# Snowpack-Mediated Aerosol-Climate Interactions

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(On the Web at http://dust.ess.uci.edu/smn/smn_clm_snw_aer.pdf)

## Abstract

1. Examine forcing of and response to snowpack heating by dust (natural) and soot (FF/BF/BB) in current and LGM climates
2. Quantify relative forcing efficacies of dust, soot in snowpack
3. Speculate about dust's role in glacial terminations

## 1. Absorbing Aerosols in Cryosphere

1. Warren and Wiscombe (1980); Clarke and Noone (1985): Soot perturbs *in situ* snowpack reflectance
2. Jacobson (2004): FF/BF snowpack forcing warms climate $\sim 0.06$ K
3. Hansen and Nazarenko (2004); Hansen et al. (2005): Soot-snowpack forcing 0.08 W m$^{-2}$ warms climate 0.065 K. Efficacy $E \approx 1.7 \times \mathrm{CO_2}$
4. Flanner et al. (2006): Soot-snowpack forcing Efficacy $E \approx 1.8 \times \mathrm{CO_2}$

This study examines dust *and* soot snowpack in current and LGM climates:

1. Current Climate: Dust+Soot-snowpack forcing 0.050 W m$^{-2}$ warms climate 0.16 K ($\sim 50\%$ is Anthropogenic). Efficacy $E \approx 4.2 \times \mathrm{CO_2}$
2. LGM Climate: Dust+Soot-snowpack forcing 0.28 W m$^{-2}$ warms climate 0.95 K. Efficacy $E \approx 4.8 \times \mathrm{CO_2}$
3. Dust+Soot forcing efficacy very high due to
   (a) Representing positive feedbacks in snowpack
   (b) More absorption to trigger snow-ice-albedo feedback non-linearity
   (c) Deposition timing and location

## 2. 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 (GFED) (van der Werf et al., 2003; Randerson et al., 2005)
4. BC/OC Emissions factors (Andreae and Merlet, 2001, updated)
5. BC 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., 2006b)
7. Glaciogenic dust sources for LGM (Mahowald et al., 2006a)
8. Dust Optical Properties (Sokolik and Toon, 1999; Dubovik et al., 2002; Sinyuk et al., 2003)
9. SNow, ICe, and Aerosol Radiative model (SNICAR) (Flanner and Zender, 2005, 2006; Flanner et al., 2006)
10. Experiment(Control): Dust+Soot are (not) radiatively active in snowpack

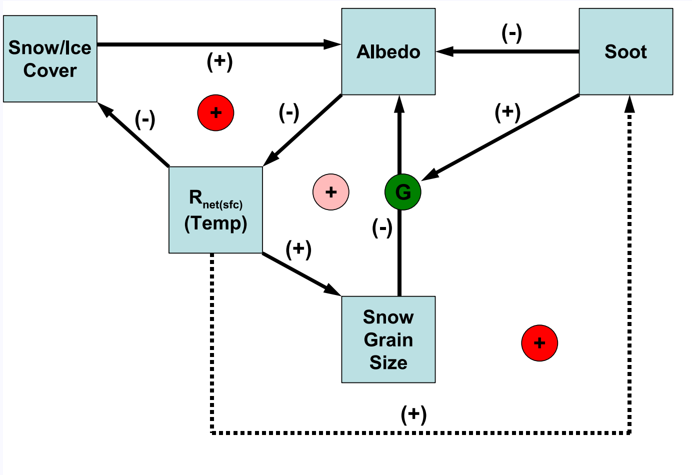



Figure 1: Soot and Dust amplify snow-albedo feedback via multiple paths.

