Black Carbon in 3D Mountains/Snow, Radiative Transfer and Regional Climate Change

*Kuo-Nan Liou
Joint Institute for Regional Earth System Science and Engineering (JIFRESSE) and Atmospheric and Oceanic Sciences Department
University of California, Los Angeles, CA, USA

*With contributions from Y. Takano, W. L. Lee, Y. Gu, C. He, Q. Li, R. Leung, P. Yang, Q. Yue, Z. Liu, and T. Fickle.
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- Evidence of Mountain Snowmelt and Albedo Reduction: Regional Climate Change
- BC Concentration Over the Tibetan Plateau: GEOS-Chem Simulations and its Radiative Forcing in Snow Grains
- 3D Mountain/Snow & Absorbing Aerosols: A Combined Regional Climate System Using WRF as a Testbed. Part I. 3D
- The Concept of Aerosol/Mountain-Snow/Albedo Feedback

6th International Conference on Atmosphere, Ocean, and Climate Change, Hong Kong, August 19-21, 2013

Century Variation

Kyetrak Glacier, Tibet

Rongbuk Glacier, Tibet

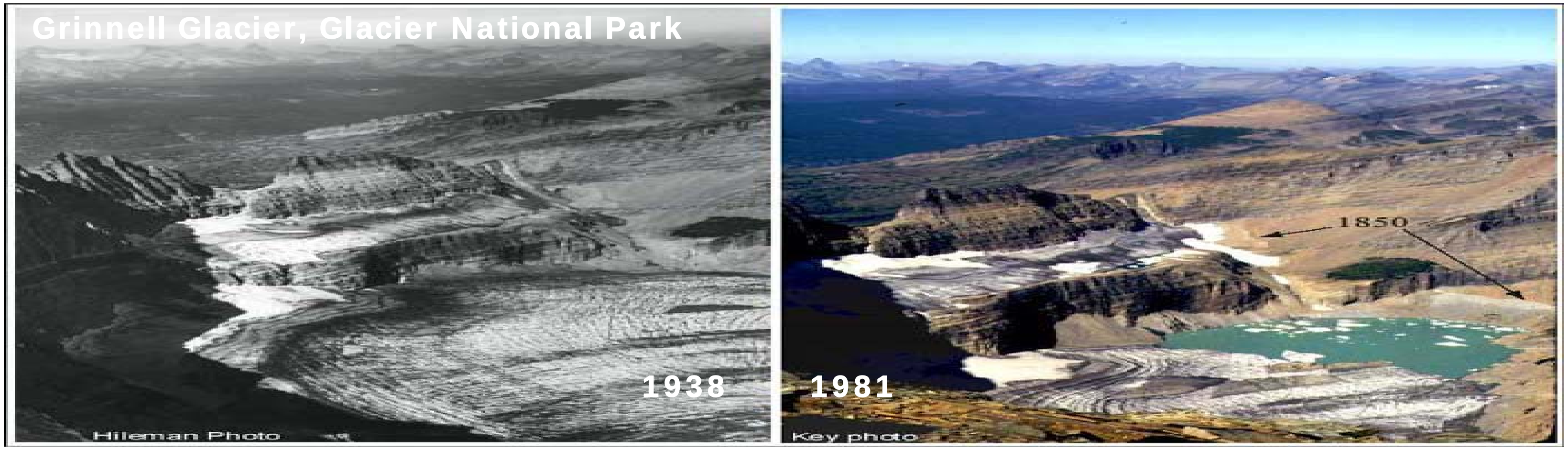
Pasterze Glacier, Austria (German SERA)

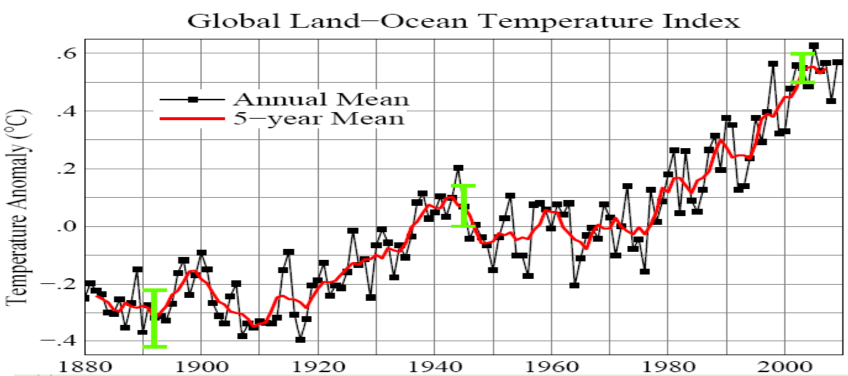
Rhone Glacier, Switzerland (Swiss FIT)

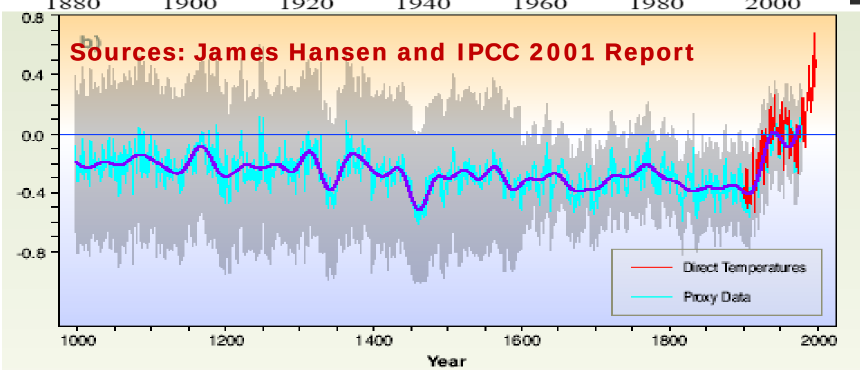
Mount Kilimanjaro, Tanzania

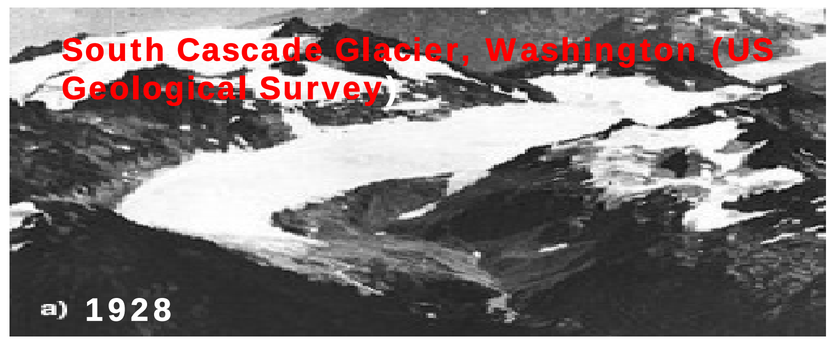
Qori Kalis Glacier, Peru (World Data center for Glaciology)

Strong evidence for global warming; however, addition of man-made absorbing aerosols since the onset of the Industrial Resolution must also play a substantial role in the retreat of glaciers in a non-linear fashion.



