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A review of measurement and modeling of light-absorbing particles in snow and ice and their climatic and hydrological impact

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Funding support: US Department of Energy Earth System Modeling program

U.S. DEPARTMENT OF ENERGY

2015 AGU Fall Meeting, December 15 2015

Observational evidence on darkening effects of snow impurities

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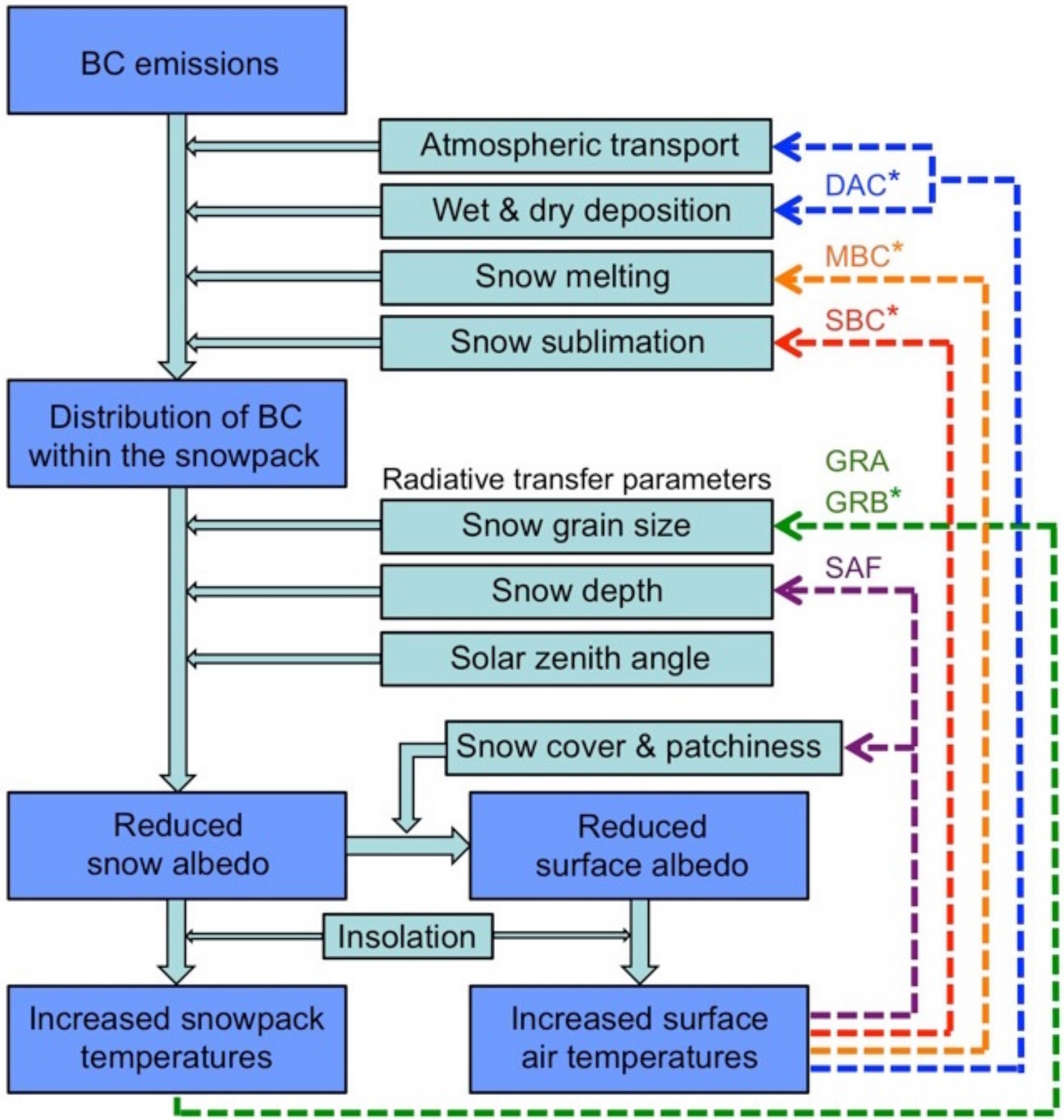
LAPs-in-snow feedback processes

(Bond et al., 2013, JGR)



Snow grain size feedback:
Warming → larger grain size → more absorption/heating

Melt enrichment feedback:
Warming → more snow melt → retention of BC at the surface → accelerated melting

Snow albedo feedback:
Warming → more snow melt → early exposure of underlying surface → lower albedo

Accelerated warming in the Arctic and reduction of snowpack: role of LAPs in snow/ice?