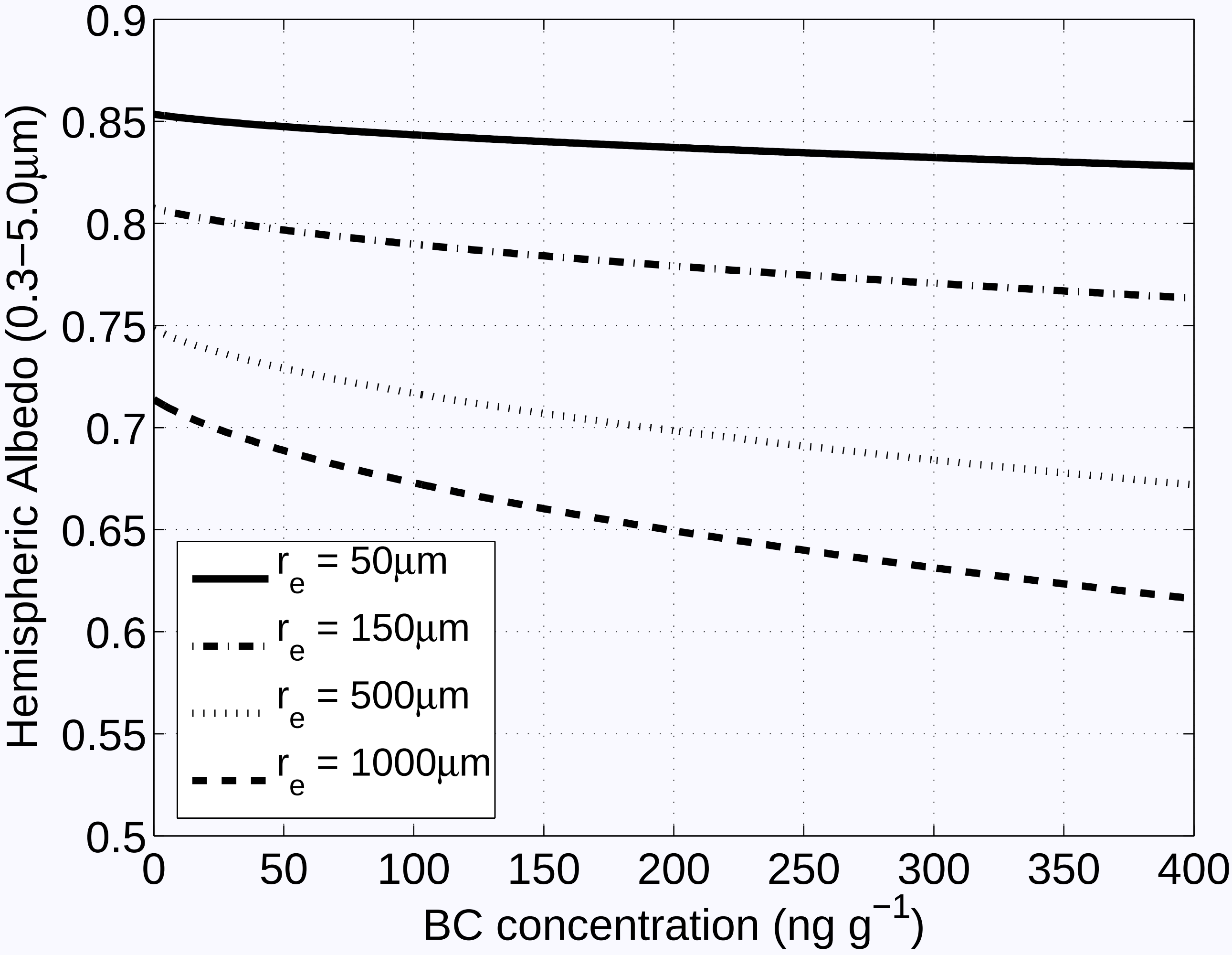



Figure 2: Hemispheric broadband albedo decreases with soot concentration and snow effective radius. (Flanner and Zender, 2006, *JGR*)

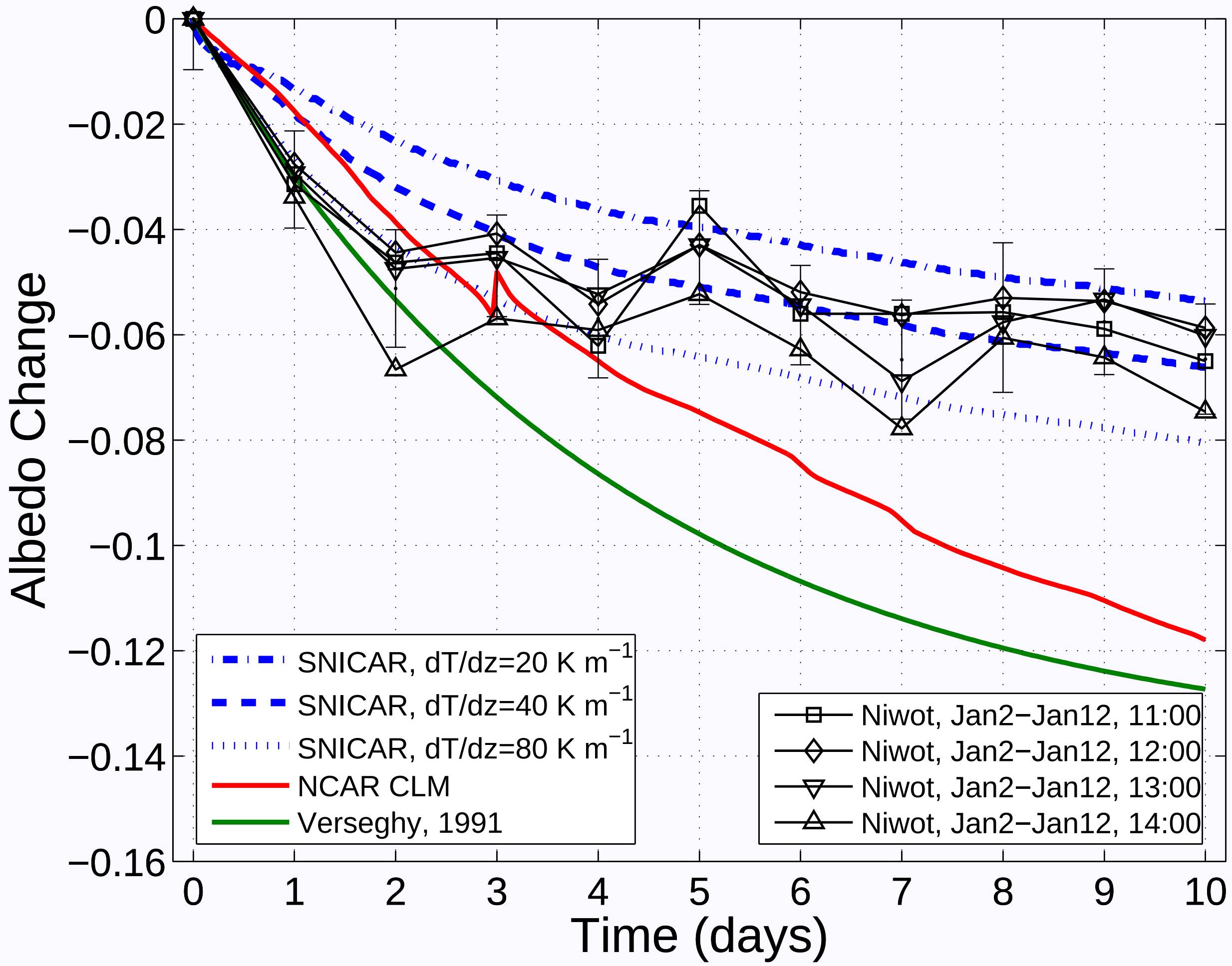



Figure 3: Observed and modeled albedo decay at Niwot Ridge January 2, 2001. (Flanner and Zender, 2006, *JGR*)

