Radiative Transfer and Regional Climate Change

Kuo-Nan Liou

Joint Institute for Regional Earth System Science and Engineering, and
Department of Atmospheric and Oceanic Sciences
University of California, Los Angeles, CA 90095, USA

Abstract. We first address the importance of three-dimensional (3D) radiative transfer over mountains/snow in the regional context along with its parameterization in terms of deviations from the conventional plane-parallel model commonly used in climate models. This is followed by a discussion on the development of a new approach for light absorption and scattering by black carbon (BC) and snow grains in which the aggregation shape and internal mixing property of BC and the morphology of snow grains are accounted for by using a combination of the geometric-optics and surface-wave approach. It is submitted that in addition to surface temperature increase produced by global warming, understanding of the reduction of snow albedo over intense topography must take into consideration its 3D and inhomogeneous nature and the associated deposition of BC into snow layers as a coupled regional climate system.

Keywords: 3D radiative transfer, Light absorption by black carbon, Regional climate change.
PACS: 92.70.Kb, 92.60.Vb, 92.60.Mt

INTRODUCTION

This paper is an adaptation of a lecture given by the author on the occasion of the International Radiation Commission's quadrennial Gold Medal Award.

Radiative transfer is an interdisciplinary subject and was initially studied principally by astrophysicists and later by planetary scientists and meteorologists for atmospheric applications. This field has also been an important research area in applied optics and mechanical and nuclear engineering. Because the impact of radiative transfer in the atmosphere on dynamic processes takes time to be fully effectual, it has been generally assumed that its significance is more on climate, a time scale of perhaps more than a month, rather than weather forecast involving a few days.

My presentation explored two unsolved radiative transfer issues that are specifically critical to regional climate and climate change: first, the issue of 3D radiative transfer in mountains/snow and second, snow albedo modification by mixing with absorbing BC (or soot) aerosols. In the following, I highlight the importance of BC in the reduction of snow albedo vis-a-vis aerosols-mountain snow-albedo feedback that would have an irreversible impact on climate and climate change within the regional context.

The retreat of mountain snow has been well-documented in a number of locations, including the Kyetrak and Rongbuk Glaciers in Tibet, China; Mount Kilimanjaro in Tanzania; the Qori Kalis Glacier in Peru; and the Grinnell Glacier of Glacier National Park as well as the South Cascade glacier of Washington State in the United States. As an example, the left and center pictures in Fig. 1 are photographs taken of the Kyetrak Glacier in Tibet, by E. O. Wheeler in 1921 and D. Breashears in 2009, respectively, illustrating a substantial retreat of glacier over the last 80 years. 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 must also play a substantial role in this reduction in a non-linear fashion.

The global reduction of snow field has been reported in IPCC [1] based on decadal analysis of the Northern Hemisphere March-April snow covered area obtained from ground-based and NOAA satellite datasets. Significant differences in the distribution of average snow cover between earlier (1967-1987) and later (1988-2004) period portions of the satellite era are evident, particularly over the Tibetan Plateau and the Sierra Nevada Mountains. 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 southern California's water resources come from the Sierras.

With respect to the Tibetan Plateau, the BC concentration measured results at the Zuoqiupu Glacier from 1955-2005 have been analyzed for annual and 5-year running means for monsoon, non-monsoon, and annual cases [2]. The source of BC is primarily from the Indian subcontinent. Concurrent analysis of the corresponding surface air

Radiation Processes in the Atmosphere and Ocean (IRS2012)
AIP Conf. Proc. 1531, 35-38 (2013); doi: 10.1063/1.4804701

temperature and snow accumulation appears to demonstrate that the reduction in snow in that area is related not only to surface air temperature, but also to an increase in BC. The right picture in Fig. 1 depicts the theme of this presentation, namely the transfer of solar radiation in 3D and inhomogeneous mountain and snow surfaces and wet and dry deposition of black carbon and dust particles in snow layer. Both radiative processes are closely associated with snow dynamics at mountain surfaces and the consequence of regional climate change.

FIGURE 1. The left and center pictures are photographs taken by E. O. Wheeler in 1921 and D. Breashears in 2009, respectively, of the Kyetrak Glacier in Tibet, illustrating a substantial retreat of glacier over the last 80 years. The picture on the right depicts the theme of this presentation, namely the transfer of solar radiation in 3D and inhomogeneous mountain and snow surfaces and wet and dry deposition of black carbon and dust particles in snow layer.