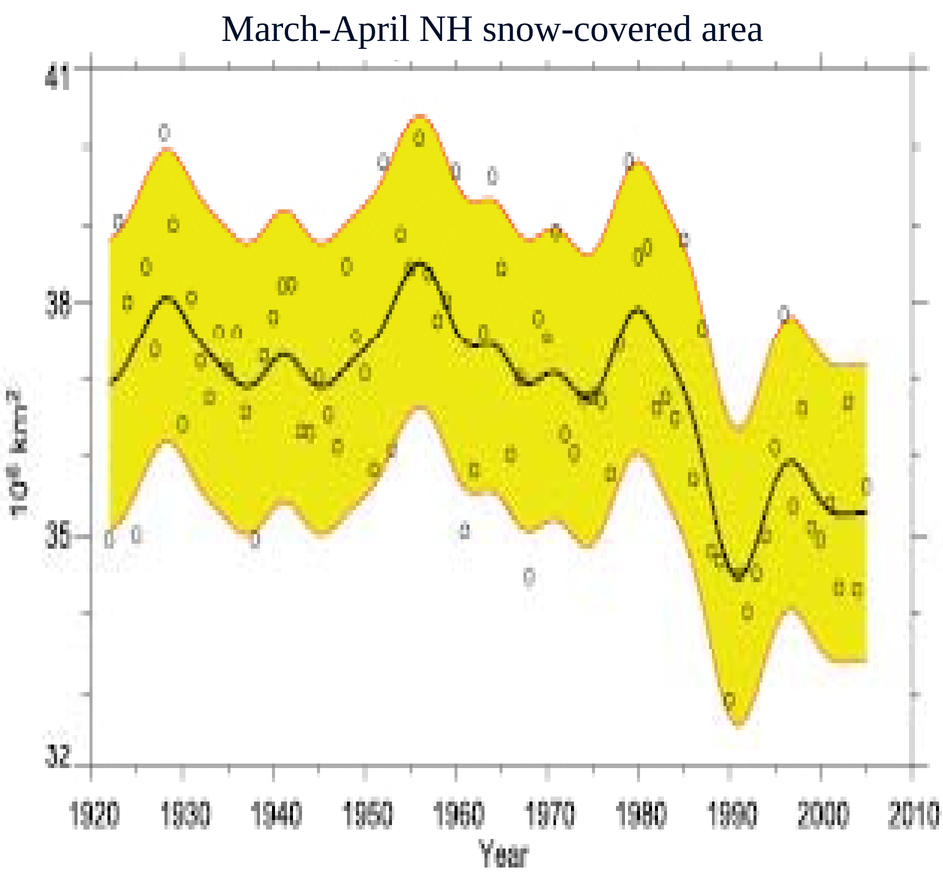




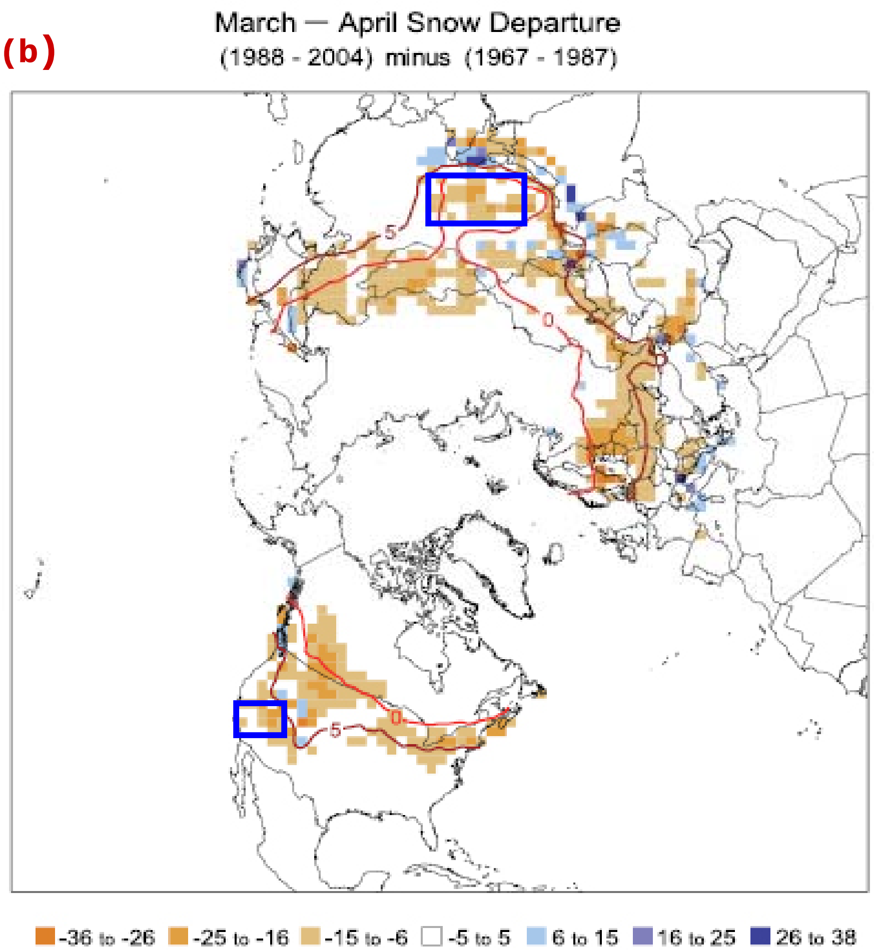


Decadal variation: (a) NH March-April average snow-covered area (Brown 2000) and NOAA satellite data set. The smooth curve shows decadal variation, and the shaded area shows the 5-95% range of the data estimated after first subtracting the smooth curve. (b) Differences in the distribution of NH March-April average snow cover between earlier (1967–1987) and later (1988–2004) portions of the satellite era. Negative values indicate greater extent in the earlier portion of the record. Red curves show the 0 and 5^0 C isotherms averaged for March and April 1967 to 2004 (after IPCC 2007).

(a)

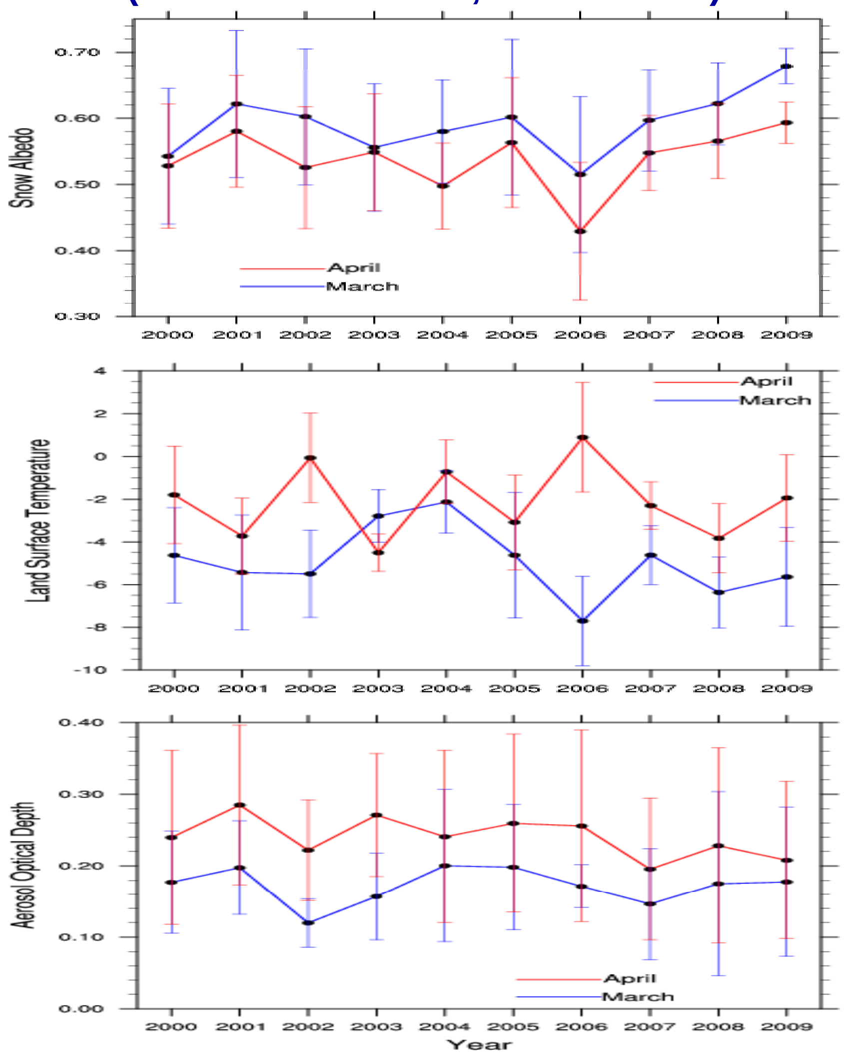


(b)