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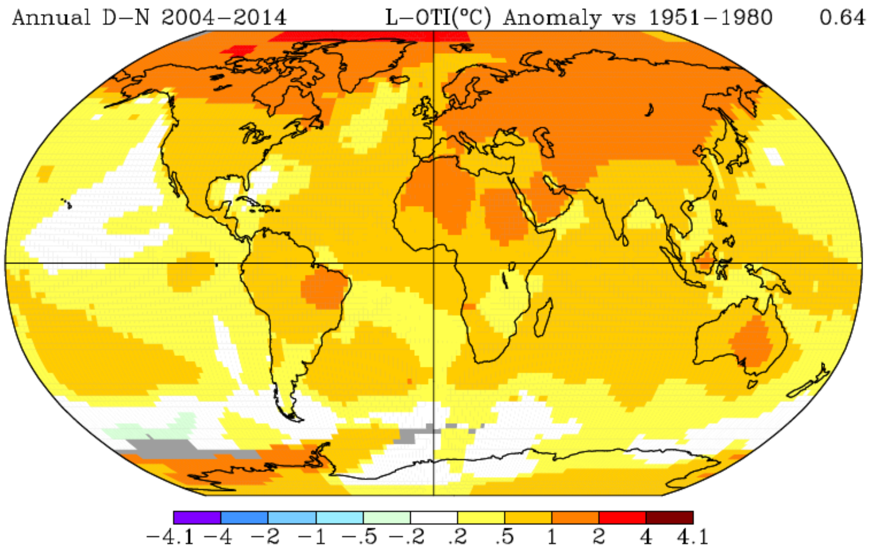
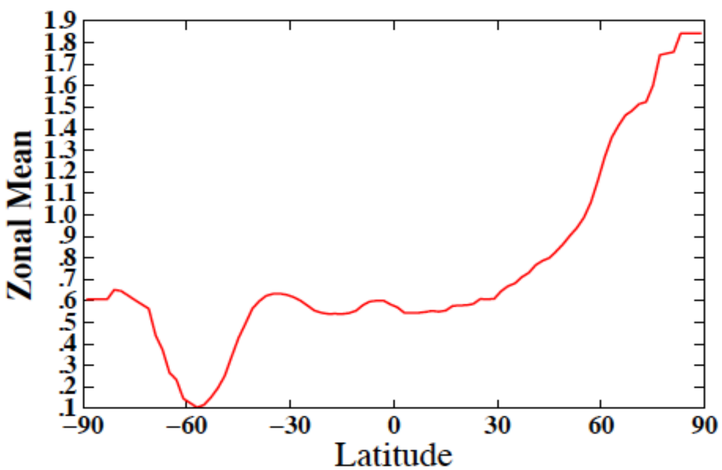
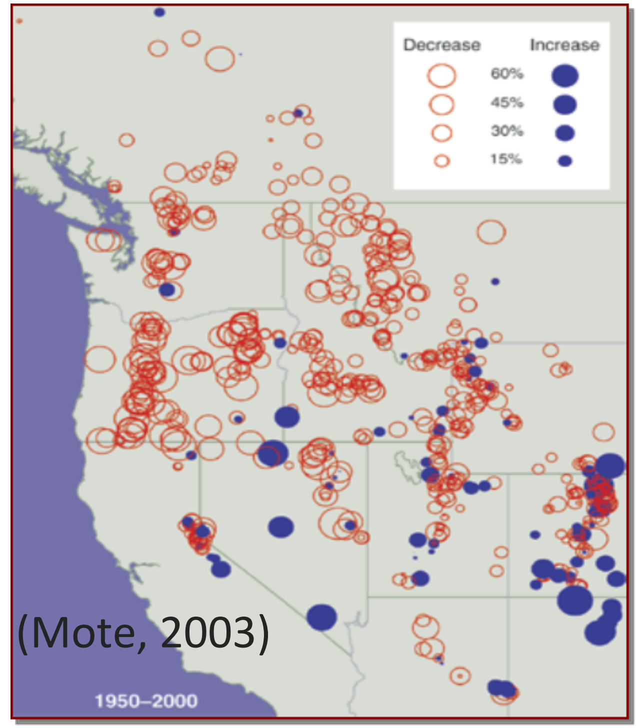
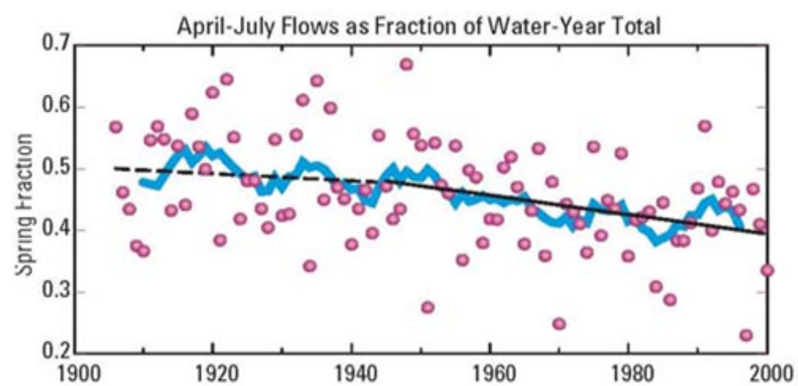




Temperature change (NASA GISS STA)





Measurements: primary techniques

- Thermo-optical analysis: OC and EC mass (e.g., Chow et al., 1993; Birch and Cary, 1996; Watson et al., 2005)
  - Making snow and atmospheric measurements comparable
  - Different operational protocols can lead to up to an order of magnitude range
  - Capture efficiency of filters for water samples can be quite low

- Laser-induced incandescence: refractory BC mass size distributions and total mass (Schwarz et al., 2006, 2008; Moteki and Kondo, 2010)
  - Injection from a nebulization system to Single Particle Soot Photometer (SP2)
  - Provides the most direct measurement of rBC
  - Challenges specific to analyzing snow water samples
    - Efficiency for nebulization system to get BC into the sample air stream
    - BC is attached to larger particles (e.g. dust) and/or sticks to sample tube
    - Snow BC size may be larger than 80–700 nm that SP2 efficiently measures

Measurements: primary techniques

- Filter-based optical analysis: spectrally-resolved total absorption (e.g. Clarke and Noone, 1985; Grenfell et al., 2011; Doherty et al., 2010, 2014b)
  - direct measurement for snow albedo reduction
  - simple and allows for analysis of a large number of samples
  - cannot measure what components lead to that absorption
  - needs assumptions about the mass absorption cross-sections by BC and non-BC components (highly uncertain)

- Gravimetric analysis: total particulate mass (e.g. Aoki et al., 2006; Painter et al., 2012, 2013a,b)
  - primarily for a specific dominant component (e.g., dust)
  - straightforward and amenable to processing a large number of samples
  - less prone to poorly understood biases
  - Requires sufficient snow that mass of particles is greater than the uncertainty in the mass of the filter itself

Measurements: Arctic snow survey
(Doherty et al. 2010)

