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, Z. Liu, Q. Li, R. Leung, P. Yang, and T. Fickle. Research work supported in part by NSF and DOE.

- Evidence of Mountain Snowmelt and Climate Change
- BC and Snow Cover Reduction in the Tibetan Plateau
- Some Evidence of Snow Albedo Reduction in the Sierras
- Radiative Forcing by BCs (Aggregates)
- 3D Mountain/Snow Effects on Surface Solar Fluxes
- The Concept of Aerosols/Mountain-Snow/Albedo Feedback
- Connection to WRF and the Community Land Model (CLM), and Summary

IRC Symposium, Berlin, Germany, August 9, 2012
Kyetrak Glacier, Tibet

1921 Photograph by E. O. Wheeler

2009 Photograph by D. Breashears

Rongbuk Glacier, Tibet

1921 Photograph by G. L. Mallory

2007 Photograph by D. Breashears
Mount Kilimanjaro, Tanzania

Qori Kalis Glacier, Peru (World Data center for Glaciology)
Strong Evidence for Global Warming; however, absorbing aerosols have also contributed to and amplified the retreat of glaciers.
(a) NH March-April average snow-covered area (Brown 2000) and NOAA satellite data set. The smooth curve shows decadal variations, and the shaded area shows the 5 to 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°C isotherms averaged for March and April 1967 to 2004 (after IPCC 2007).
Top: Black carbon concentration (ng/g) determined at the Zuoqiupu Glacier of the Tibetan Plateau from 1955 to 2005. Shown are annual and 5-year running mean results for non-monsoon, monsoon (lower due to high precipitation rate), and annual cases. The BC source is Asia, primarily the Indian subcontinent.

Middle: Surface air temperature anomaly in terms of annual and 5-year mean on the Tibetan Plateau relative to 1951-1980 mean, averaged over the area with altitude greater than 4,000 m above sea level.

Bottom: Annual snow accumulation on the Zuoqiupu Glacier (kg/m²/yr) from 1956 to 2006 along with 5-year running mean results, revealing reduction since 1990 (after Xu et al. 2009).
Monthly averages of snow albedo for pixels with 100% snow cover, land surface temperature, and aerosol optical depth over the Tibetan Plateau in March and April from 2000 to 2010 taken from the MODIS data products. Error bars indicate one standard deviation (paper in preparation).
Black carbon (BC, soot) aerosol concentration over Southeast Asia and India measured during the INDOEX experiment (March 14-21, 2001); (yellow = high, blue = low)

“2001 Perfect Dust Storm”

TOMS Aerosol Index - time series (after Tsay et al. 2008)
Aerosol optical depths determined from MODIS of NASA satellites for March and April 2000-2009, a 10 year period, illustrating the transport of absorbing aerosols from China and Southeast Asia across the Pacific to the United States (only 4 years are shown; courtesy of W. L. Lee, Academia Sinica).
Total aerosol optical depths for March and April 2006 simulated from a chemical transport model, illustrating the effects of absorbing aerosols generated in China on the west coast of the United States (courtesy of Q. Li, UCLA).
Northern California (local)

Southern California (local)
Sierra Nevada (America)
BC/Dust-Snow Impact on Regional Climate

Rocky (America)

Tibetan Plateau (China)

Alps (Europe)
Monthly averages of snow albedo for pixels with 100% snow cover, land surface temperature and aerosol optical depth over the Sierras in March and April from 2000 to 2009. Error bars indicate one standard deviation. A significant negative correlation between snow albedo and aerosol optical depth: $a = 0.56 - 0.038T - 0.026\tau$ (Lee and Liou 2012, Atmo. Env.).
Light Absorption & Scattering by BC/Dust

BC: Highly Absorbing
Dust: Absorbing & Scattering

Absorption: Transform to Heat
Scattering: Redirect the energy in different directions

Direct Radiative Forcing & Regional Climate

Absorption of Sunlight by BC/Dust

Atmospheric Heating

Vertical Temperature Profile

Regional Circulation

Solar Dimming at the Surface

Regional Surface Temperature & Precipitation
Simulated annual mean differences in (a) precipitation (%) and (c) surface air temperature (K) between Experiments B and A, along with the observed (b) precipitation (%) and (d) surface air temperature anomalies (K) over China in the 1990s. Exp A consists of 10% BC and 90% non-absorbing aerosols ($\omega = 0.92$). Exp B consists of 15% BC and 85% of non-absorbing aerosols ($\omega = 0.88$). The sea surface temperature, greenhouse gases, and other forcings are fixed in these two experiments so that aerosols are the only forcings in 5-year simulations (after Gu, Liou et al. 2010).
Light Scattering and Absorption by Dust and Black Carbon: Fundamental to the Understanding of Aerosol Climate Forcings