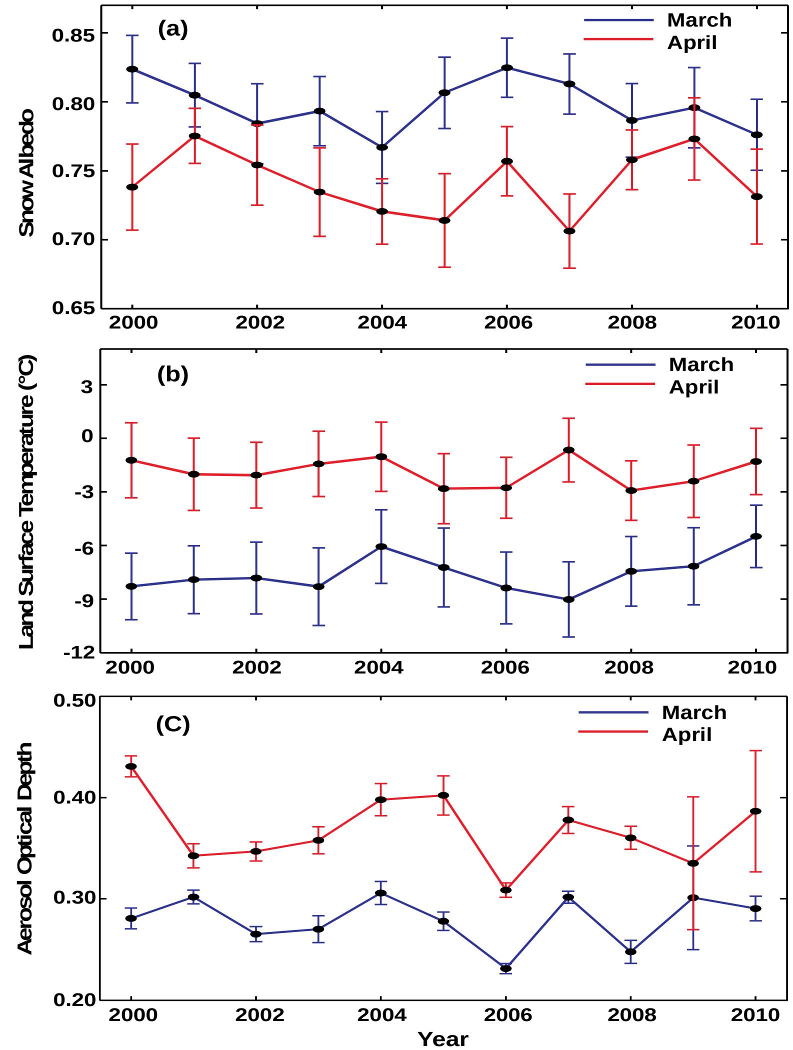


<u>Seasonal variation</u>: Monthly averages of snow albedo for pixels with 100% snow cover, land surface temp. and aerosol opt. depth in March and April from 2000 to 2010 based on analysis of MODIS data. Error bars indicate one SD. A significant negative correlation between snow albedo and aerosol optical depth is shown.

The Sierras: α = 0.56-0.038T-0.026τ (Lee and Liou 2012, Atmos. Env.)



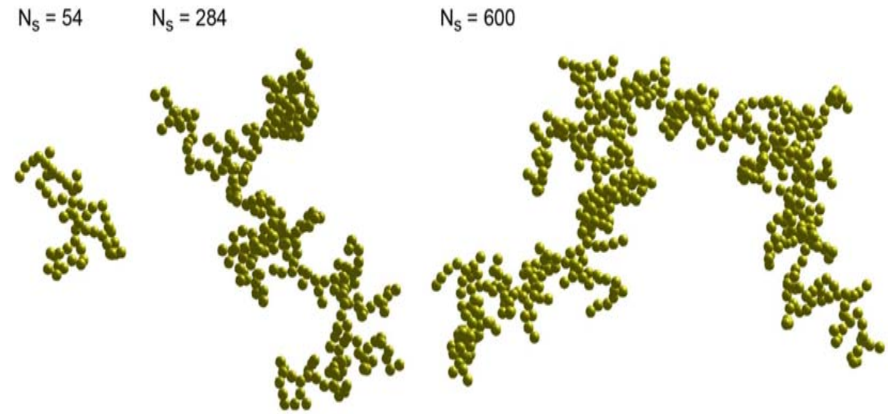
The Southern Tibetan Plateau: α = 0.77−0.021T−0.012τ (in preparation)



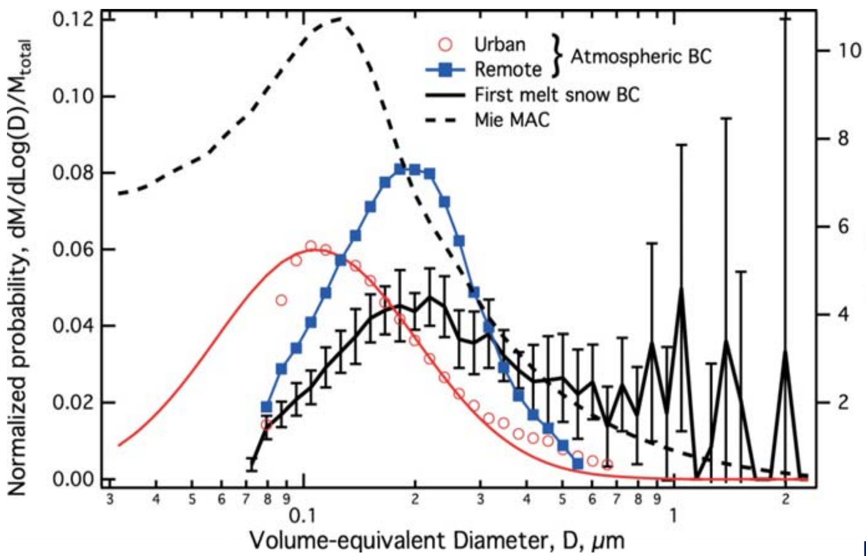
Black Carbon (BC): Composition, Size, Shape, and Source

BC: A solid form of mostly pure carbon that **absorbs solar radiation at all wavelengths**. Produced by incomplete combustion. **Internally mixed** with non-absorbing aerosols.

Soot: A complex light absorbing mixture of mostly BC and organic carbon (OC), usually includes other inorganic materials such as metal and sulfate.

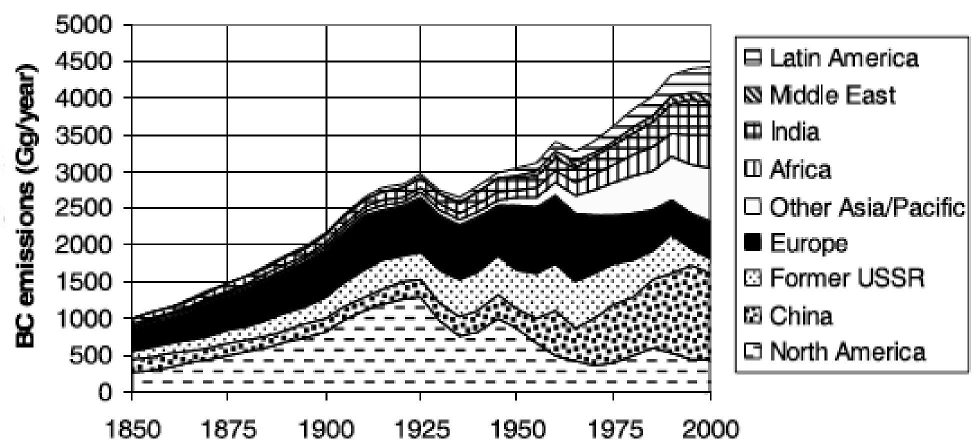


BCs are fractal aggregates, which can contain numerous primary spheres. The numbers of 54, 284, and 600 are shown for light absorption and scattering calculations (Takano, Liou, et al. 2013).