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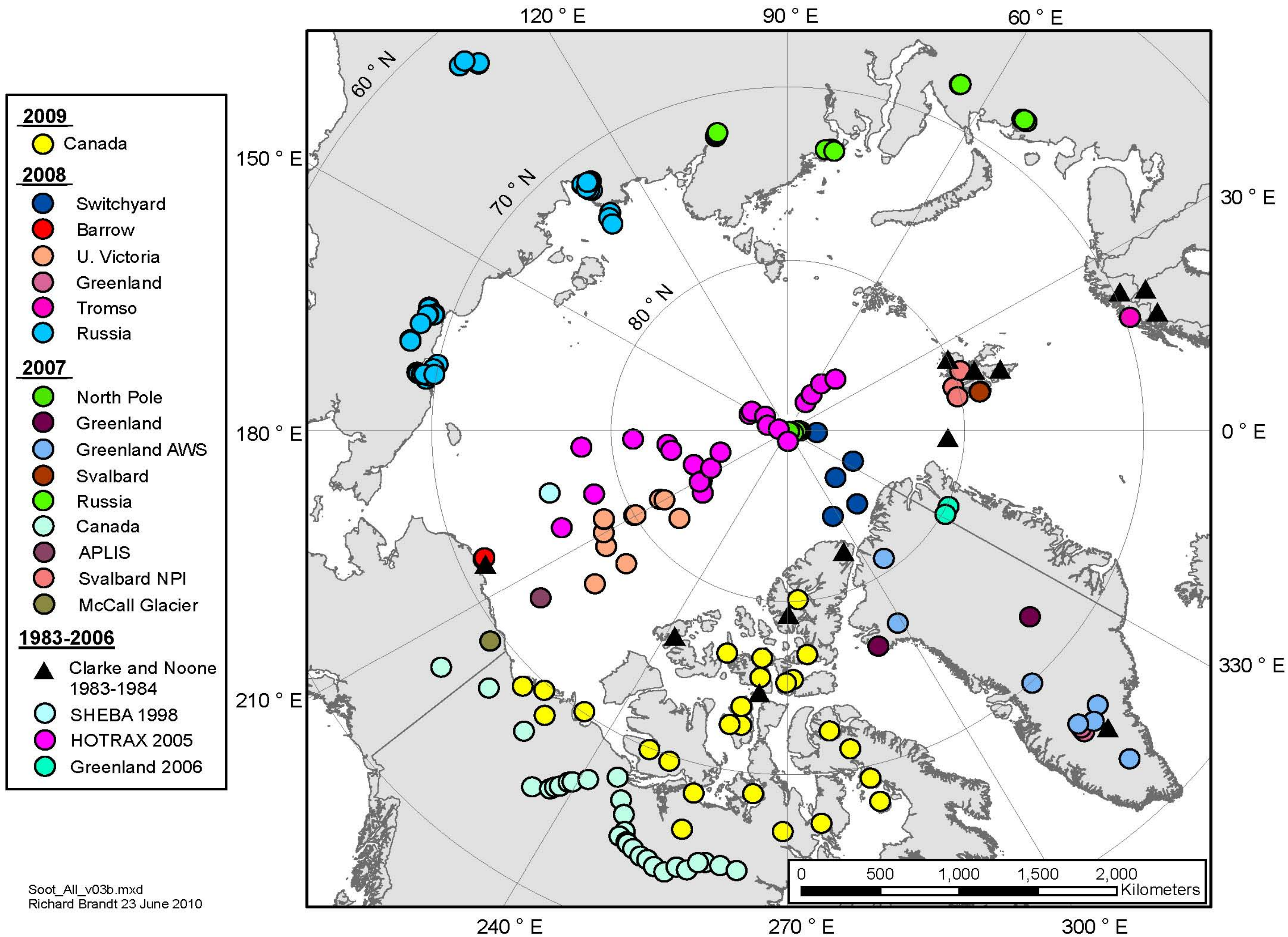

Measurements: northern China

(Huang et al., 2011; Wang et al., 2013)

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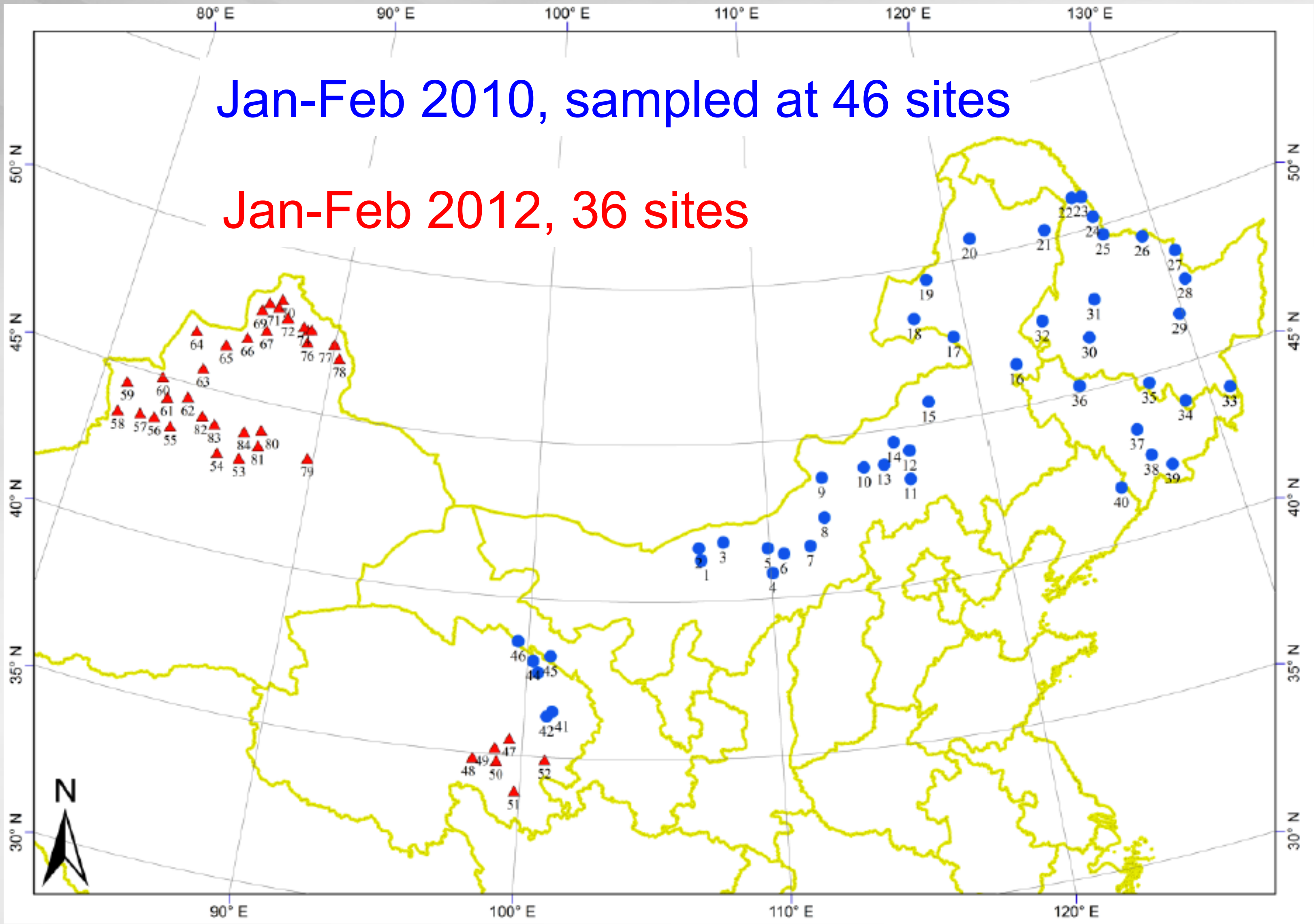

