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Project Title: "Collaborative Project: 3D Radiative Transfer Parameterization Over Mountains/Snow for High-Resolution Climate Models: Fast physics and Applications"

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Principle Investigator: Kuo-Nan Liou, Distinguished Professor and Director
Joint Institute for Regional Earth System Science and Engineering (JIFRESSE)
607 Charles E Young Drive East, 4242 Young Hall
University of California, Los Angeles, California 90095-7228
Tel: (310) 794-9832; Fax: (310) 794-9796
E-mail: knliou@atmos.ucla.edu

Under the support of the aforementioned DOE Grant, we have made two fundamental contributions to atmospheric and climate sciences: (1) Develop an efficient 3-D radiative transfer parameterization for application to intense and intricate inhomogeneous mountain/snow regions. (2) Innovate a stochastic parameterization for light absorption by internally mixed black carbon and dust particles in snow grains for understanding and physical insight into snow albedo reduction in climate models.

(1) With reference to item (1), we have divided solar fluxes reaching mountain surfaces into five components: direct and diffuse fluxes, direct- and diffuse-reflected fluxes, and coupled mountain-mountain flux. "Exact" 3D Monte Carlo photon tracing computations can then be performed for these solar flux components to compare with those calculated from the conventional plane-parallel (PP) radiative transfer program readily available in climate models. Subsequently, Parameterizations of the deviations of 3D from PP results for five flux components are carried out by means of the multiple linear regression analysis associated with topographic information, including elevation, solar incident angle, sky view factor, and terrain configuration factor (Lee et al. 2011). We have derived five regression equations with high statistical correlations for flux deviations and successfully incorporated this efficient parameterization into the Weather Research Forecasting (WRF) model, which was used as the testbed in connection with the Fu-Liou-Gu PP radiation scheme that has been included in the WRF physics package.

(a) First, we investigated 3D mountain/snow effect on solar flux distribution and their impact on surface hydrology over the Western United States, specifically the Rocky Mountains and Sierra Nevada using the WRF applied at a 30 km grid resolution. Over the Sierra-Nevada, we show that the 3D effect could produce up to −50 to + 50 Wm^{-2} deviations in surface solar fluxes over mountain areas, resulting in a temperature increase of up to 1°C on the sunny side. Upward surface sensible and latent heat fluxes are modulated accordingly to compensate for the change in surface solar fluxes. Snow water equivalent (SWE) and surface albedo both show decreases on the sunny side of the mountains, indicating more snowmelt and reduced snow albedo associated with stronger solar insolation induced by the mountain effect. Soil moisture increases on the sunny side of the mountains due to enhanced snowmelt, while decreases on the shaded side. Substantial differences are found in the morning hours from 8–10 a.m. and in the afternoon around 3–5 p.m., while differences around noon and in the early morning and late afternoon are comparatively smaller. Variation in the surface energy balance can also affect atmospheric processes, such as cloud fields, through the modulation of vertical thermal structure. Negative changes of up to −40 gm^{-2} are found in the cloud water path associated with reductions in the surface insolation over the cloud region. Changes in sensible and latent heat fluxes and surface skin temperature follow the solar insolation pattern. Differences in the domain-averaged diurnal variation over the Sierras show that the mountain area receives more solar insolation during early morning and late afternoon, resulting in enhanced upward sensible heat and latent heat fluxes from the surface and a corresponding increase in surface skin temperature (Gu et al., 2012).

(b) Second, we investigated the impact of 3D mountains/snow effects during seasonal transition covering a time period from 1 November 2007 to 31 May 2008, during which abundant snowfall occurred. A comparison of the WRF/3D radiative transfer simulation with the observed SWE and precipitation from Snowpack Telemetry (SNOTEL) sites shows reasonable agreement in terms of spatial patterns and daily and seasonal variability, although the simulation generally has a positive precipitation bias. We show that 3D mountain features have a profound impact on the diurnal and monthly variation of surface radiative and heat fluxes, and the consequent elevation dependence of snowmelt and precipitation distributions. In particular, during winter months, large deviations (3D - PP) of the monthly mean surface solar flux are found in morning and afternoon hours due to shading effects for elevations below 2.5 km. During spring, positive deviations shift to the earlier morning. Over mountaintops higher than 3 km, positive deviations are found throughout the day, with the largest value of ~ 40–60 Wm^{-2} occurring at noon during the snowmelt season of April to May. The monthly SWE deviations averaged over the entire domain show an increase in lower elevations due to reduced snowmelt, which leads to a reduction in cumulative runoff. Over higher elevation areas, positive SWE deviations are found because of increased solar radiation available at the surface. Overall, this study shows that deviations of SWE due to 3D radiation effects range from an increase of 18% at the lowest elevation range (1.5–2 km) to a decrease of 8% at the highest elevation range (above 3 km). Since lower elevation areas occupy larger fractions of the land surface, the net effect of 3D radiative transfer is to extend snowmelt and snowmelt-driven runoff into the warm season. Because 60–90% of water resources originate from mountains worldwide, the aforementioned differences in simulated hydrology due solely to 3D interactions between solar radiation and mountains/snow merit further investigation in order to understand the implications of modeling mountain water resources and their vulnerability to climate change and air pollution (Liou et al., 2013).