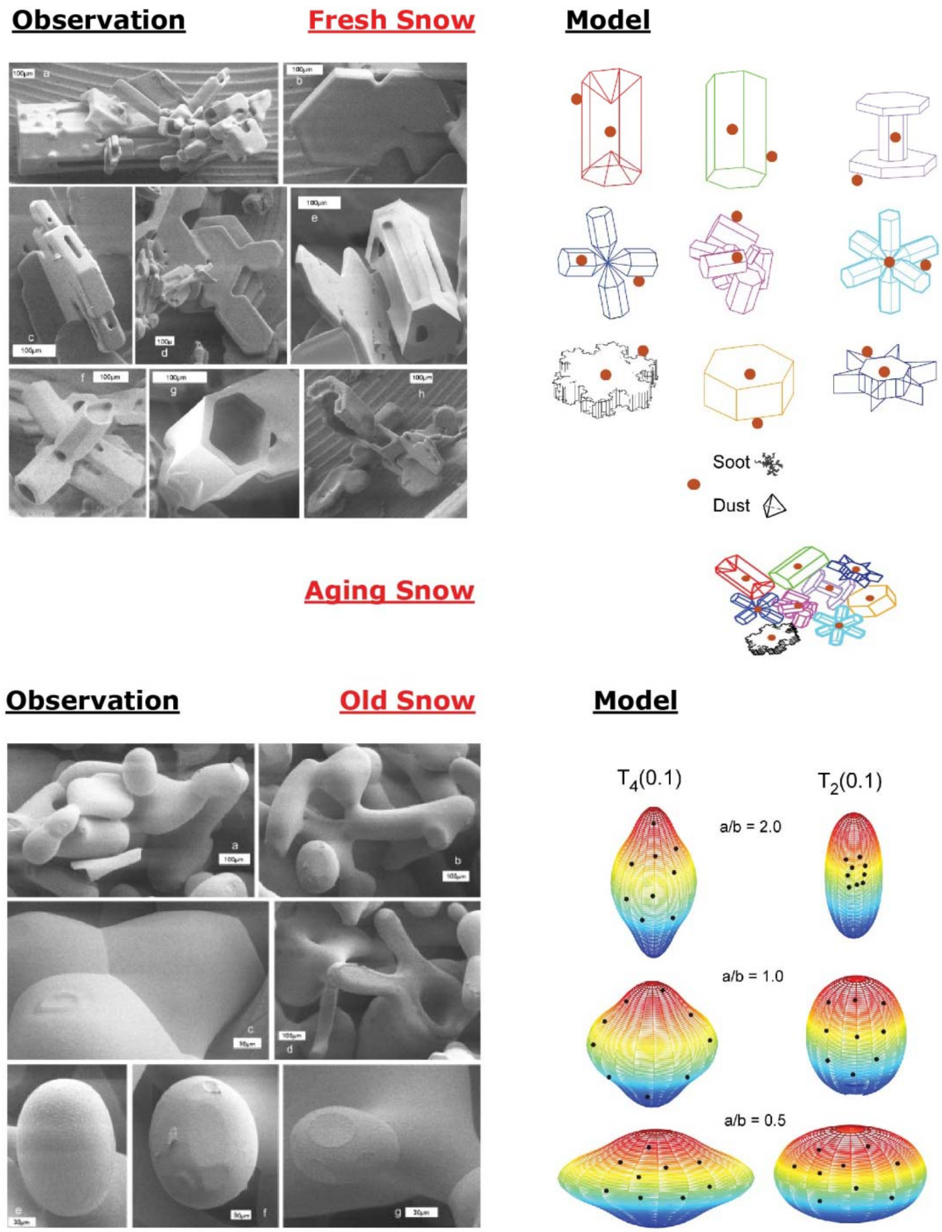


Normalized BC mass size distributions from the atmosphere (remote and urban) and from the five snow samples as a single average (after Schwarz et al. 2013). Average radius is ~ 0.1 μm.

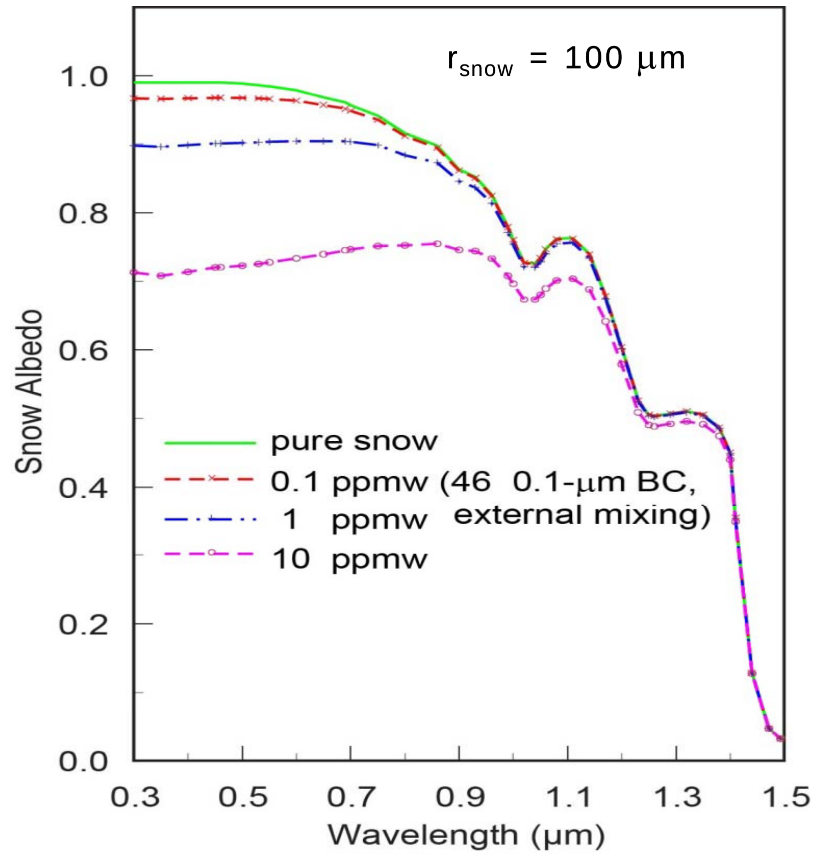
Asian Sources of BC Particles



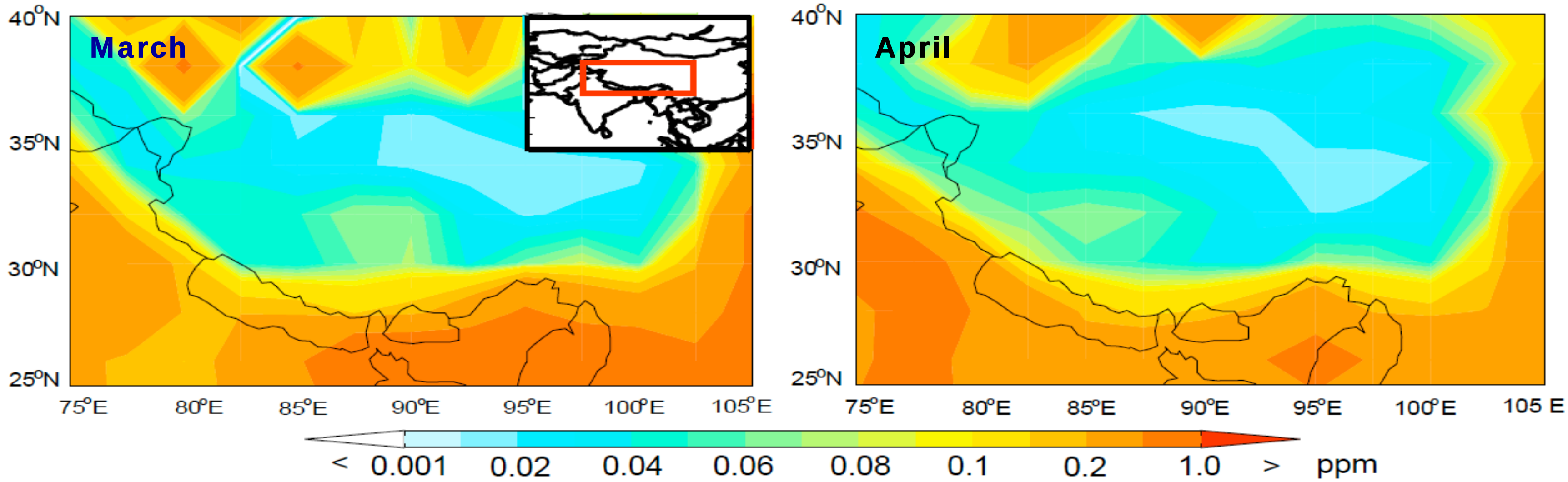
BC aerosols emitted from different areas (after Bond et al. 2007). **Emissions from Asian countries, such as China and India, grew rapidly in the latter half of the 20th century.** North America and Europe dominated BC emissions in the early industrial era.