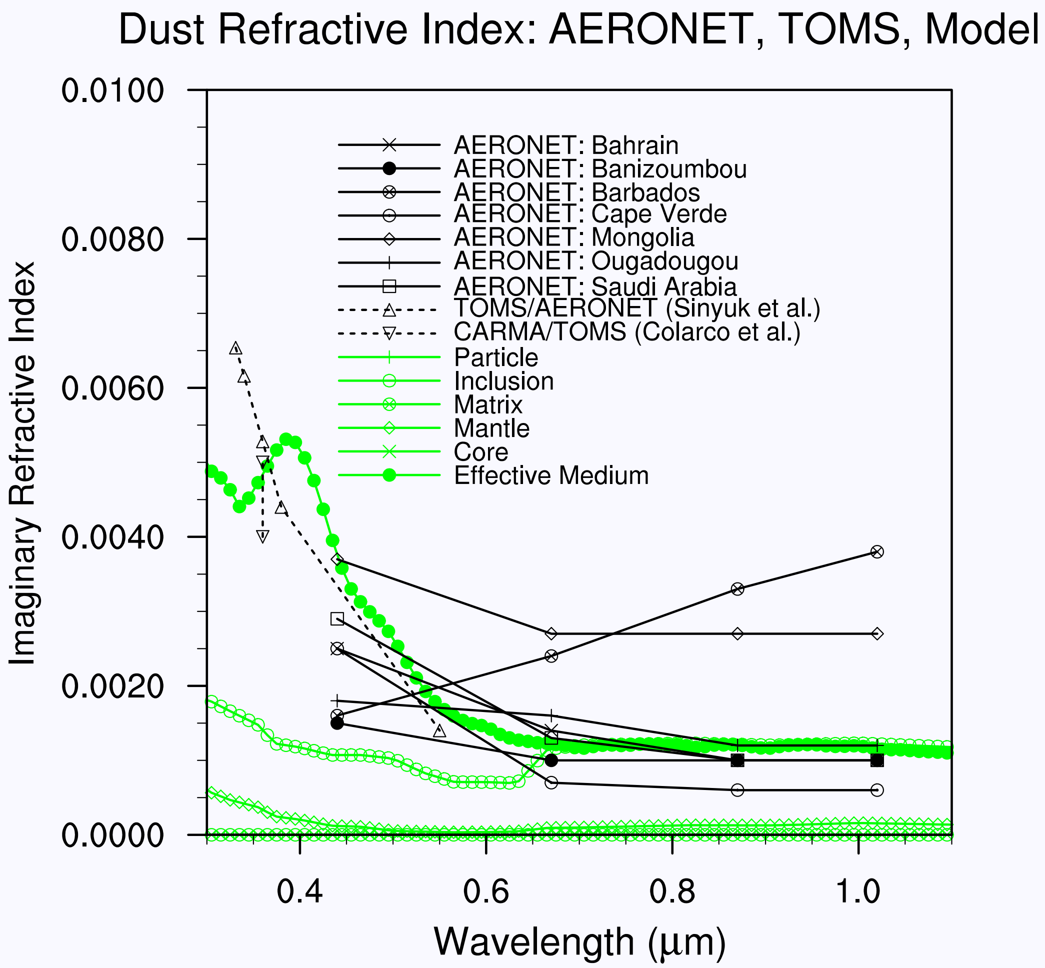



Figure 4: Refractive index and single scattering albedo for dust based on 48% Quartz, 25% Illite, 25% Montmorillonite, 1% Limestone, 1% Hematite. Data from Dubovik et al. (2002), Colarco et al. (2002), and Sinyuk et al. (2003).

Figure 5: February 15 dust-fall in snowpack near Niwot Ridge, Colorado on May 17, 2006. (Courtesy Tom Painter, NSIDC)

Figure 6: Dust and soot on snow near Niwot Ridge, Colorado on May 17, 2006. Soot deposited by hand same day. Dust-fall February 15. (Courtesy Tom Painter, NSIDC)

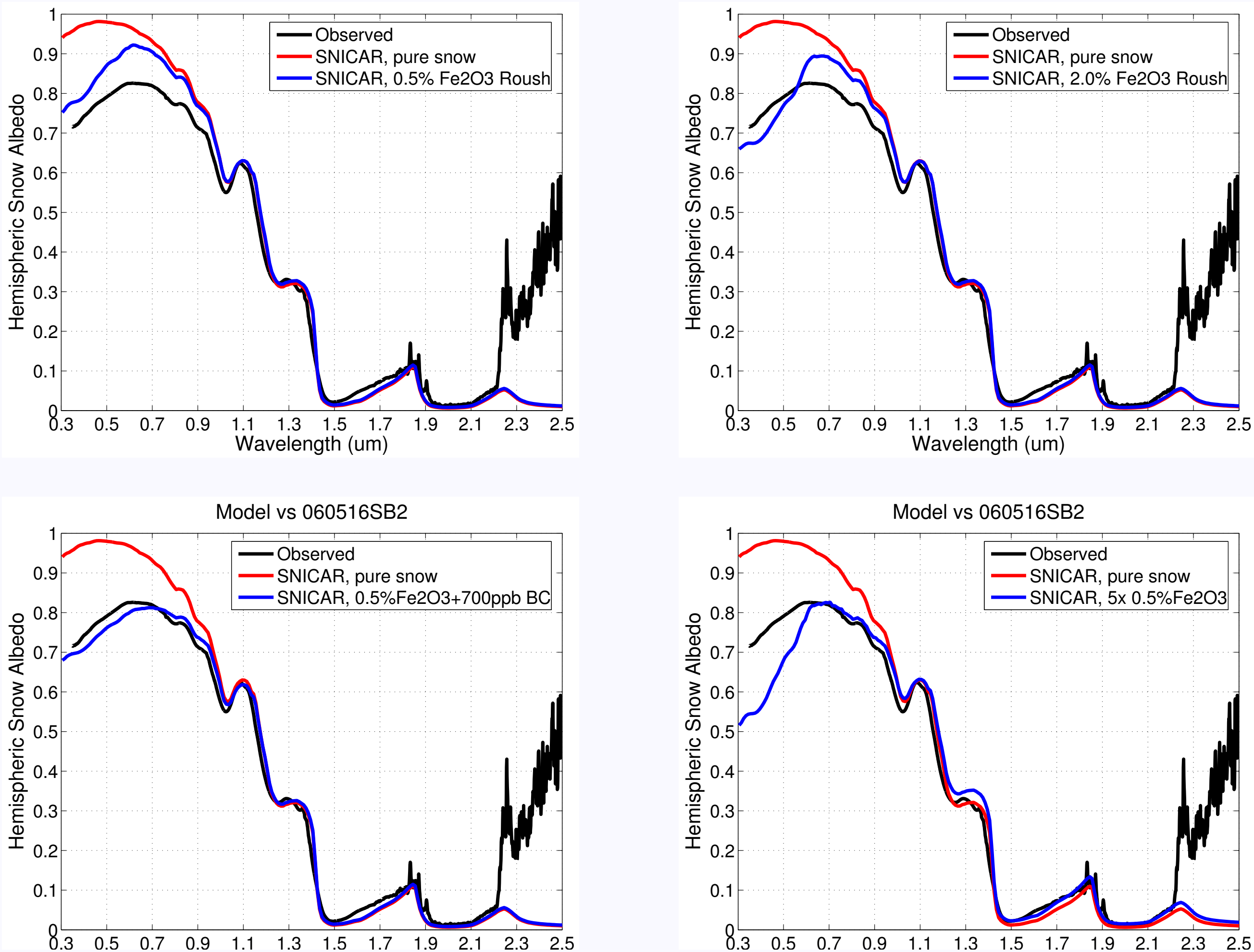



Figure 7: Measured (black) and modeled snowpack spectral hemispheric albedo $\mathcal{R}(\lambda)$. Model with (blue) and without (red) measured $100\,\mu g\, g^{-1}$ dust contribution. (Courtesy Tom Painter, NSIDC)