3D RADIATIVE TRANSFER OVER MOUNTAINS/SNOW AND ITS PARAMETERIZATION

It appears unlikely that analytical solutions, such as 2-stream, Eddington, and 4-stream approximations for radiative transfer, can be derived for intricate mountains/snow fields. The only solution appears to be by means of the Monte Carlo simulation, which can be applied to any geometry; however, formidable computational efforts are required to achieve reliable accuracy. We have made substantial advances in modeling the transfer of solar and thermal IR radiation involving intense topography following Monte Carlo photon tracing [3-5]. The transfer of solar radiation is composed of five components- direct, diffuse, direct-reflected, diffuse-reflected, and coupled fluxes - related to the solar incident angle, elevation, sky view factor, and terrain configuration factor (left panel, Fig. 2).

We have developed an innovative parameterization approach for tedious Monte Carlo calculations involving 3D and conventional plane-parallel (PP) spectral radiative transfer [4]. This approach uses differences between the two for the five solar flux components and carries out multiple regression analysis among the differences (or deviations) and a number of key topographic parameters mentioned above. Since all climate models have surface solar flux results computed from a plane-parallel radiative transfer model, we can then add the deviation to these results to account for 3D mountain effects.

In the center graphs of Fig. 2, we compare the deviations (from PP results) of the five flux components computed from 3D Monte Carlo simulations (real values) and multiple regression equations (predicted values) using a domain of 10 km. The upper panel displays direct and diffuse fluxes. The middle panel is for direct-reflected and diffuse-reflected fluxes. The lower panel shows the coupled flux with a surface albedo of 0.1 and 0.7. The most important component is direct flux (~ 700 W/m^2), followed by direct-reflected flux.

Five universal regression equations for flux deviations have been derived which have the following general form: $F^*_i = a_i + \Sigma_j b_{ij} y_j$, i = 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, F^*_{dir}, we have $a_1 + b_{11} y_1 + b_{12} y_2$, where y_1 is the mean cosine of the solar zenith angle, y_2 is the mean sky view factor, and b_{11} and b_{12} are regression coefficients. This parameterization is applicable to clear as well as cloudy conditions using cloud optical depth as a scaling factor. The flux deviation results can be directly added to the existing surface radiative flux values determined from a land-surface model to account for 3D mountain effects, as pointed out previously.

We have successfully incorporated the preceding 3D radiative transfer parameterization in the Weather Research and Forecasting (WRF) Model using the Sierra Nevada Mountains in the Western United States as a testbed [6]. The domain covered a horizontal resolution of 30 km and 26 vertical levels employing the input parameters from the NCEP Final Analysis and a 2-day model integration was performed in March 2007. Substantial solar flux deviations (3D-PP) are obtained for 9AM, noon, and 3PM local times, the patterns of which are dependent on the sun's position with respect to mountain orientation. Increases and decreases in surface solar fluxes will affect surface processes and induced changes in sensible heat fluxes, which range from about -20 to +20 W/m^2. A similar range is also seen for latent heat fluxes. As a result, the surface temperature simulated in the 3D run increases on the sunny side, but decreases on the shaded side in comparison to the control run using a PP radiative transfer program (right panel, Fig. 2). Recent results obtained from climate simulations using the Community Land Model (CLM) illustrate similar patterns for surface heat components. We anticipate that 3D radiative transfer effects would enhance significant diurnal surface temperature variation and induce substantial small-scale dynamic variability, particularly in high-resolution climate model simulations for the physical understanding of surface processes.