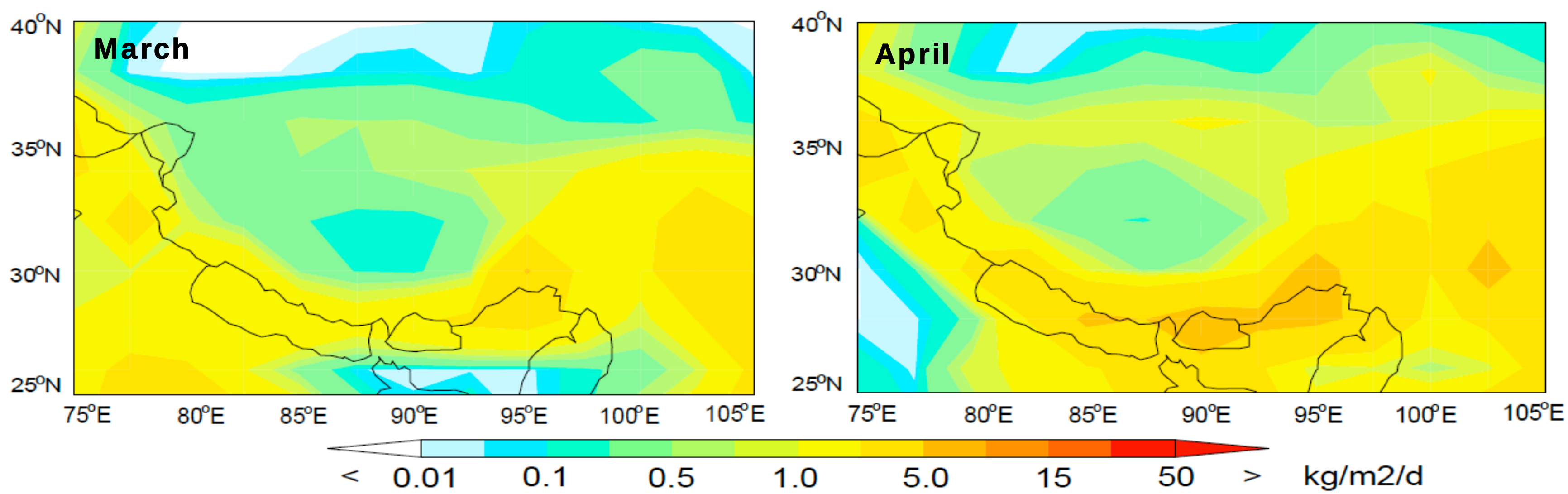
Left panel: Observed and modeled snow grains for fresh (~100 μm), aging, and old (> 1000 μm) snow conditions with the inclusion of BC/dust in a model based on stochastic processes. Below are spectral snow albedo (μ_0 = 0.5; semi-infinite optical depth) values calculated from the adding-doubling radiative transfer method for pure snow and three BC depositions.



GEOS-Chem driven by assimilated meteorology from GEOS-5/GMAO with a resolution of 2°x2.5° and 47 vertical layers, including improvements in dry and wet depositions and global anthropogenic emission inventories (Li et al. 2013, UCLA)

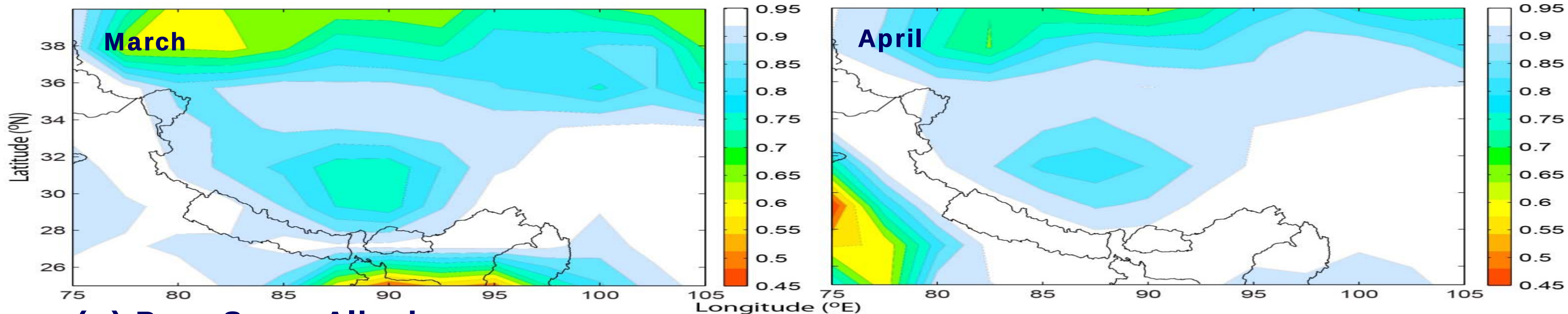


BC concentrations (ppm) simulated from a GEOS-Chem over the Tibetan Plateau in 2006