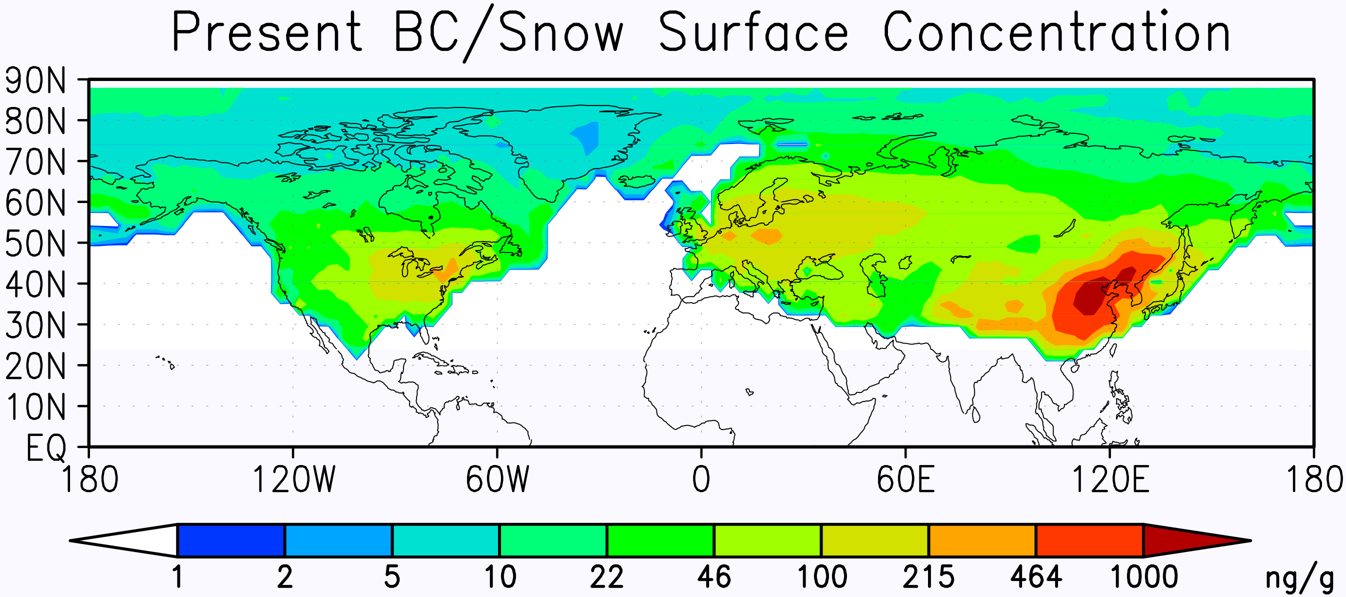



Figure 8: Present day soot concentration in snowpack, 1998 emissions. Global mean $\sim 24\,\mathrm{ng\,g^{-1}}$.