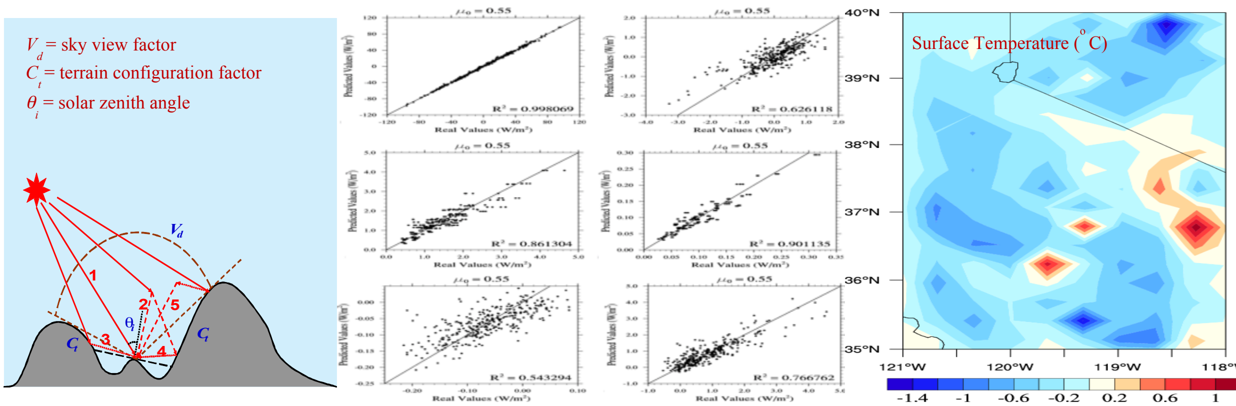

FIGURE 2. Left panel: The transfer of solar radiation is composed of five components- direct (1), diffuse (2), direct-reflected (3), diffuse-reflected (4), and coupled fluxes (5) - related to the solar incident angle, elevation, sky view factor, and terrain configuration factor. Center panel: A comparison of the deviations (from PP results) of the five flux components computed from 3D Monte Carlo simulations and multiple regression equations using a domain of 10 km. Right panel: Surface temperature distribution differences corresponding to 3D and PP cases in WRF 2-day simulations (see text for further discussion).

LIGHT ABSORPTION BY BLACK CARBON AND SNOW GRAINS

BC particles, which have highly complex and often inhomogeneous morphologies, are produced by incomplete combustion and composed of mostly pure carbon that strongly absorbs sunlight. The direct radiative forcing of BC is determined by the physical connection of its absorption to its vertical temperature profile and the consequence of regional circulation, leading to regional surface temperature and precipitation perturbations. Recent investigations reveal that the magnitude of the direct forcing due to BC may be the second most important component of global warming after carbon dioxide. Also, BC, acting as condensation and/or ice nuclei, can inhibit cloud formation.

The strength of BC absorption is dependent on its refractive index, shape, and size distribution; it also depends on the mixing state - whether it is internally or externally mixed with other nonabsorbing materials. The identical amount of BC under different types of mixing can result in substantially different absorption properties. BCs are byproducts of solid, liquid, or vapor combustions, generated directly through the aggregation of molecules formed in combustion processes from coal, biomass burning, and biofuel. In view of the above, the aggregation shape and mixing state are critically important in determining BC's single-scattering properties and radiative forcing in the atmosphere.

To have a fundamental understanding of the radiative properties of BC, we must consider its basic geometric structure, size, composition, and optical properties. We have recently developed a new theoretical approach, which combines a stochastic process to build aggregates, followed by geometric photon tracing including reflection/refraction, diffraction, and surface waves. The building blocks can be homogeneous or coated spheres with smooth or rough surfaces [7, 8]. We show an example of the stochastic process to construct aggregates that resemble their observed shape in the air (left panel, Fig. 3). The light absorption and scattering program by small irregular particles based on the geometric-optics and surface-wave approach has been verified by comparison with existing results for columns and plates.

In the center panel of Fig. 3, we show substantial differences between realistic aggregate shapes and commonly assumed spheres in terms of reflection, absorption, and transmission for typical BC radii of 0.03 and 0.07 μm as a function of aerosol mass path. Because of their irregular shapes, the optical depth can be determined from mass extinction coefficient and aerosol mass path. Aggregates reflect and absorb more light than their spherical counterparts; therefore, spheres are not a good approximation for BC in radiative transfer calculations.

The right panel of Fig. 3 illustrates the importance of the contamination of snow grains by BC/dust. Internal mixing produces much greater absorption compared to its external counterpart, in terms of a larger single-scattering co-albedo. The subsequent radiative transfer calculations illustrate reduction of snow albedo associated with the contamination of BC and dust particles, depending on their size. Due to its larger absorption, BC has a more substantial impact than dust particles do on the reduction of snow albedo. A 1-μm sized soot particle internally mixed with snow grains could effectively reduce snow albedo by as much as 5-10 %. We are in the process of developing parameterization of the spectral extinction coefficient, single-scattering albedo, asymmetry factor for snow grains externally and internally mixed with a number of BC sizes based on deposition rates for incorporation into a surface snow model.