Measurements: western North America

(Doherty et al., 2014)

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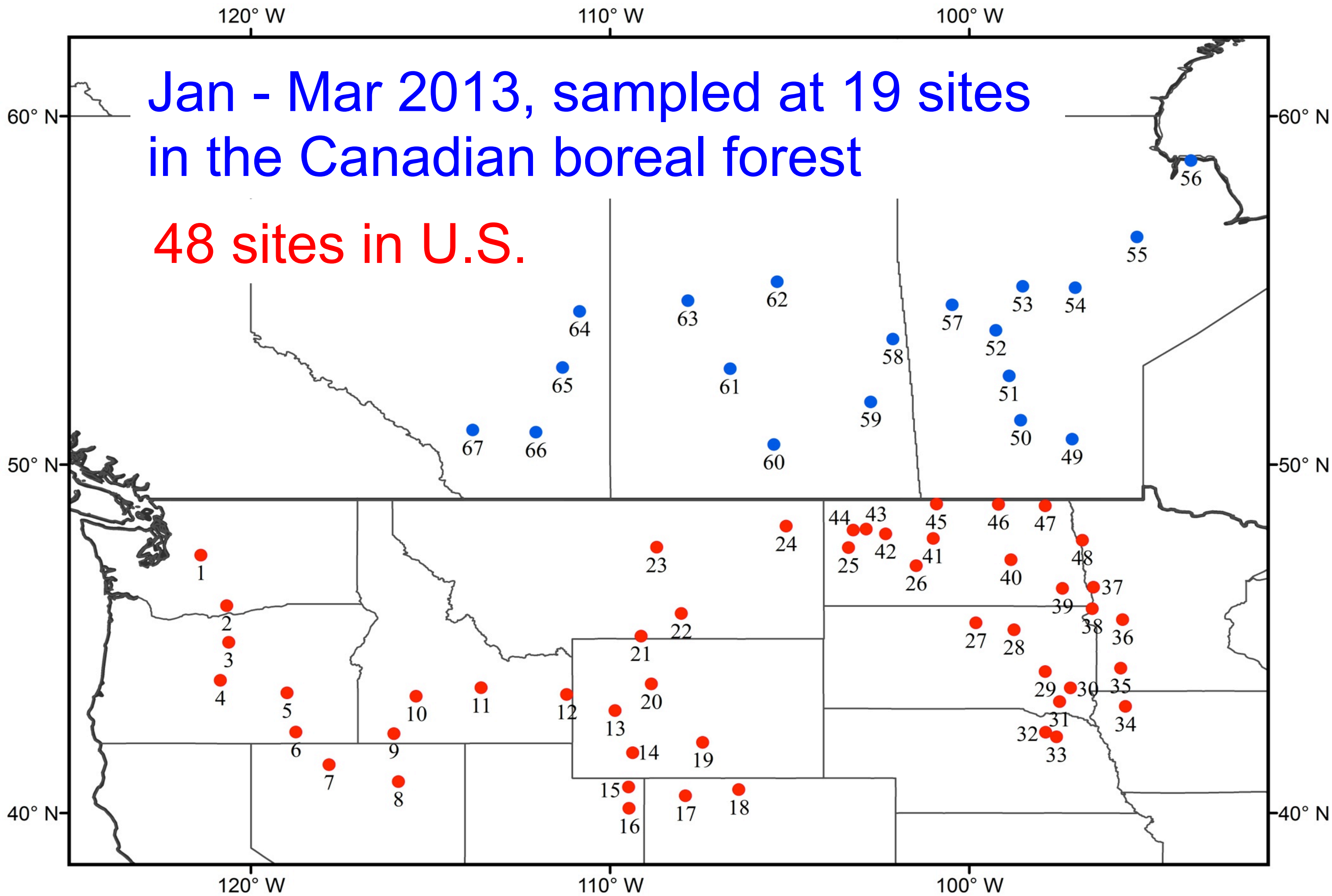
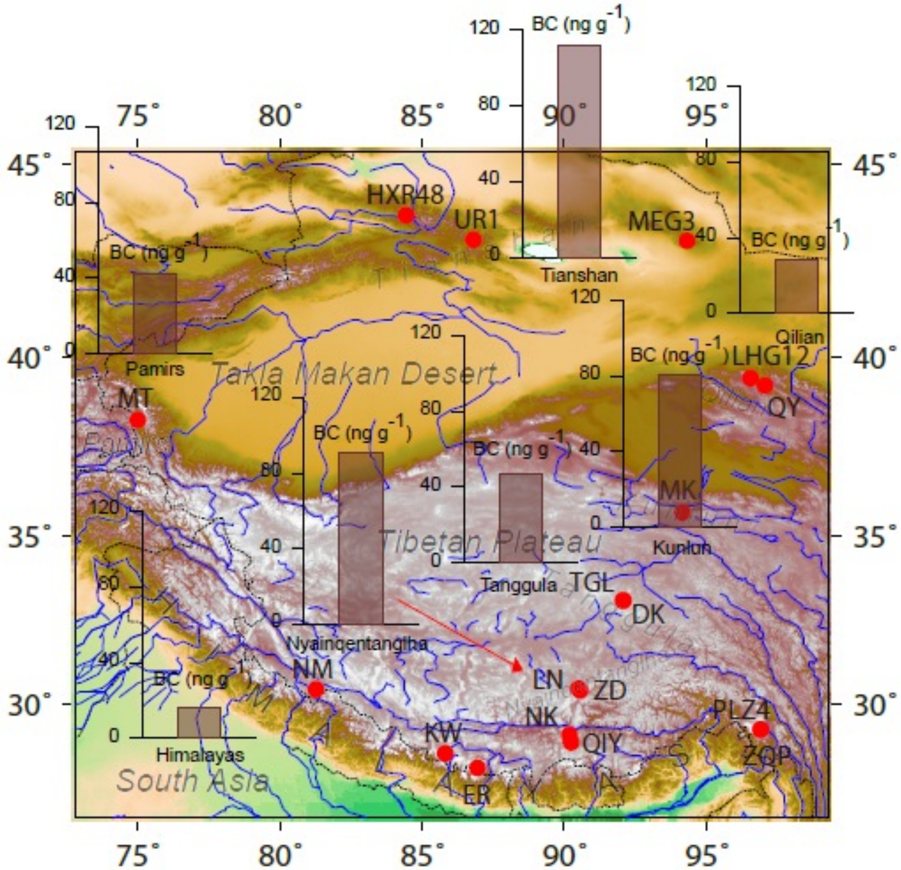
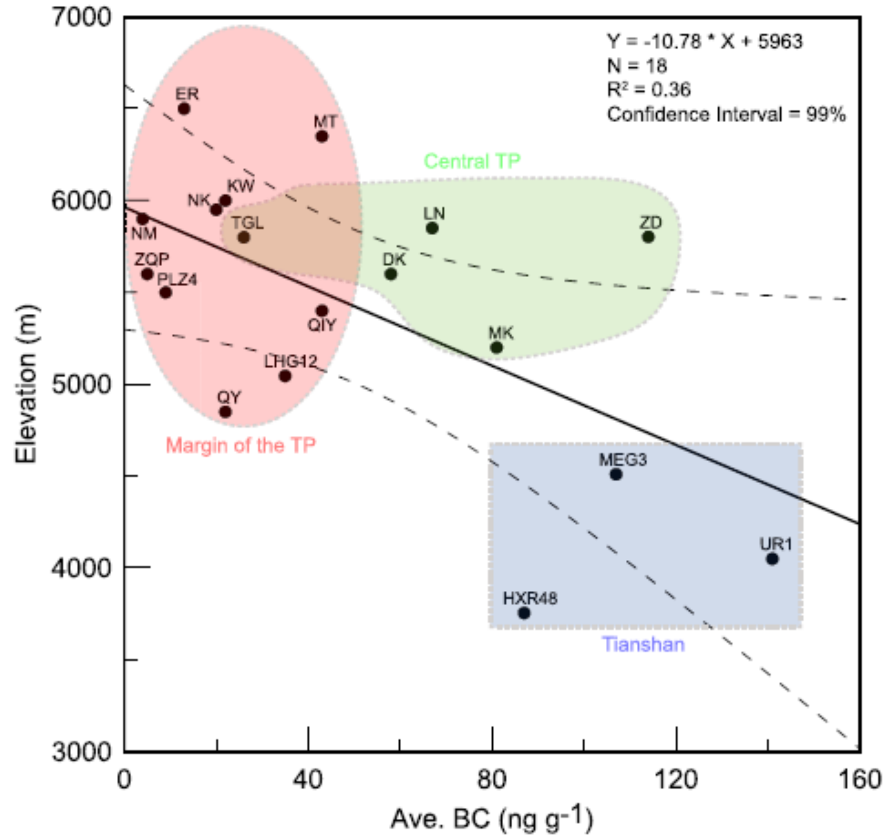


BC sampled in High Asia snowpack and glaciers



Xu et al., 2006, 2009a,b, 2012;
Ming et al., 2008, 2009, 2013a,b



(Ming et al., 2012)

Ice cores sampled to study the history of BC and OC

Summary of BC concentrations in snow

Location	BC (ng/g)
Greenland	1 – 4
Arctic Ocean	4 – 10
Arctic Canada	8 – 14
Arctic Russia	10 – 60
Northeastern China	50 – 2000
Northwestern China	20 – 600
High Asia Glaciers	5 – 140
Western North America	25 – 90
Antarctic	0.2 – 0.7

LAPs in snow and darkening effects in climate models

(Qian et al., 2015)

✓ **BC only:**

- **GATOR-GCMOM:** (Jacobson, 2004)
- **GISS-ModelE** (Koch et al., 2009), **ModelE2** (Dou et al., 2012; Bauer and Menon, 2012)
- **CICERO-OsloCTM2** (Rypdal et al., 2009; Skeie et al., 2011; Lund and Berntsen, 2012)
- **WRF-chem** (Qian et al., 2009, followed Jacobson, 2004)

