure: Left: ash on Mt. Ruapehu. Right: spectral albedo of polluted snow

Part-per-billion levels of BC significantly reduce snow albedo because:

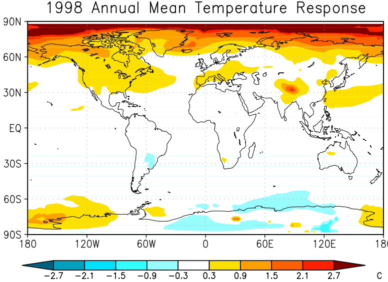
- Black carbon visible absorptivity is $\sim 10^5$ greater than ice
- Snow scatters visible radiation efficiently via refraction
  - A reflected blue photon typically undergoes $\sim$ 1000 scattering events before emerging from the top of snowpack
- BC can persist longer in near-surface snow than atmosphere

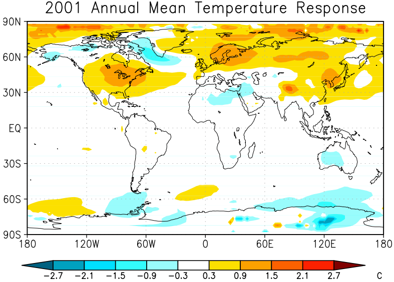
Spatial/temporal characteristics of BC/snow forcing



- Forcing operates mostly in local springtime, when and where there is large snow cover exposed to intense insolation, **coincident with peak snowmelt**
- Global forcing is dominated by fossil fuel and biofuel sources of BC, but biomass burning might dominate Arctic forcing
- Global-mean forcing (including snow and sea-ice): $\sim 0.03 - 0.06\,\mathrm{W\,m^{-2}}$ (*Flanner, Koch, Skeie, Rypdal, Hansen, Jacobson*)

Equilibrium temperature response from snow darkening





- Strong high-latitude warming from surface darkening
- . . . but radiative forcing was rather small
- . . . indicating large *efficacy*

Efficacy

Table: **Efficacy** $\left[\frac{\Delta T_s/F}{\Delta T_s(CO_2)/F(CO_2)}\right]$ (*Hansen et al.*, 2005)

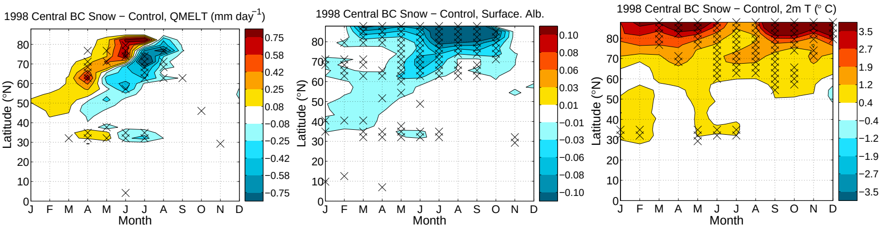
Experiment	Forcing ($W\,m^{-2}$)	$\Delta\ T_s$	Efficacy
1998	$+0.054(0.007-0.13)$	$+0.15$	4.5
2001	$+0.049(0.007-0.12)$	$+0.10$	3.3
$10\times$ 1998	$+0.28$	$+0.44$	3.1

- Equilibrium climate experiments indicate that BC/snow forcing has efficacy of $\sim 3\pm 1$. Reasons:
  1. All of the forcing energy is deposited directly in the cryosphere, a component of the Earth System responsible for powerful albedo feedback
  2. Energy is deposited to surface (important where atmosphere is stable)
  3. Snow metamorphism feedbacks (possibly)