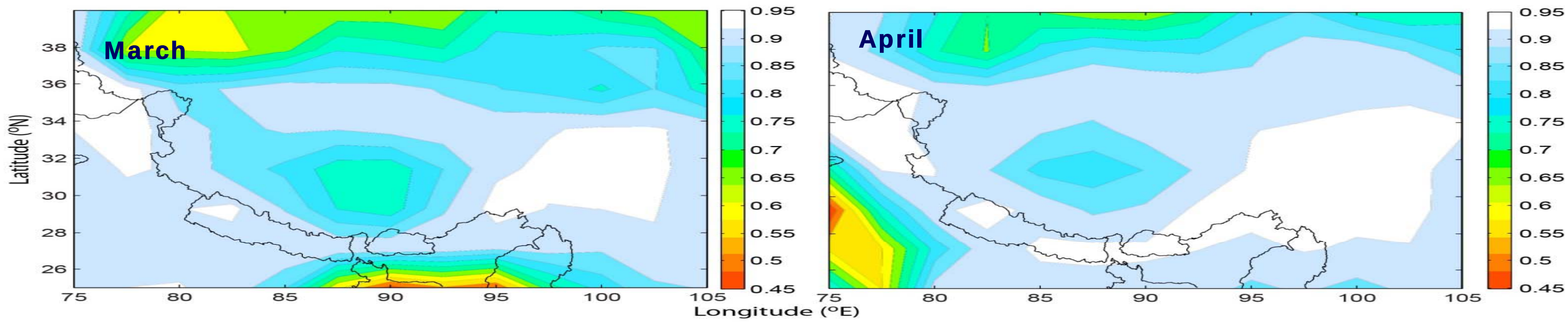


SWE ($Kg/m^2/d$) simulated from a GEOS-Chem over the Tibetan Plateau in 2006

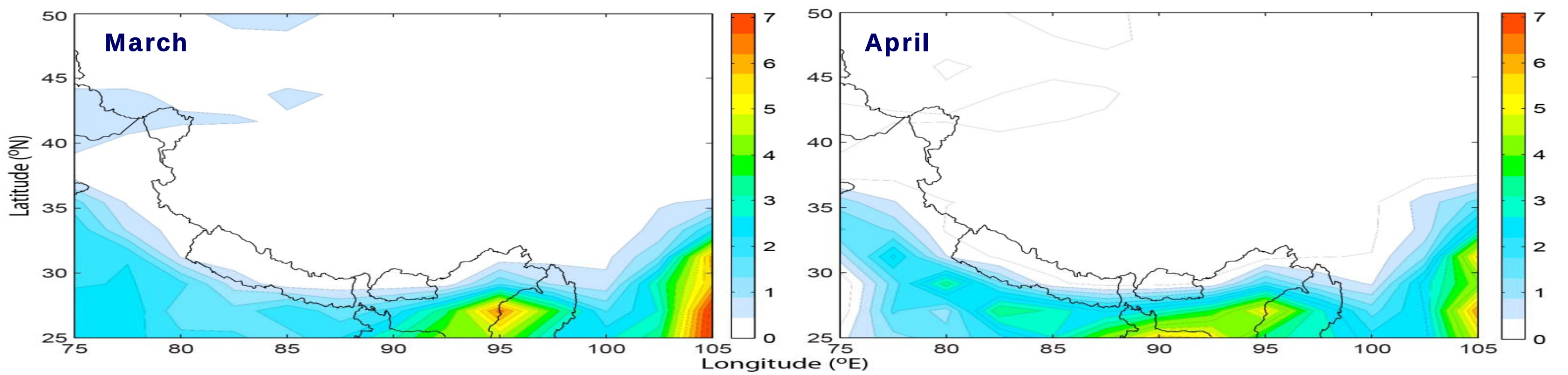
Computed Snow Albedo (Visible) Using the BC and SWE Simulated from GEOS-Chem Based on a Two-Layer Snow Model (Top: Fresh; Bottom: Old)



(a) Pure Snow Albedo

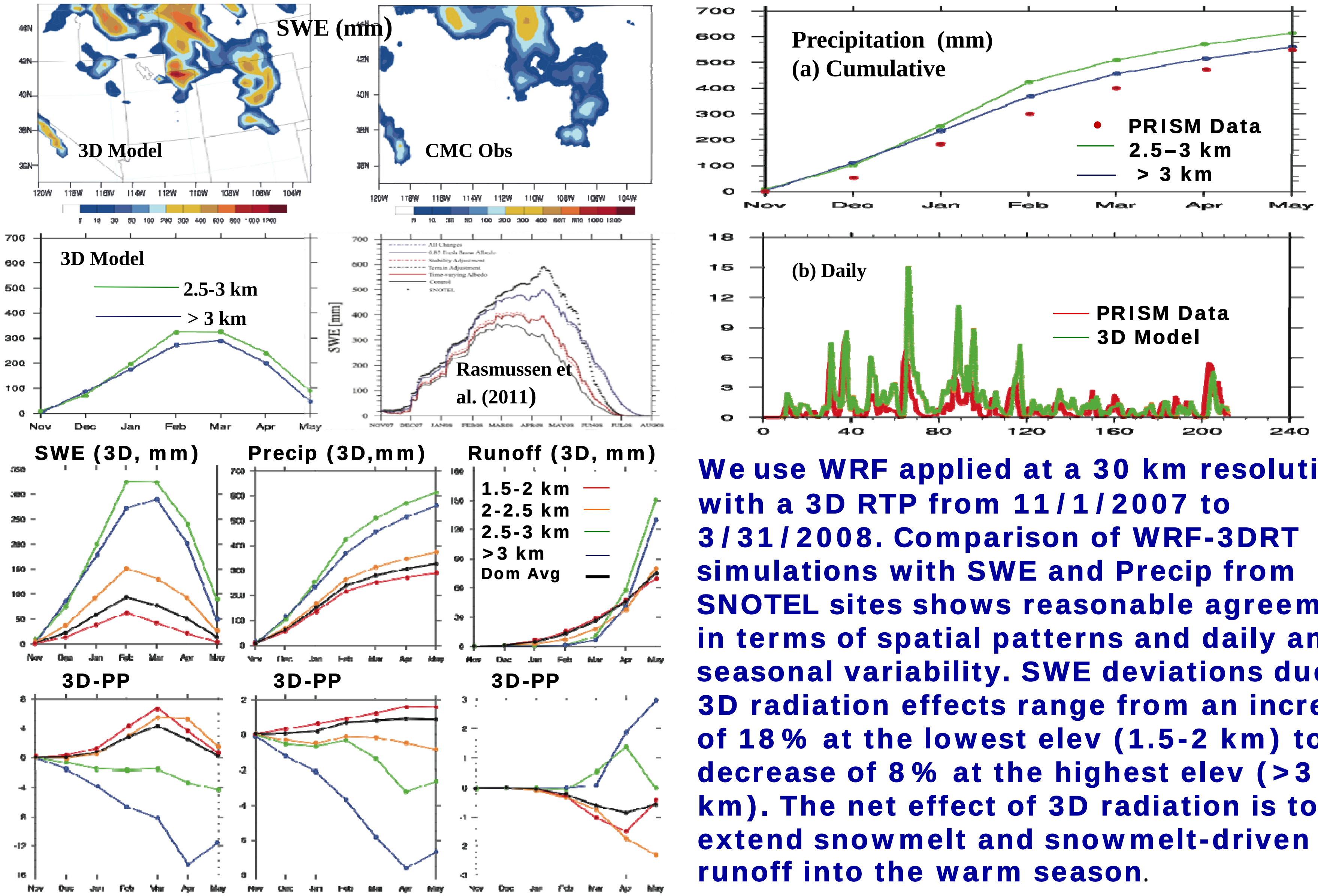


(b) Snow Albedo Contaminated by BC (External Mixing)



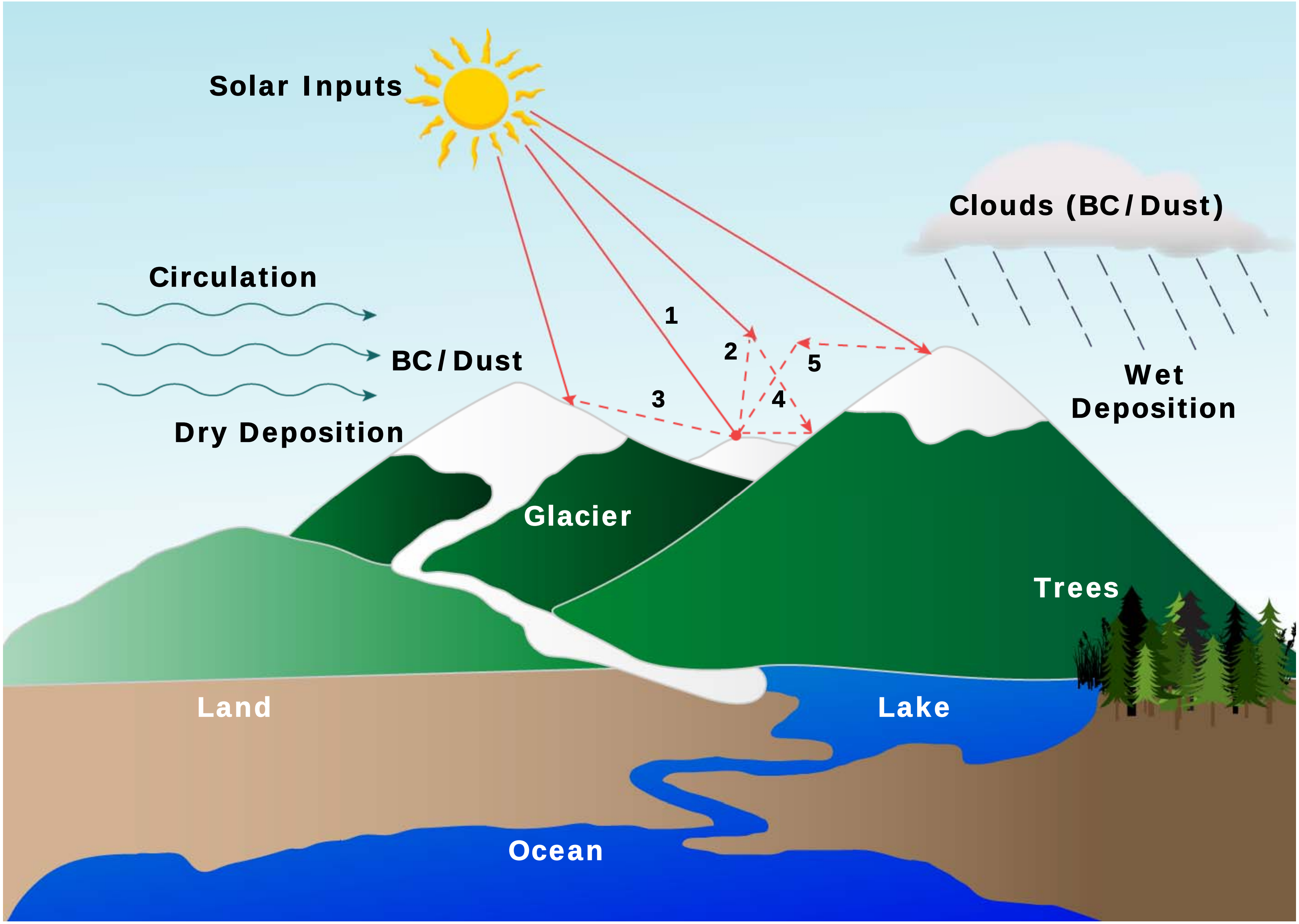
(c) Snow Albedo Reduction (%) produced by BC, up to 6% in the Southern Tibetan Plateau.