✓ **Dust + BC:**

- **MRI-ESM1**, **MRI-CGCM3** (Aoki and Tanaka, 2008, 2011; Yukimoto et al., 2012)
- **MIROC5, MIROC-ESM** (Watanabe et al., 2010, 2011)
- **NorESM** (Bentsen et al. 2013)
- **LMDZ-ORCHIDEE-INCA** (Krinner et al., 2006; Ménégoz et al., 2013, 2014)

✓ **Dust + BC + OC:**

- **Updated GATOR-GCMOM** (Jacobson, 2012; tar ball is treated)
- **NASA GEOS-5 with GOSWIM** (Yasunari et al., 2011, 2014)
- **NCAR CESM (CCSM) or CAM** (Flanner et al. 2007, 2009, 2012; Qian et al., 2011, 2014; Wang et al., 2014a, b; Zhang et al., 2015a,b)
- **WRF-chem** (Zhao et al., 2014; followed CAM5)

Impact of LAPs in snow on the water cycle

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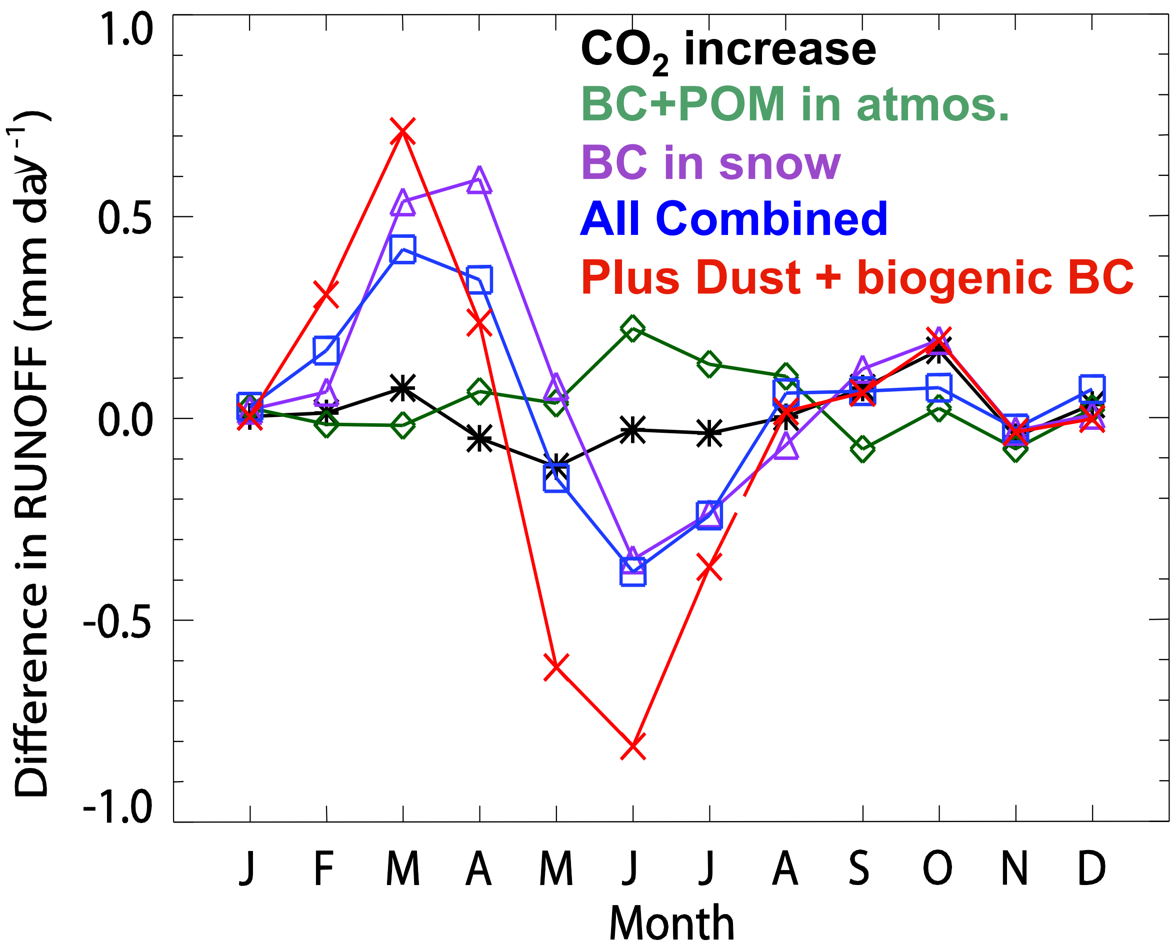
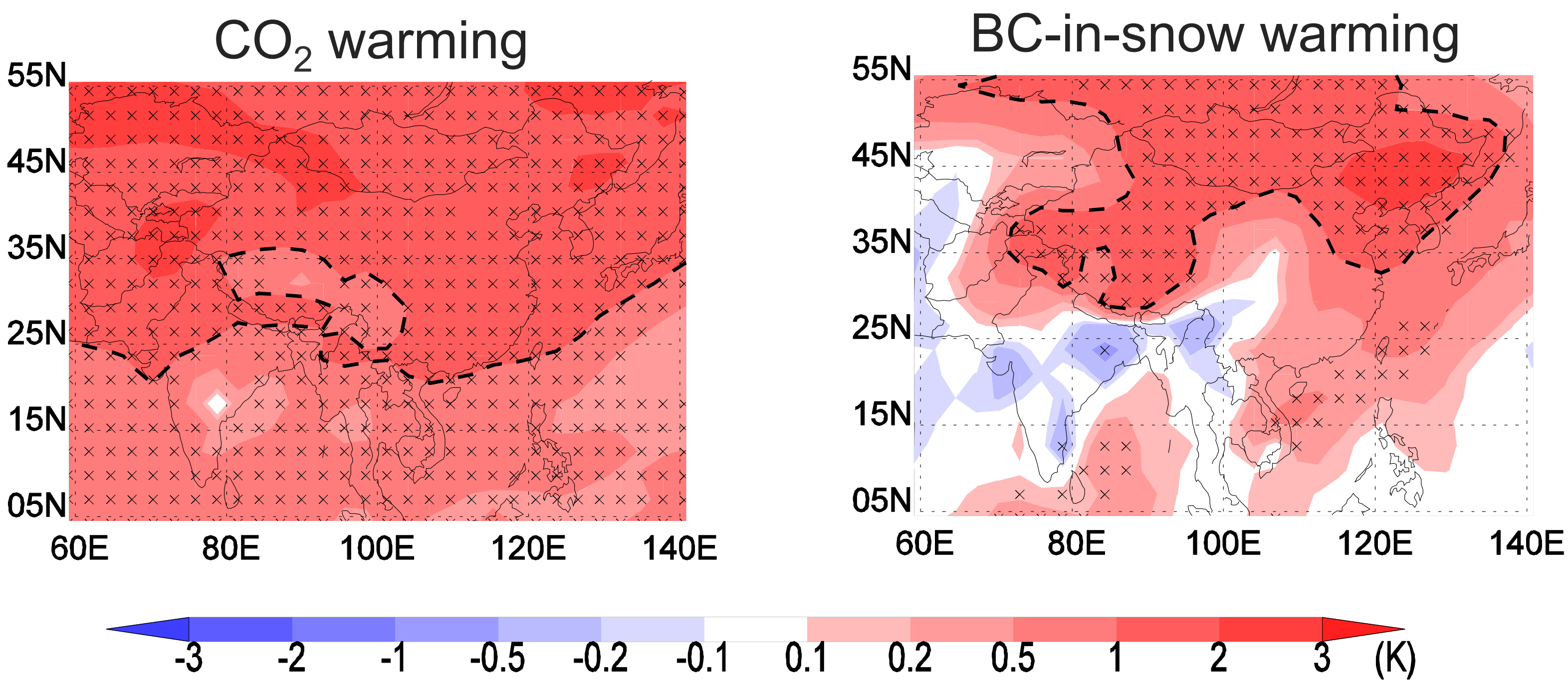