Albedo feedback as a cause for large efficacy

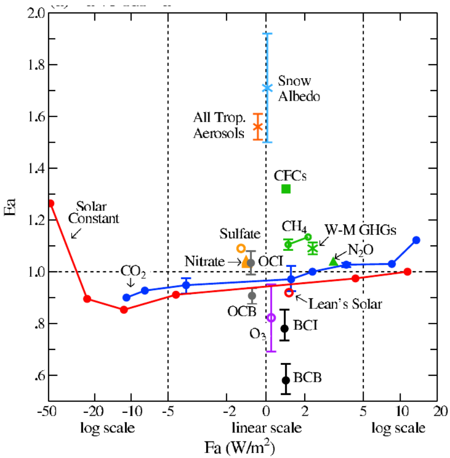
Equilibrium differences between simulations with and without BC in snow:

earlier snowmelt — reduced surface albedo — surface air warming



- All indications of snow-albedo feedback

Efficacy: The bigger picture



- Efficacy of different agents and different forcing magnitudes (*Hansen et al*, 2005)

Efficacy extremes

Negative efficacy is feasible from high-altitude BC, which produces heating that can decouple the surface and upper troposphere

Fig. 3. Northern Hemisphere troposphere and stratosphere temperature perturbations (in Kelvins; 1 K = 1°C) after the baseline nuclear exchange (case 1). The hatched area indicates cooling. Ambient pressure levels in millibars are also given.

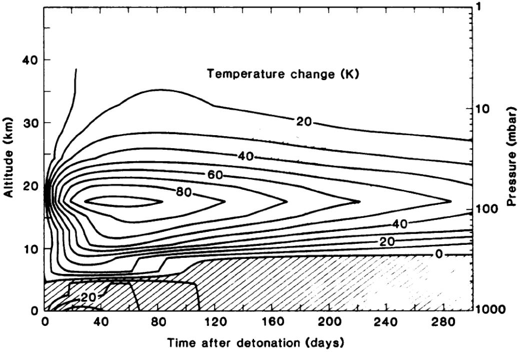


Figure: Turco et al (1983): Negative efficacy through nuclear war

Arctic: Unique vulnerability to positive aerosol RF

- Pervasiveness of reflective surfaces increases the likelihood that atmospheric aerosols exert a positive radiative forcing (e.g., *Cess*)
- Deposition of absorbing species to snow and ice increases the radiative lifetime of these species
- Arctic is a net *sink* for black carbon (deposition $>$ emission)
- Prevalence of *thin* clouds facilitates a significant longwave aerosol indirect effect in the Arctic (*Garrett and Zhao*, 2006), offsetting some, but not all, of the indirect cooling (*Alterskjær* et al., 2010).

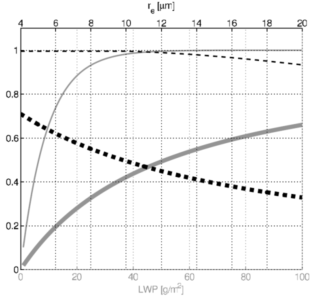
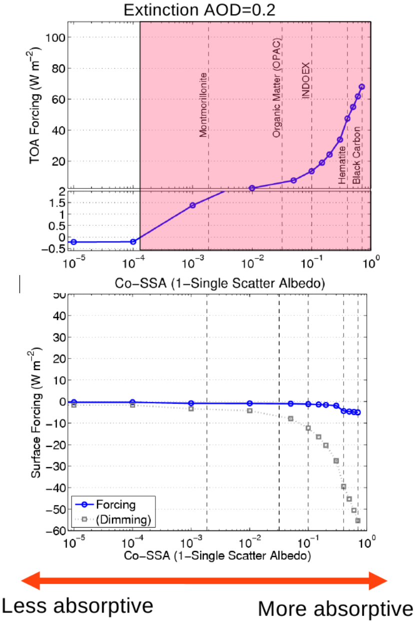


Figure 8. Solid gray lines are cloud SW albedo (thick) and LW emissivity (thin) as a function of liquid water path (bottom axis, r_e = 11.6 μm). Dashed black lines are cloud SW albedo (thick) and LW emissivity (thin) as a function of effective radius (top axis, LWP = 43.5 g/m^2). Cloud ice fraction = 0.