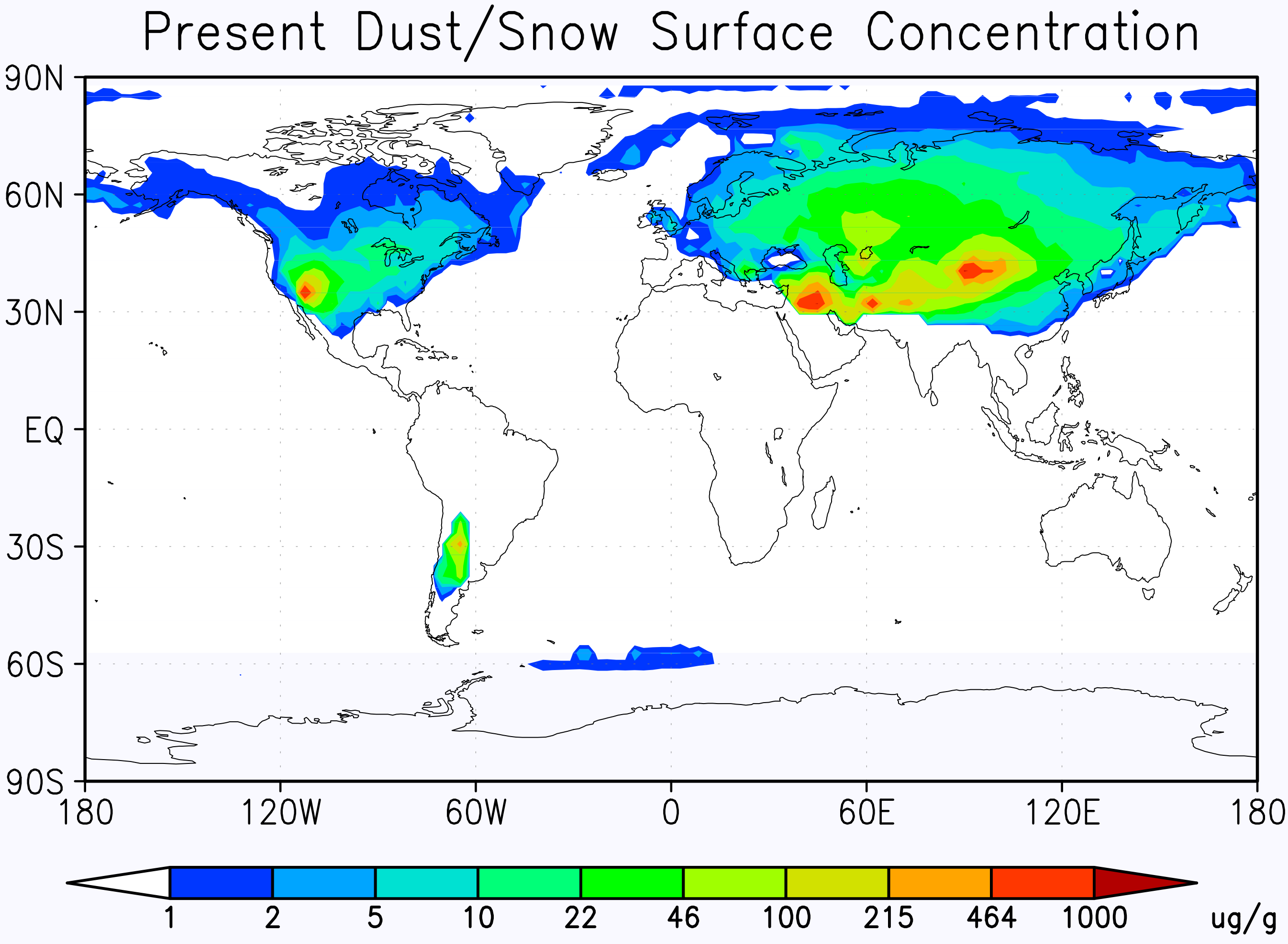



Figure 9: Present day dust concentration in snowpack. Global mean $\sim 5.7\,\mu g\,g^{-1}$.

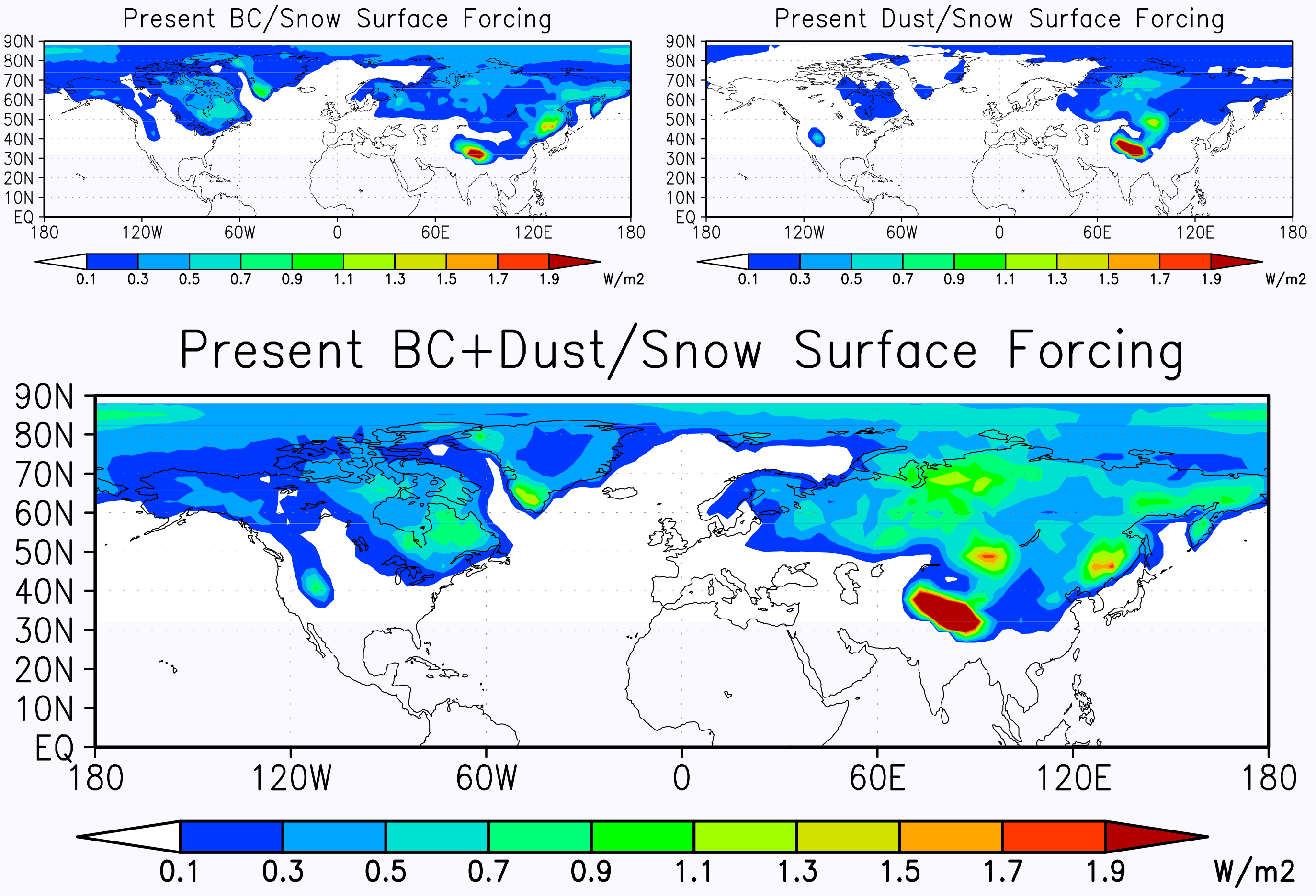
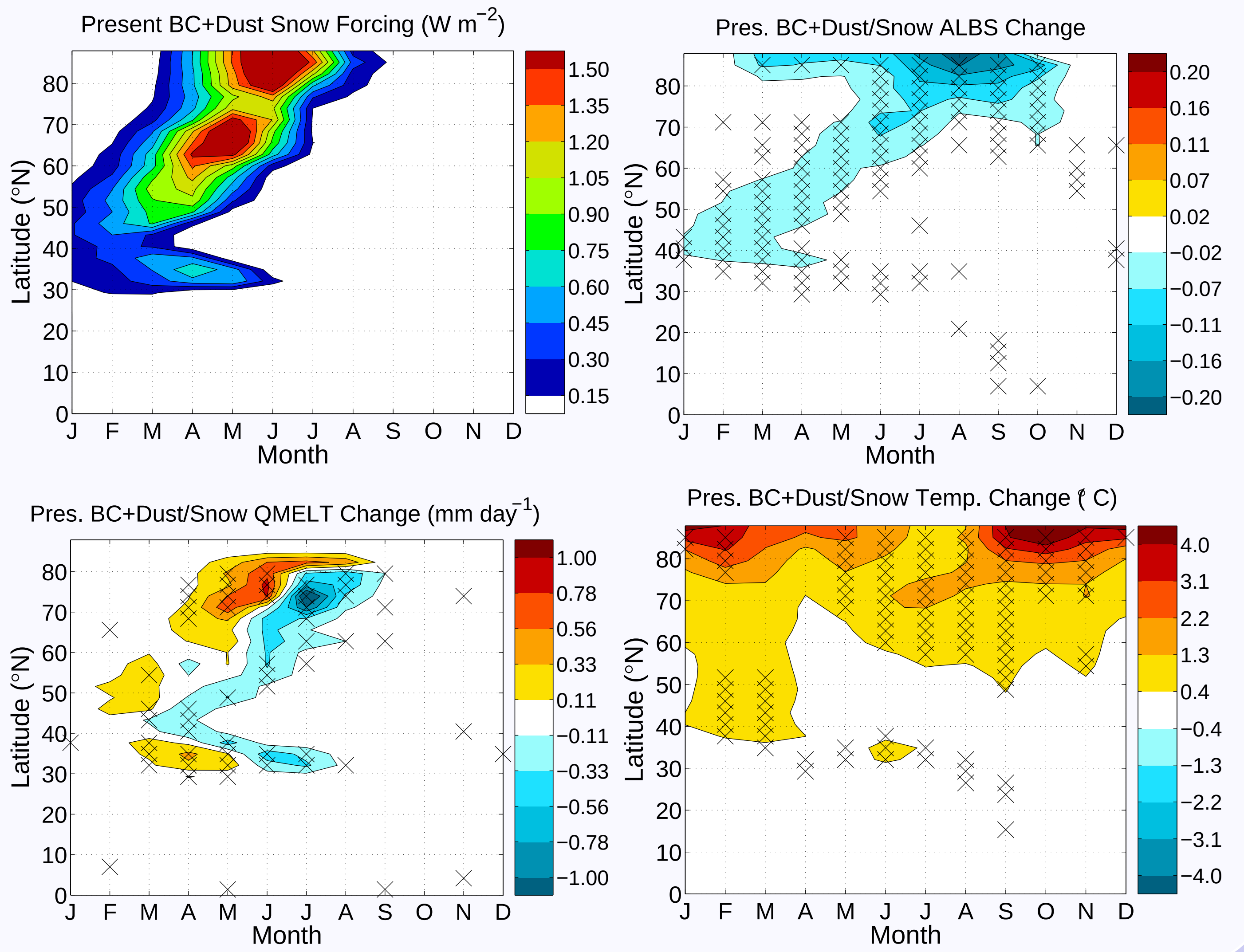