A WRF Simulation of the Impact of 3D Radiative Transfer on Surface Hydrology over the Rocky-Sierra Mountains (Liou et al. 2013, in review)

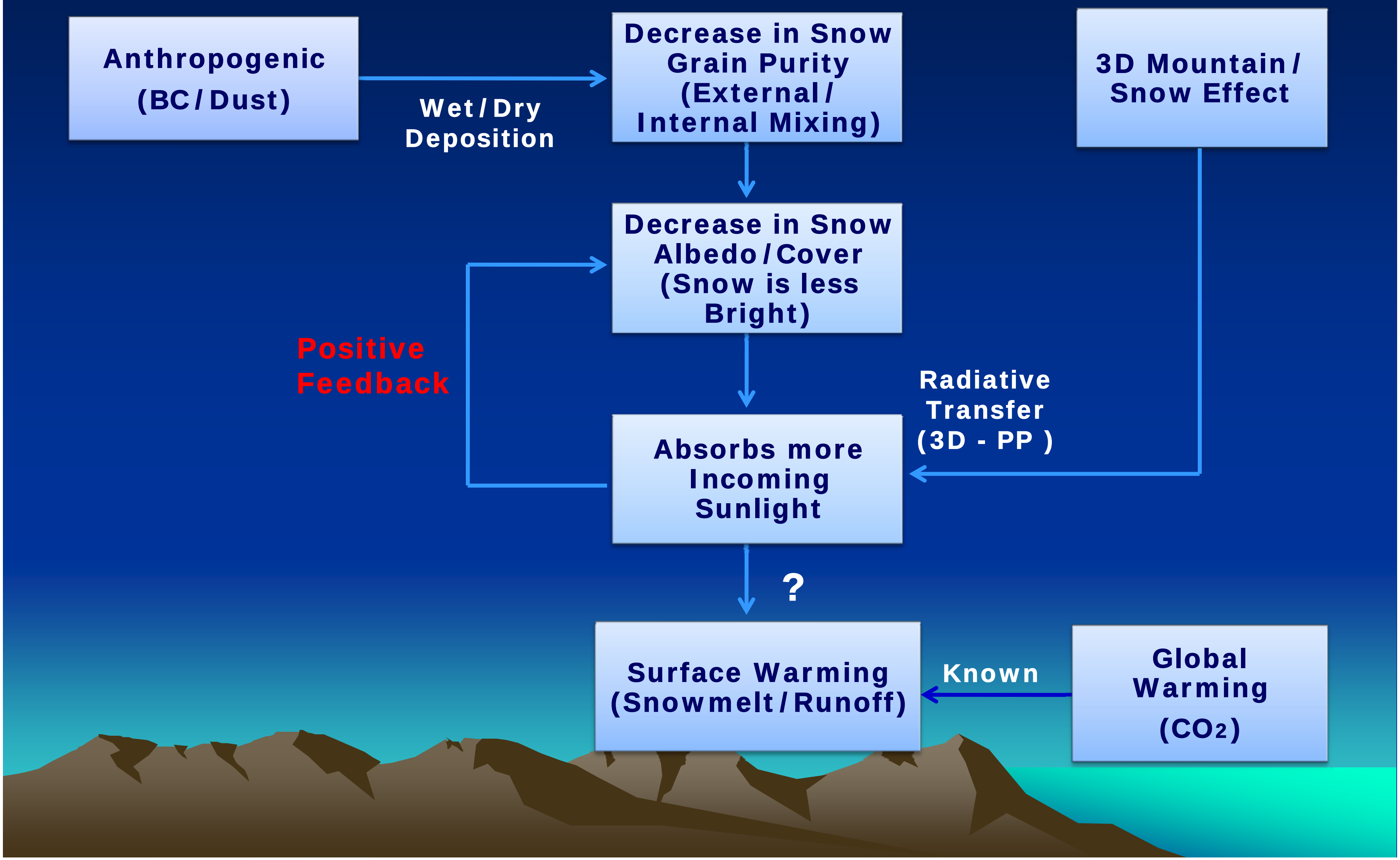


We use WRF applied at a 30 km resolution with a 3D RTP from 11/1/2007 to 3/31/2008. Comparison of WRF-3DRT simulations with SWE and Precip from SNOTEL sites shows reasonable agreement in terms of spatial patterns and daily and seasonal variability. SWE deviations due to 3D radiation effects range from an increase of 18% at the lowest elev (1.5-2 km) to a decrease of 8% at the highest elev (>3 km). The net effect of 3D radiation is to extend snowmelt and snowmelt-driven runoff into the warm season.

3D Mountain / Snow & Absorbing Aerosols: A Combined Regional Climate System



An Illustration of Mountain / Snow-Albedo Feedback due to Absorbing Aerosols



Summary Remarks

- Evidence of Mountain Snowmelt and Albedo Reduction on Century, Decadal, and Seasonal Time Scales: Snapshots and Satellite Data.
- Postulation and Illustration of Mountain Snow Albedo Reduction Associated with Black Carbon (Soot) Based on a GEOS-Chem Modeling Study over the Southern Tibetan Plateau.
- Development of a Two-Layer Snow Grain Model for interactions with Soot Particles: External Mixing (Complete) and Multiple Internal Mixing (in Progress).
- Illustration of 3D Radiative Transfer Incorporation in a WRF Simulation: The Shading and Elevation Effects on SWE and Runoff.
- Illustration of the Concept of Aerosol/Mountain (3D)-Snow/Albedo Feedback as a Regional Climate System.

Black Carbon in 3D Mountain/Snow, Radiative Transfer, and Regional Climate Change

6th International Conference on Atmosphere, Ocean, and Climate Change, Hong Kong, August 19-21, 2013

Kuo-Nan Liou, University of California, Los Angeles, CA, USA

* Mr. Chairmen and distinguished colleagues, I am pleased to have the opportunity to present this talk on the occasion of the *6th International Conference on Atmosphere, Ocean, and Climate Change* sponsored by COAA. My talk will focus on the following subjects: (1) evidence of mountain snowmelt and albedo reduction in the context of regional climate change; (2) BC concentration over the Tibetan Plateau produced by GEOS-Chem simulations and radiative forcings in snow grains; (3) 3D mountain/snow & absorbing aerosols: A combined regional climate system using WRF as a testbed; and (4) the concept of aerosol/mountain-snow/albedo feedback. I would also like to acknowledge the contributions of a number of my colleagues who assisted me in the course of my research of these topics (Slide 1).