Atmospheric aerosol forcing over pure snow



Top-of-atmosphere:

- Mixtures with SSA$<$ 0.9999 ($\lambda = 500\,\mathrm{nm}$) produce warming
- **Warming from organic matter**

Surface:

- Large *dimming* from absorbing aerosols, but only a slight cooling effect because of snow's high reflectance

Complexities and challenges in modeling Arctic climate

- Unique cloud properties (mixed-phase, thin)
- Huge seasonality in shortwave forcing and spectrum of dominant forcing
- Stably stratified atmosphere during much of the year
  - Reduced coupling between atmospheric energy forcings and surface temperature
  - Increased coupling between surface energy forcings and surface temperature
- A large component of the Arctic energy budget is meridional energy transport ($\sim 100\,\mathrm{W\,m^{-2}}$). Small perturbations to this term can overwhelm local forcings.
- To what extent do local forcings matter?

Arctic climate response to Arctic atmospheric BC

- Complex response to Arctic atmospheric aerosol forcing

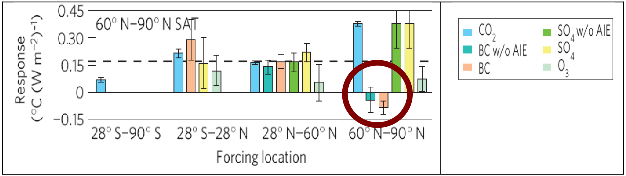


Figure: Shindell and Faluvegi (2009)

- Arctic *cooling* in response to Arctic atmospheric BC, caused by:
  1. Surface dimming
  2. Stable atmospheric conditions in the Arctic, and increased stability from heating aloft
  3. Reduced poleward heat flux into Arctic
  4. Increased low cloud cover (semi-direct effect)

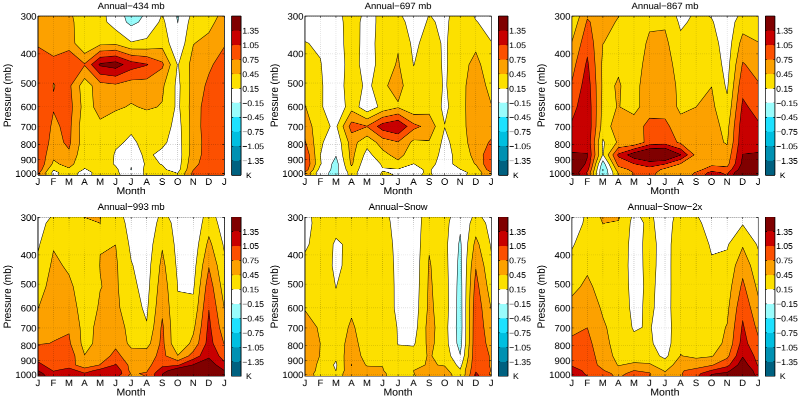
Arctic BC experiments

- Goal: Explore the dependence of local climate response to the altitude and season of BC forcing
- Relevant because different sources enter the Arctic at different altitudes (e.g., inside or above polar dome) and some are more likely to deposit on snow and sea-ice

Table: Equilibrium climate simulations with the NCAR CESM1. Fixed AAOD of 0.005 in Arctic