Figure 10: Present day global surface forcing by soot and dust in snowpack. Global mean $\sim 0.056\,\mathrm{W\,m^{-2}}$.


Present BC+Dust Snow Forcing (W m$^{-2}$)
Latitude (°N)
0
10
20
30
40
50
60
70
80
J F M A M J J A S O N D
Month
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
0.20
0.16
0.11
0.07
0.02
−0.02
−0.07
−0.11
−0.16
−0.20
Pres. BC+Dust/Snow QMELT Change (mm day$^{-1}$)
1.00
0.78
0.56
0.33
0.11
−0.11
−0.33
−0.56
−0.78
−1.00
Pres. BC+Dust/Snow Temp. Change (° C)
4.0
3.1
2.2
1.3
0.4
−0.4
−1.3
−2.2
−3.1
−4.0

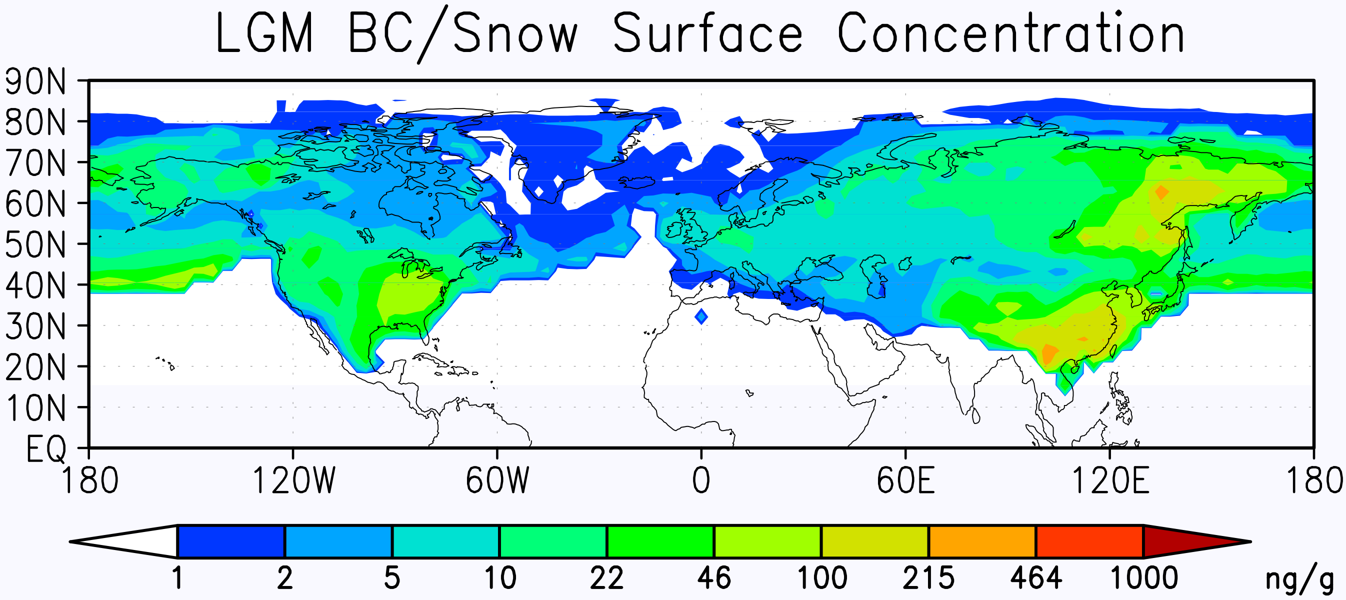



Figure 12: LGM soot concentration [ng $g^{-1}$] in snowpack, 1998 fire emissions from non-ice regions. Global mean $\sim 1.5\,\mathrm{ng\,g^{-1}}$.