Shift the seasonal cycle of runoff over Tibetan Plateau by LAPs in snow

Qian et al., 2011

Thermal and dynamical influences on South and East Asian monsoon

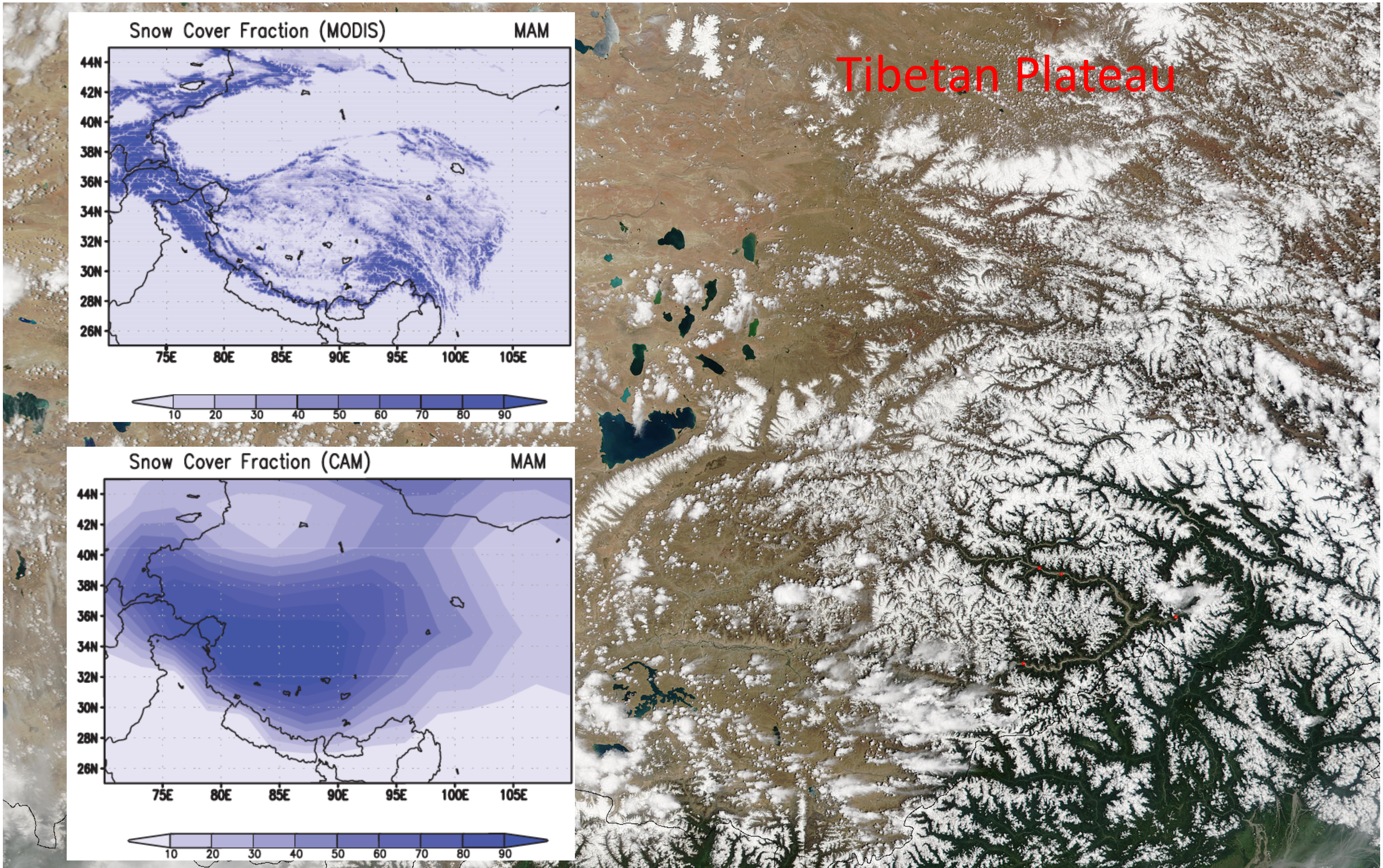


Increased thermal contrast between land and ocean can alter Asian monsoon circulation and climate