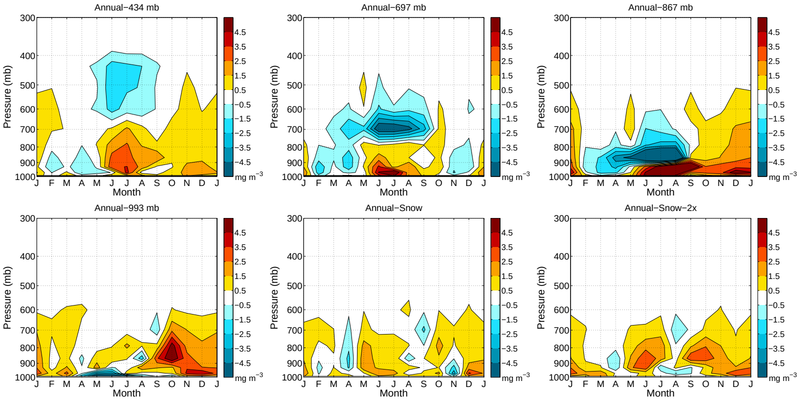
Tag	Experiment Description
Annual-434mb	BC in atmospheric layer centered at 434 mb
Annual-697mb	BC in atmospheric layer centered at 697 mb
Annual-867mb	BC in atmospheric layer centered at 867 mb
Annual-993mb	BC in lowest atmospheric layer
Annual-Snow	BC in surface snow or sea-ice layer
Annual-Snow-2x	Doubled BC in surface snow or sea-ice layer

Arctic temperature responses



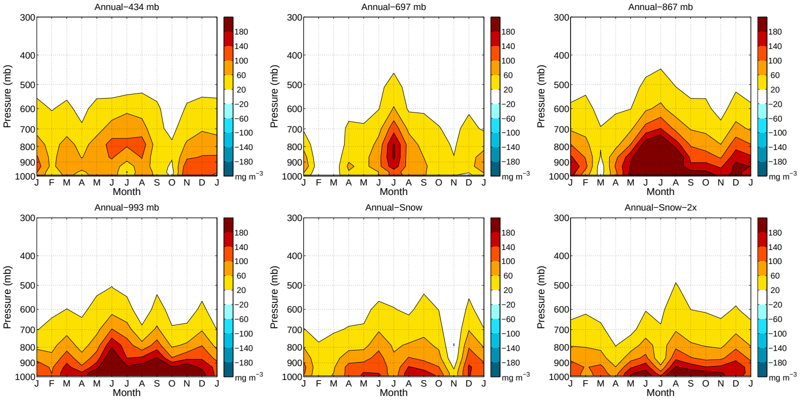
- Atmospheric heating occurs within layer of BC forcing
- Weak propagation of heating to surface when BC is aloft
- Strong surface warming from low-altitude and within-snow BC
- Strong winter warming in most experiments

Arctic cloud responses



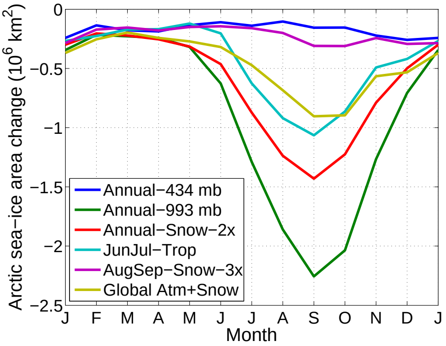
- Decreased cloud cover in layer of heating because of decreased RH
- Increased cloud cover beneath BC because of increased stability
- Low cloud "burn-off" in Annual-993 mb amplifies summer warming
- Clouds **cool** Arctic during summer and **warm** during winter

Arctic water vapor responses



- Increased water vapor resulting from 1) atmospheric warming and 2) decreased sea-ice cover, permitting greater evaporation
- Propagating sea-ice, water vapor and cloud anomalies help warm winter

Changes in sea-ice area



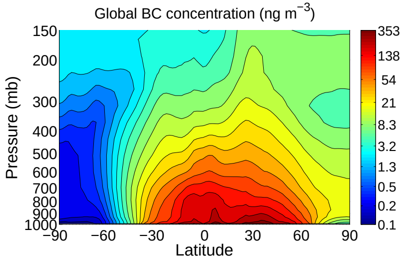
- Low-altitude BC strongly influences summer and autumn sea-ice area
- Sea-ice area recovers by mid-winter in all experiments, consistent with observations showing sea-ice area “memory” of only 2–5 months (*Blanchard-Wrigglesworth et al.*, 2011)