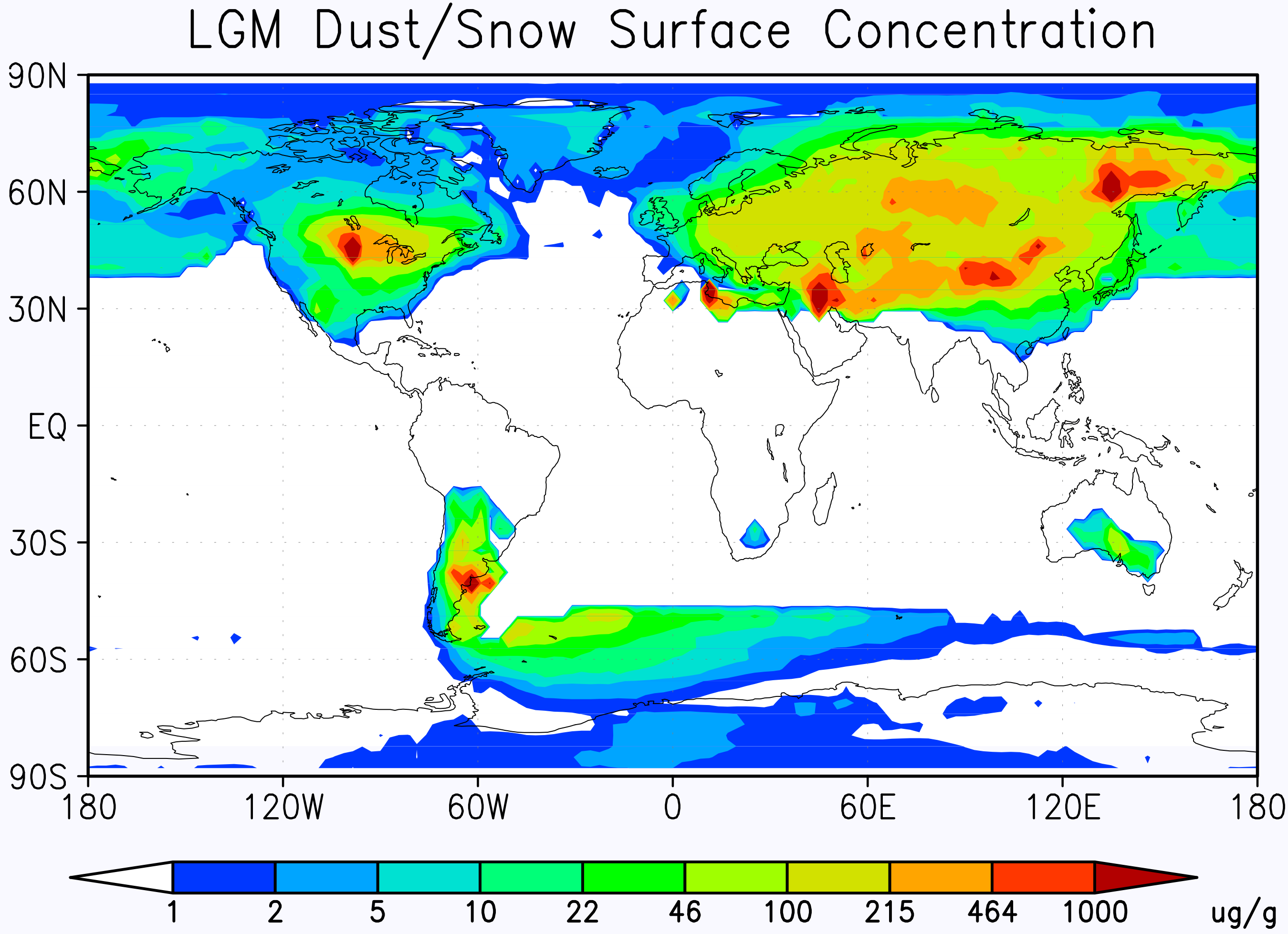



Figure 13: LGM dust concentration [$\mu g\,g^{-1}$] in snowpack using Glaciogenic sources inferred by Mahowald et al., 2006, *JGR*. Global mean $\sim 6.9\,\mu g\,g^{-1}$.