Qian et al., 2011

Uncertainties in model representation and evaluation

- **Emissions**
  - Biomass burning emissions; magnitude, and temporal/spatial distributions
  - Large uncertainty in dust emissions
- **Transport and deposition**
  - Circulation, PBL structure, clouds, aerosol-cloud interactions
  - Aerosol chemistry
  - Snow surface roughness
- **Post-depositional and snow aging processes**
  - Melt-water scavenging of LAPs in snow
  - Mixing states within LAPs and snow grains
- **Model-measurement comparison**
  - Time and location mismatch
  - Comparing apples and oranges
- **Snowpack simulation**
  - Spatial resolution and complex terrain



The size of glaciers and seasonal snowpacks is too small to be resolved by all current global climate models.

Some thoughts on ways forward

▶ Measurement

- Measurement inter-comparison and best estimates
- Snow grain size and optical properties of ice-LAPs mixture
- Remote sensing (for broader area snow albedo reduction)
- Laboratory measurements (e.g., for Melt-water scavenging efficiency)
- More frequent snow measurements, e.g., to capture the melting process

▶ Modeling

- Improved aerosol representation and deposition
- SOA, snow algae and other organics via biological activities
- High-resolution modeling
- Dedicated model inter-comparisons (at various timescales)

Source attribution (by sectors and/or regions)

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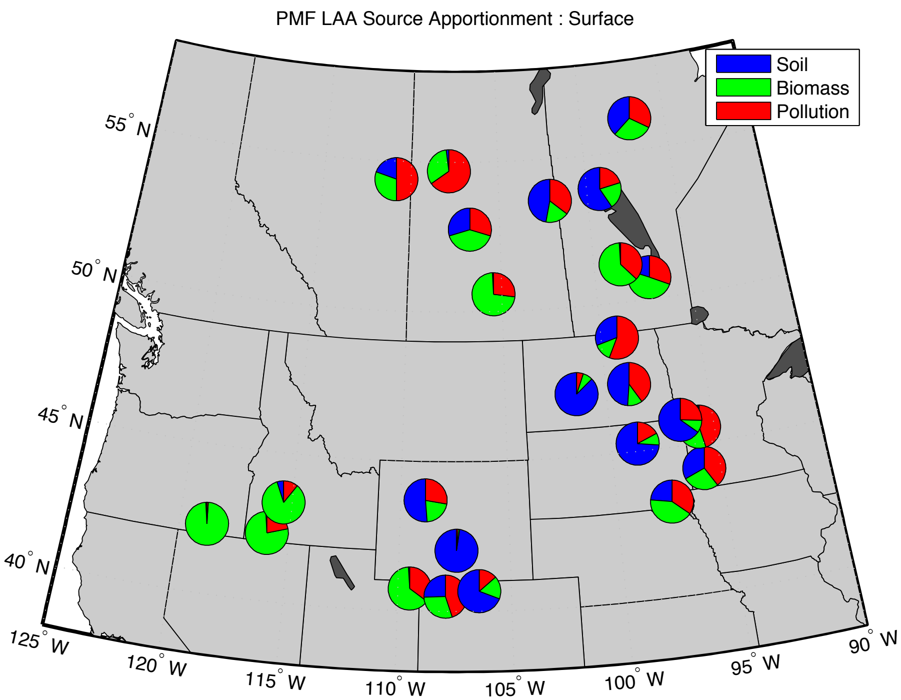
Source Attribution of BC in Snow at North American sites

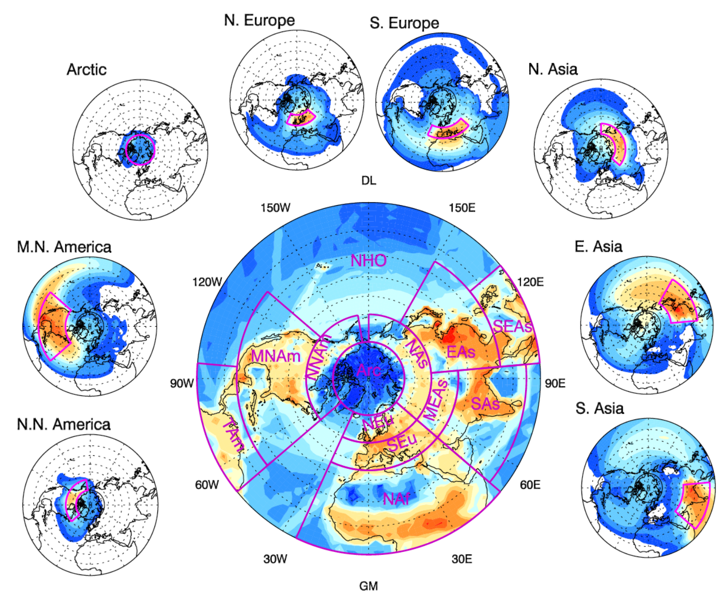
→ chemical "fingerprints" which describe most of the variability in BC



Doherty et al., JGR, 2014

Quantify contributions of regional and sectoral sources to BC in the atmosphere and deposited on snow/ice over the target region

→ CAM5 model with explicit source tagging capability



Wang et al., JGR, 2014;
Zhang et al., 2015a,b, ACP