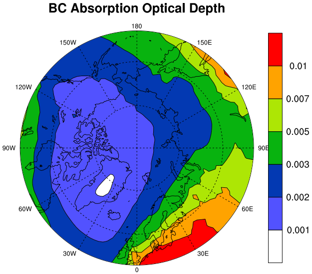
Sensitivity to season of BC forcing

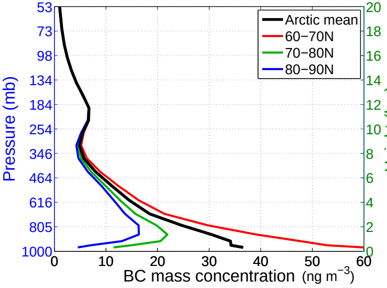
Experiment[a]	TOA Forc.[c] [W m^{-2}]	Sfc. Forc.[d] [W m^{-2}]	ΔT_{sfc} [K]	Sensitivity[e] [K (W m^{-2})$^{-1}$]	Sensitivity[f] [K (Gg yr)$^{-1}$]	Δ SW$_{sfc}$[g] [W m^{-2}]	Δ MET[h] [W m^{-2}]	ΔE_{atm}[i] [MJ m^{-2}]
Fixed Arctic AAOD of 0.005 Operating Annually								
Annual-434 mb	+1.46	-0.52	0.35 ± 0.26	0.2 ± 0.2	0.03 ± 0.02	**-1.1**	**-0.8**	**+10.6**
Annual-697 mb	+1.17	-0.54	0.14 ± 0.23	0.1 ± 0.2	0.01 ± 0.02	**-0.8**	-0.7	**+5.8**
Annual-867 mb	+0.88	-0.56	0.87 ± 0.27	1.0 ± 0.3	0.07 ± 0.02	+0.5	**-0.6**	**+12.6**
Annual-993 mb	+0.51	-0.54	1.42 ± 0.25	2.8 ± 0.5	0.11 ± 0.02	**+1.4**	**-0.8**	**+7.5**
Annual-Snow	+0.37	+0.39	0.54 ± 0.27	1.4 ± 0.7	0.07 ± 0.03	**+0.9**	-0.2	**+5.9**
Annual-Snow-2x[b]	+0.69	+0.73	1.03 ± 0.23	1.5 ± 0.3	0.07 ± 0.01	**+1.9**	**-0.6**	**+7.8**
Fixed Arctic AAOD of 0.010 Operating Seasonally								
AprMay-Trop	+0.66	-0.25	0.81 ± 0.29	1.2 ± 0.4	0.18 ± 0.07	**+0.7**	-0.3	**+10.6**
JunJul-Trop	+0.55	-0.45	0.69 ± 0.23	1.3 ± 0.4	0.16 ± 0.05	+0.3	-0.3	**+10.4**
AugSep-Trop	+0.27	-0.26	0.43 ± 0.28	1.6 ± 1.0	0.10 ± 0.06	+0.3	-0.2	**+5.2**
AprMay-Snow	+0.36	+0.38	0.48 ± 0.27	1.3 ± 0.8	0.15 ± 0.09	+0.5	-0.1	**+5.8**
JunJul-Snow	+0.21	+0.22	0.27 ± 0.26	1.3 ± 1.3	0.17 ± 0.16	+0.3	-0.0	+2.3
AugSep-Snow-3x[b]	+0.13	+0.14	0.49 ± 0.24	3.7 ± 1.8	0.14 ± 0.07	+0.2	**+0.6**	**+8.1**