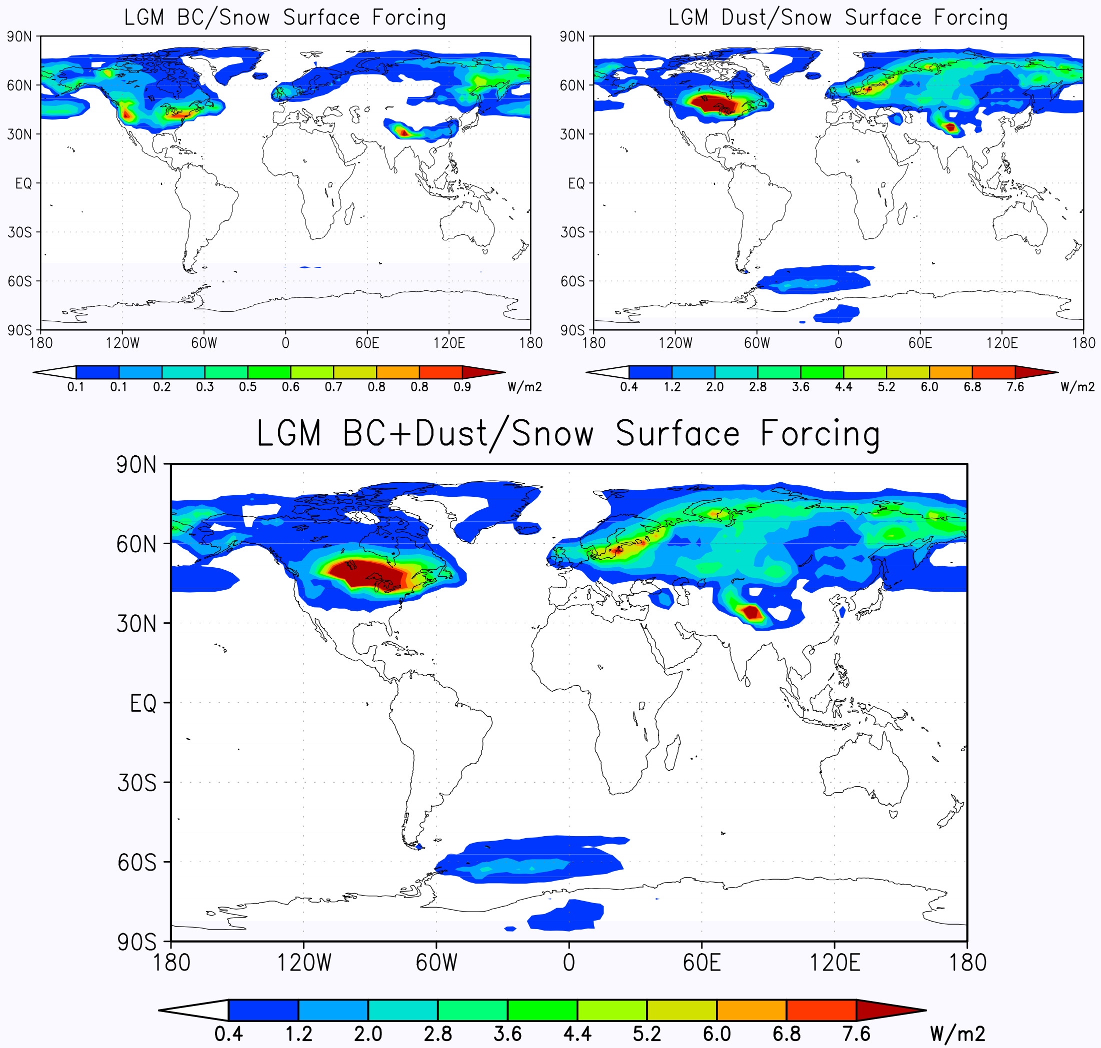
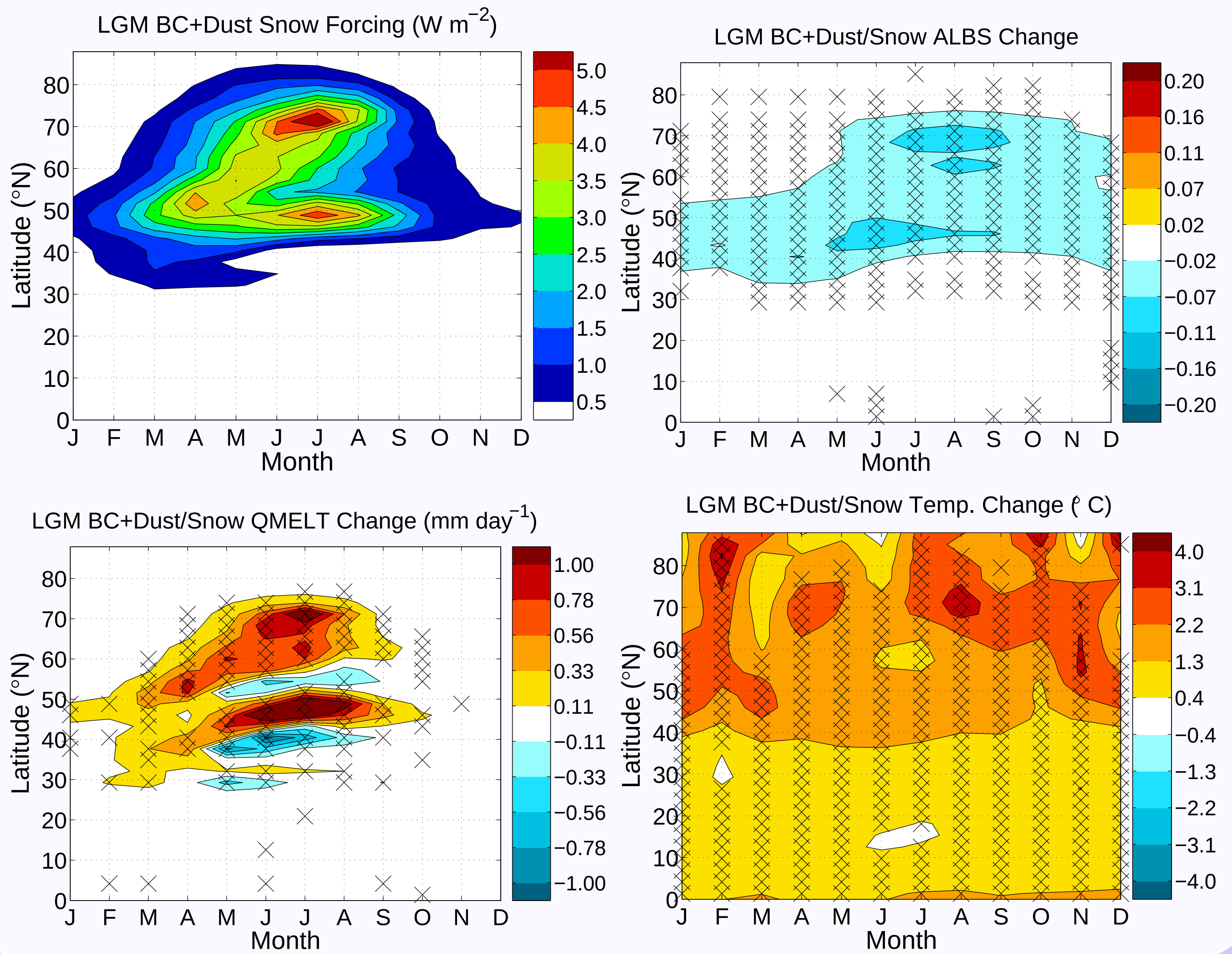



Figure 14: LGM forcing by soot and dust in snowpack.


LGM 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
5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5
LGM 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
0.20 0.16 0.11 0.07 0.02 −0.02 −0.07 −0.11 −0.16 −0.20
LGM 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
1.00 0.78 0.56 0.33 0.11 −0.11 −0.33 −0.56 −0.78 −1.00
LGM 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
4.0 3.1 2.2 1.3 0.4 −0.4 −1.3 −2.2 −3.1 −4.0

## 3. Conclusions

Current climate:

- Dust-snowpack forcing $<$ soot forcing, dust efficacy $>$ soot efficacy
- Dust+Soot-snowpack forcing $0.050\,\mathrm{W\,m^{-2}}$ warms climate $0.16\,\mathrm{K}$ ($\sim 50\%$ by anthropogenic soot) with efficacy $E \sim 4.2 \times \mathrm{CO_2}$
- Significant climate affects on melt seasonality, Arctic $T$

LGM climate:

- Dust-snow forcing increases ten-fold, causes 90% of $0.95\,\mathrm{K}$ warming
- Sustained ice-sheet darkening can (did?) change global climate

Overall:

- Introducing new forcing agents (dust) and feedback processes in snowpack model (subsurface melt, snow aging) dramatically increases forcing efficacy by triggering snow-ice-albedo feedbacks
- Polar amplification mechanisms are stronger than previously thought