**Dust**

**Black Carbon**

- Internal mixing with layered structure:
  - Non-absorbing shell (organics, sulfates, etc.)
  - Black carbon core

- External mixing:
  - Black carbon
  - Non-absorbing particles

- Internal mixing in soot aggregates:
  - Open soot cluster
  - Closed soot cluster

- 200 nm scale

- Non-absorbing - Black Carbon
Construction of aggregates based on stochastic processes using homogeneous and shell spheres (smooth and irregular) as building blocks (Liou et al. 2010, 2011): closed and open cells, and observed soot.

Light absorption and scattering by small irregular particles based on the geometric-optics and surface-wave approach verified by comparison with existing results for columns and plates (Liou, Takano and Yang 2011).
Reflection (Albedo), absorption, and transmission for a soot layer as a function of aerosol mass path (AMP) on a black surface using a solar zenith angle of 60°. The 0.03 μm radius is the mean observed equivalent radius for BC aerosols. Note: substantial differences between the two BC shapes using diffusion limited aggregate and equal-mass (and equal-volume) spheres.

Optical depth $\tau$ can be obtained by $\tau = a_e \text{AMP}$, where $a_e$ is the specific extinction coefficient ($\text{m}^2/\text{g}$). The adding-doubling method was used for radiative transfer calculations.
Visible single-scattering co-albedo (the ratio of absorption and extinction coefficients) and snow albedo as a function of soot and dust equivalent radii for a snow grain of 50 μm in equivalent radius for pure and contaminated conditions (μ0 = 0.5 and optically semi-infinite snow layer). Large differences in snow albedo are shown with external and internal mixing cases. A 1 μm soot particle internally mixed with snow grains could effectively reduce snow albedo as much as 5-10% (Liou et al. 2011).
The effect of internal and external mixings in snow grains and spherical assumption on the asymmetry factor (upper panel), single-scattering co-albedo (middle panel) and snow albedo \( (\mu_0 = 0.5, \text{optically semi-infinite layer; lower panel}) \) covering 0.2 to 5\( \mu \)m solar spectrum. The snow grain size is 100 \( \mu \)m with 3 BC sizes of 0.1, 1, and 10 \( \mu \)m. (a) Sphere (asymmetry factor), and (b) and (c) internal and external mixing (single scattering albedo). For application to CLM-WRF, total BC deposition can be converted to a mean BC size.
Solar radiation:
- Direct: solar incident angle $\theta_i$
- Diffuse: sky view factor $V_d$
- Direct reflected: terrain configuration factor $C_t$
- Diffuse reflected: terrain configuration factor $C_t$
- Coupled: terrain configuration factor $C_t$

Thermal infrared radiation:
- Emitted in the atmosphere or from the surface
- Starting location sampled from a set of pre-divided cubic cells
  Random direction and isotropic emission (emissivity & temperature)
Comparison of the deviations of the five flux components computed from Monte Carlo simulations (real values) and multiple regression equations (predicted values). The upper panel is for direct (left) and diffuse (right) fluxes. The middle panel is for direct-reflected (left) and diffuse-reflected (right) fluxes. The lower panel shows the coupled flux with a surface albedo of 0.1 (left) and 0.7 (right). The most important component is direct flux (~ 700 W/m$^2$), followed by direct-reflected flux (Lee et al. 2011).

We have derived 5 universal regression equations for flux deviations which have the following general form:

$$ F^*_i = a_i + \sum b_{ij} y_j, \quad i = \text{dir, dif, dir-ref, dif-ref, and coup}, $$

where $a_i$ is the intercept, $y_j$ is a specific variable, and $b_{ij}$ are regression coefficients. For example, for the deviation of direct flux, we have $F^*_{\text{dir}} = a_1 + b_{11} y_1 + b_{12} y_2$, where $y_1$ is the mean cosine of the solar zenith angle and $y_2$ is the mean sky view factor. This parameterization is applicable to clear as well as cloudy conditions using cloud optical depth as a scaling factor.
Simulating 3D Radiative Transfer Effects Over the Sierra Nevada Mountains Using WRF: HYDRO 1km Geographic Data

Elevation (m)  Slope (degree)
Differences in sensible and latent heat fluxes and surface temperature at 9 AM local time, March 29, 2007 in WRF simulations associated with the production of solar flux differences (3D-PP).