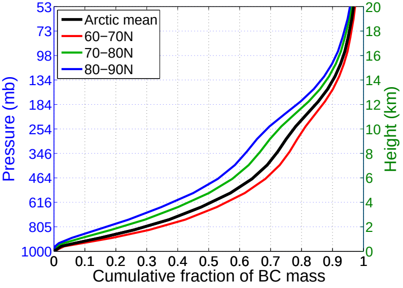
- Specific forcing decreases as the summer progresses. Why?
- . . . But *efficacy* increases with summer progression. Why?
- . . . Meaning the mass-normalized response shows little variability during April–September

Simulated distribution of BC









Arctic response to Arctic and extra-Arctic BC

Table 2. Arctic and Global Response to 2× Present-Day BC Emissions

Experiment[a]	Arc. TOA Forc. [W m^{-2}]	Glb. TOA Forc. [W m^{-2}]	Arctic ΔT_{sfc} [K]	Arc. Sens. [K (W m^{-2})$^{-1}$]	Global ΔT_{sfc} [K]	Δ SW$_{\mathrm{sfc}}$[b] [W m^{-2}]	Δ MET[b] [W m^{-2}]	ΔE_{atm}[b] [MJ m^{-2}]
Arc:Atm	+0.58	+0.04	-0.21 ± 0.32	-0.4 ± 0.6	-0.10 ± 0.04	**-0.8**	+0.0	+3.5
Arc:Atm+Snow	+0.84	+0.05	+0.38 ± 0.31	+0.5 ± 0.4	+0.05 ± 0.04	+0.7	**-0.7**	**+8.4**
EArc:Atm	0	+0.62	+0.35 ± 0.24	N/A	+0.10 ± 0.04	-0.3	**+0.7**	**+5.5**
EArc:Atm+Snow	0	+0.65	+0.55 ± 0.32	N/A	+0.21 ± 0.05	+0.3	**+0.8**	**+10.9**
Glb:Atm+Snow	+0.86	+0.70	+0.78 ± 0.30	N/A	+0.27 ± 0.04	+0.5	+0.1	**+12.8**

- Surface **cools** when BC emissions operate only in Arctic atmosphere
- Surface **warms** when BC emissions operate in Arctic atmosphere+snow
- Surface **warms** when BC emissions operate only in extra-Arctic
- Extra-Arctic BC **increases** meridional energy transport into Arctic

Future directions?

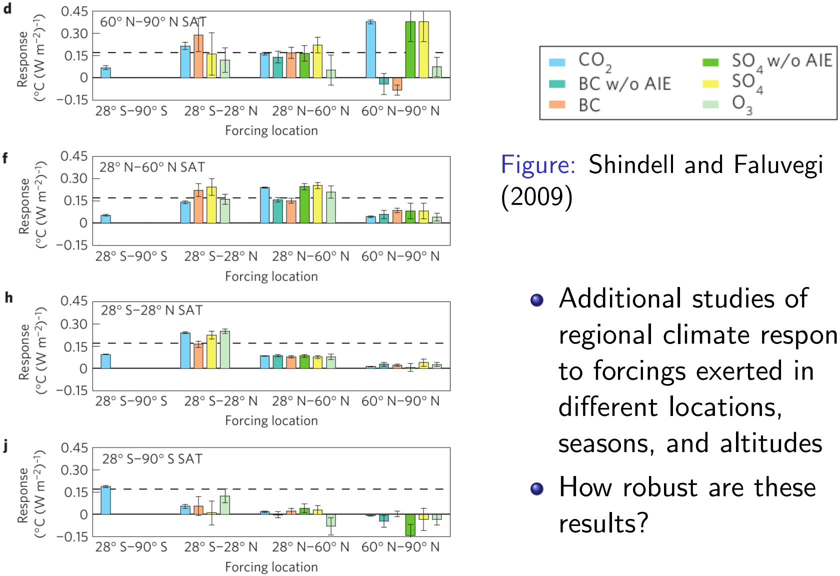


Figure: Shindell and Faluvegi (2009)

- Additional studies of regional climate response to forcings exerted in different locations, seasons, and altitudes
- How robust are these results?