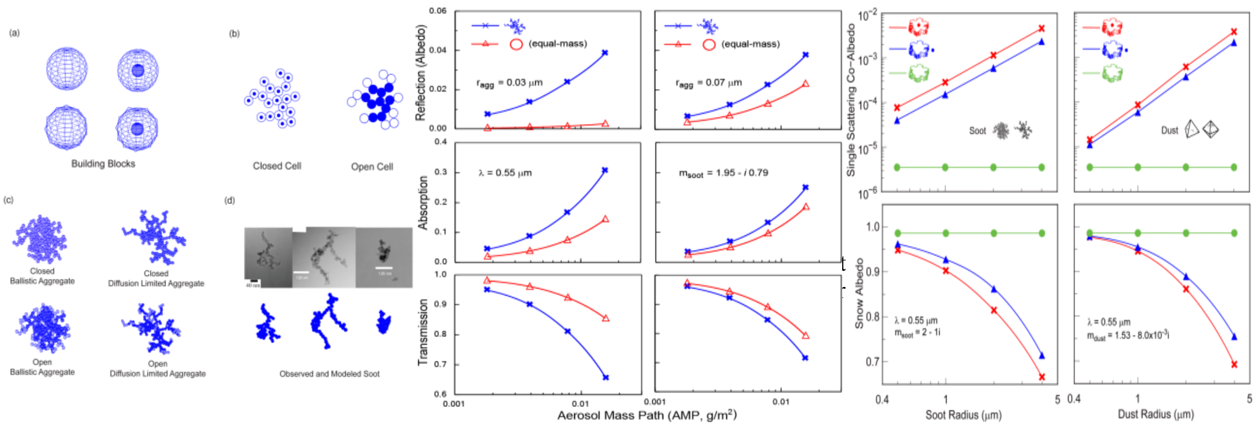

FIGURE 3. Left panel: (a) basic building blocks for aggregates, including homogeneous and shell-core spheres with smooth and/or rough surfaces; (b) open- and closed-cell definitions; (c) ballistic and diffusion-limited aggregates constructed by means of stochastic procedures; and (d) observed BC particles in the air and computer generated models. Center panel: Reflection, absorption, and transmission for typical BC sizes of 0.03 and 0.07 μm as a function of aerosol mass path related to optical depth and mass extinction coefficient. Aggregates reflect and absorb more light than their spherical counterpart. Left panel: Single-scattering co-albedo and snow albedo as a function of soot/dust radius internally and externally mixed with a snowflake of 50 μm. Results for pure snow are also displayed for comparison purposes.

SUMMARY REMARKS

We have illustrated the importance of 3D radiative transfer over mountains/snow in the regional context as well as its parameterization in terms of deviations from the conventional PP model commonly used in climate models. A new approach based on a combination of the geometric-optics and surface-wave approach for light absorption and scattering calculations of BC and snow grains has subsequently been presented in which the aggregation shape and internal mixing property of BC, as well as the morphology of snow grains, are accounted for. Finally, it is pointed out that understanding of the reduction of snow albedo over intense topography must consider its 3D and inhomogeneous nature and the associated deposition of BC into snow layers as a coupled regional climate system.

The research work contained in this paper has been supported in part by DOE Grant SC0006742 and NSF Grant AGS-0946315. I thank Yoshi Takano and Tara Fickle for their assistance in the preparation of this paper.

REFERENCES

1. Intergovernmental Panel on Climate Change, *Climate Change 2007*, edited by S. Solomon et al., Cambridge UK, 2007.
2. B. Xu et al., *Proc. Natl. Acad. Sci.* **106**, 22114-22118 (2009).
3. K. N. Liou, W. L. Lee and A. Hall, *Geophys. Res. Lett.* **34**, doi:10:029/2007GL031762 (2007).
4. W. L. Lee, K. N. Liou and A. Hall, *J. Geophys. Res.* **116**, doi:10.1029/2010JD014722 (2011).
5. W. L. Lee, K. N. Liou and C. Wang, *Theor. Appl. Climatol*. **109**, doi: 10.1007/s00704-012-0767-7 (2012).
6. Y. Gu, K. N. Liou, W. L. Lee and L. R. Leung, *Atmos. Chem. Phys.* **12**, 9968-9976 (2012).
7. K. N. Liou, Y. Takano and P. Yang, *J. Quant. Spectrosc. Radiat. Transf.* **111**, 1980-1989 (2010).
8. K. N. Liou, Y. Takano and P. Yang, *J. Quant. Spectrosc. Radiat. Transf.* **112**, 1581-1594 (2011).