* For your enjoyment, I have selected a number of time-lapse images (Slides 2-5) to illustrate the retreat of mountain snow in a number of locations, including the Kyetrak and Rongbuk Glaciers in the Tibetan Plateau, China; the Pasterze and Rhone Glaciers in the European Alps; Mount Kilimanjaro in Tanzania, North Africa; the Qori Kalis Glacier in Peru, South America; and in the United States, the Grinnell Glacier of Glacier National Park and the South Cascade glacier of Washington State. The time span from these snapshots covers roughly about 100 years, which is referred to as century variation. It appears quite evident that the reduction of mountain snow fields over the globe must be related to global warming. However, I would submit that the addition of man-made absorbing aerosols since the onset of the Industrial Revolution must also play a substantial role in this reduction in a non-linear fashion.

* Slide 6: The global reduction of snow fields can also be seen from this Slide taken from IPCC (2007). Panel (a) illustrates the NH March-April snow covered area obtained from ground-based and NOAA satellite datasets. The smooth curve shows decadal variation. Panel (b) shows differences in the distribution of NH March-April average snow cover between earlier (1967-1987) and later (1988-2004) portions of the satellite era. Yellow colors represent snow cover reduction. I have selected two specific regions: the

Tibetan Plateau and the Sierra-Nevada Mountains, for this presentation. The Tibetan Plateau, with its mighty mountains, is considered to be the third pole of the Earth because of the vast amount of snow cover. The Sierra Nevada Mountains have substantial snow events in the winter and spring, representing important water resources not only for northern but also southern California. In fact, about 45% of S.C. water resources come from the Sierras.

* Slide 7 shows the monthly averages of snow albedo for pixels with 100% snow cover, and associated land surface temperatures and aerosol optical depths over the Southern Tibetan Plateau and the Sierras in March and April from 2000 to 2010 taken from the MODIS data products. Error bars indicate one standard deviation. Let me focus on the Southern Tibetan Plateau. The negative correlation between snow albedo and aerosol optical depth in this dataset is statistically significant. Seasonal variation of the snow albedo reduction from March to April is due in part to the presence of aerosols in association with BC deposition over Southern Tibet.

* Slide 8: For radiative forcing calculations, we need to know the size distribution, shape, and composition of BC, which is a solid form made of mostly pure carbon that absorbs solar radiation at all wavelengths. It is produced by incomplete combustion of fossil fuel and biomass burning. BC is generally coated by non-absorbing aerosols, a process known as internal mixing. BC is also referred to as soot, which is actually a complex light absorbing mixture of mostly BC and organic carbon (OC) that usually includes other inorganic materials such as metal and sulfate. The bottom left diagram shows normalized BC mass size distributions from the atmosphere (remote and urban) and from the five snow samples as a single average. The averaged radius of BC is on the order of 0.1 μm. BCs are fractal aggregates, which can contain numerous primary spheres. The numbers of 54, 284, and 600 are shown for light scattering and absorption calculations. With respect to the sources of BCs, I wanted to note that emissions from Asian countries, such as China and India, grew rapidly in the latter half of the 20th century, while North America and Europe dominated BC emissions in the early industrial era, as shown in the bottom right diagram.

* Slide 9: This slide displays the shape and size of snow grains. The left panel illustrates observed and modeled snow grains for fresh, aging, and old snow conditions with the inclusion of BC in a model based on stochastic processes. The shape of fresh snow spans from column, plate, bullet rosette to irregular, similar to ice particles in the

atmosphere, although they are much larger with a maximum dimension ranging from about 100 to more than 1000 μm. For old snow, we see smooth edges, and the grain shape can be modeled by ellipsoids with maximum dimensions on the order of more than 1000 μm. The figure shows the spectral snow albedo values calculated from the adding-doubling radiative transfer method for pure snow and 3 BC depositions of 0.1, 1, and 10 ppm under the condition of $\mu_0 = 0.5$ and semi-infinite optical depth. Above the 1.5 μm wavelength, the spectral albedo is close to zero due to substantial absorption by ice. This simple calculation illustrates that a 1 ppm BC externally mixed with pure snow would reduce the visible snow albedo by about 10%. We are in the midst of developing an internal mixing model on the basis of stochastic processes, which would make snow even darker.

* Slide 10: This slide shows a GEOS-Chem CTM driven by assimilated meteorology from GEOS-5/GMAO with a resolution of 2^ox2.5^o and 47 vertical layers, including improvements in dry and wet depositions and global anthropogenic emission inventories. The model simulations were carried out over the Tibetan Plateau region in March and April 2006. The top panel depicts BC concentrations simulated from the model. Relatively large BC concentrations are evident over the Southern Tibet and Himalyas regions. The other input to radiative forcing calculations is SWE, which is equivalent to precipitation obtained from the model, required for computing snow albedo.

* Slide 11: Here I have illustrated visible snow albedo computed from a 2 layer snow model (fresh snow at the top and old snow at the bottom) using the BC concentration and snow water equivalent simulated from GEOS-Chem. The top and middle panels are for pure snow and snow contaminated by BC, respectively. Differences between the two are shown in the bottom panel. The reduction in snow albedo is on the order of 1-6 % over the Southern Tibetan and Himalayan areas associated with deposition of BC in snow grains. The calculations are only for external mixing, but with the inclusion of internal mixing, we anticipate larger reduction in snow albedo. We also need to improve the resolution of the chemical transport model to highlight the impact of BC absorption in snow.

* Slide 12: A WRF Simulation of the Impact of 3D Radiative Transfer on Surface Hydrology over the Rocky-Sierra Mountains. This work has been conducted in conjunction with Ruby Leung at PNNL. We used WRF applied at a 30 km resolution with a 3D RTP

from 11/1/2007 to 3/31/2008. Comparison of WRF-3DRT simulations with SWE and Precipitation from SNOTEL sites shows reasonable agreement in terms of spatial patterns and daily and seasonal variability. SWE deviations due to 3D radiation effects range from an increase of 18% at the lowest elevation (1.5-2 km) to a decrease of 8% at the highest elevation (>3 km). The net effect of 3D radiation is to extend snowmelt and snowmelt-driven runoff into the warm season.

* Slide 13 illustrates my conceptual approach for regional climate modeling, which displays a graphic depiction of the effect of 3D mountain/snow and absorbing aerosols via dry and wet deposition with respect to the solar inputs as a combined regional climate system.

* Slide 14 demonstrates the essence of snow-albedo feedback, a powerful amplification process involving absorbing aerosols. Through the wet and/or direct dry deposition of absorbing aerosols, snow becomes less bright. As a consequence, it will absorb more incoming sunlight, leading to surface warming. This relationship between darker snow and greater sunlight absorption forms a powerful feedback loop that can significantly amplify the increase of surface temperature. In conjunction with this, we have witnessed powerful ice-albedo feedback in the Arctic and Antarctic regions. However, we need to quantify the surface warming produced by dry and wet depositions. Also, we need to develop a model to quantify the 3D mountain radiative effect on snow albedo with reference to the conventional PP radiation program.

* Slide 15 presents summary remarks. (1) I have illustrated some evidence of mountain snowmelt and albedo reduction on the century, decadal, and seasonal time scales on the basis of snapshots and satellite data; (2) I have postulated and shown mountain snow albedo reduction associated with black carbon (or soot) based on a GEOS-Chem modeling study over the Southern Tibetan Plateau. In connection with this, we have developed a two-layer snow grain model for interactions with soot particles: external mixing is complete, but multiple internal mixing is in progress; (3) We incorporated 3D radiative transfer in a WRF simulation to demonstrate the shading and elevation effects on SWE and Runoff; and finally (4) I have presented the concept of aerosol/mountain (3D)-snow/albedo feedback as a regional climate system, which could have a most powerful impact on regional surface temperature amplification and snowmelt.

* Thank you for your attention.