<table>
<thead>
<tr>
<th>Sensible Heat Flux (W/m²)</th>
<th>Latent Heat Flux (W/m²)</th>
<th>Surface Temperature (°C)</th>
</tr>
</thead>
</table>

Connection to Surface Energy Balance Equation
(Community Land Model, CLM <-> WRF)

Basic Equation

\[
(\bar{S}_g + \bar{S}_v) + L_{\text{atm}} \downarrow - L \uparrow - (H_v + H_g) - (\lambda_{\text{vap}} E_v + \lambda E_g) = G
\]

- \( G \) = Ground Heat Flux \( (\equiv \partial T_s / \partial t) \)
- \( (\bar{S}_g + \bar{S}_v) \) = Absorbed Solar Flux \( (v = \text{vegetation}, \ g = \text{ground}) \): 3D Effect
- \( L_{\text{atm}} \downarrow \) = Incident Longwave Flux
- \( L \uparrow \) = Emitted Longwave Flux
- \( (H_g + H_v) \) = Sensible Heat Flux
- \( (\lambda_{\text{vap}} E_v + \lambda E_g) \) = Latent Heat Flux \( (\lambda = \text{certain coefficient}) \)

3D Mountain Effects

- \( S_o(3D, \alpha)[1 - \alpha(\text{snow})] \); \( S_o \) = Incident Solar Flux, \( \alpha \) = Snow Albedo
- Solar Direct & Diffuse Beam (Visible & Near-IR): 3D Monte Carlo and Plane-Parallel Radiation Parameterizations

External & Internal Mixing of BC in Snow Grains

- \( \alpha(\text{Grain Size, BC}) \) = Snow Albedo: Optical Depth, Single-Scattering Albedo & Asymmetry Factor
Anthropogenic (BC/Dust) → Wet/Dry Deposition → Decrease in Snow Grain Purity (External/Internal Mixing) → Decrease in Snow Albedo/Cover (Snow is less Bright) → Absorbs more Incoming Sunlight → Surface Warming → Global Warming (CO$_2$) → Known

Mountain Effect → 3D Radiative Transfer → ? → Positive Feedback
### Human and Natural Drivers of Climate Change

#### Radiative Forcing Components

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>RF values (W m(^{-2}))</th>
<th>Spatial scale</th>
<th>LOSU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-lived greenhouse gases</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO(_2)</td>
<td>1.66 [1.49 to 1.83]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>N(_2)O</td>
<td>0.48 [0.43 to 0.53]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>0.16 [0.14 to 0.18]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Halocarbons</td>
<td>0.34 [0.31 to 0.37]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Ozone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stratospheric</td>
<td>-0.05 [-0.15 to 0.05]</td>
<td>Continental to global</td>
<td>Med</td>
</tr>
<tr>
<td>Tropospheric</td>
<td>0.35 [0.25 to 0.65]</td>
<td>Continental to global</td>
<td>Med</td>
</tr>
<tr>
<td>Stratospheric water vapour from CH(_4)</td>
<td>0.07 [0.02 to 0.12]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>Surface albedo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land use</td>
<td>-0.2 [-0.4 to 0.0]</td>
<td>Local to continental</td>
<td>Med</td>
</tr>
<tr>
<td>Black carbon on snow</td>
<td>0.1 [0.0 to 0.2]</td>
<td>Local to continental</td>
<td>Med</td>
</tr>
<tr>
<td>Total Aerosol</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct effect</td>
<td>-0.5 [-0.9 to -0.1]</td>
<td>Continental to global</td>
<td>Med</td>
</tr>
<tr>
<td>Cloud albedo effect</td>
<td>-0.7 [-1.8 to -0.3]</td>
<td>Continental to global</td>
<td>Low</td>
</tr>
<tr>
<td>Linear contrails</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar irradiance</td>
<td>0.12 [0.06 to 0.30]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>Total net anthropogenic</td>
<td>1.6 [0.6 to 2.4]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

©IPCC 2007: WG1-AR4
3D Mountain/Snow & Absorbing Aerosols: A Combined Regional Climate System
Two radiative transfer fundamentals, namely 3D radiative transfer over mountains/snow and light absorption of BC (soot) and dust, are critically important to understanding regional climate and climate change.

Mountain snow albedo reduction appears to be linked to absorbing aerosols based on satellite data analysis over the Tibetan Plateau and the Sierras.

Developed a 3D radiative transfer parameterization for surface solar fluxes in terms of deviations from PP results and successfully incorporated in WRF and CLM.

Innovated a light absorption and scattering approach based on the principles of stochastic construction and geometric optics-surface wave integration for aggregates. Demonstrated the importance of internal mixing of BC in snow grains.

On the concept of aerosols/mountain-snow/albedo feedback as a regional Earth system.