(c) Third, we investigated the climatic impact of 3-D mountain/snow effects on solar flux distributions and surface hydrology using the global CCSM4 (CAM4/CLM4) with a 0.23° x 0.31° resolution for simulations over 6 years. In the 3D radiative transfer parameterization, we have updated surface topography data from a resolution of 1 km to 90 m to improve parameterization accuracy. In addition, we have also modified the upward-flux deviation (3D–PP) adjustment to ensure that the energy balance at the surface is conserved in global climate simulations based on 3D radiation parameterization. We show that deviations in the net surface fluxes are not only affected by 3D mountains but also influenced by feedbacks of cloud and snow in association with long-term simulations. Over the Western United States, specifically the Rocky and Sierra Nevada areas, deviations in sensible heat and surface temperature generally follow the patterns of net surface solar flux. The monthly SWE deviations show an increase in lower elevations due to reduced snowmelt, leading to a reduction in cumulative runoff. Over higher-elevation areas, negative SWE deviations are found because of the increased solar radiation available at the surface. The simulated precipitation increases for lower elevations, while it decreases for higher elevations, with a minimum in April. Liquid runoff significantly decreases at higher elevations after April due to reduced SWE and precipitation (Lee et al., 2015a). Moreover, using a 10-year climate run, we investigated the effect of the Tibetan Plateau's majestic 3D and inhomogeneous topographic features on cloudiness and large-scale dynamic features. We show that this effect appears to be substantial associated with interannual variability involving monsoon and subtropical high distributions (Lee et al., 2015b).

(2) With reference to item (2), we developed in our previous research a geometric-optics surface-wave approach (GOS) for the computation of light absorption and scattering by complex and inhomogeneous particles for application to aggregates and snow grains with external and internal mixing structures. We demonstrated that a small black (BC) particle on the order of 1 μm internally mixed with snow grains

could effectively reduce visible snow albedo by as much as 5–10% (Liou et al., 2011). Following this work and within the context of DOE support, we have made two key accomplishments below.

(a) First, we innovated a stochastic approach to model the positions of BC/dust internally mixed with two snow grain types: hexagonal plate/column and Koch snowflake. Subsequently, light absorption and scattering analysis can be followed by means of an improved GOS approach coupled with Monte Carlo photon tracing to determine BC/dust single-scattering properties. For a given shape (e.g., plate, Koch snowflake, spheroid, or sphere), the action of internal mixing absorbs substantially more light than external mixing. The snow grain shape effect on absorption is relatively small, but its effect on asymmetry factor is substantial. Due to a greater probability of intercepting photons, multiple inclusions of BC/dust exhibit a larger absorption than an equal-volume single inclusion. The spectral absorption (0.2–5 μm) for snow grains internally mixed with BC/dust is confined to wavelengths shorter than about 1.4 μm, beyond which ice absorption predominates. Based on the single-scattering properties determined from stochastic and light absorption parameterizations and using the adding/doubling method for spectral radiative transfer, we find that internal mixing reduces snow albedo substantially more than external mixing and that the snow grain shape plays a critical role in snow albedo calculations through its forward scattering strength. Also, multiple inclusion of BC/dust significantly reduces snow albedo as compared to an equal-volume single sphere. For application to land/snow models, we developed a two-layer spectral snow parameterization involving contaminated fresh snow on top of old snow for investigating and understanding the climatic impact of multiple BC/dust internal mixing associated with snow grain metamorphism, particularly over mountain/snow topography (Liou et al., 2014).

(b) Second, we studied and evaluated the snow albedo forcing and direct radiative forcing (DRF) of black BC over the Tibetan Plateau using a global chemical transport model in conjunction with a stochastic snow model and a radiative transfer model. The annual mean BC snow albedo forcing is 2.9 Wm^{-2} averaged over snow-covered plateau regions, which is a factor of 3 larger than the value over global land snowpack. BC-snow internal mixing increases the snow albedo forcing by 40–60% compared with external mixing, while coated BCs increases the forcing by 30–50% compared with uncoated BC aggregates. Intricate Koch snowflakes reduce the forcing by 20–40% relative to spherical snow grains. The annual BC DRF at the top of the atmosphere is 2.3 Wm^{-2} with uncertainties of 70–85% in the plateau after scaling the modeled BC absorption optical depth to Aerosol Robotic Network observations. Lastly, BC forcings over the Tibetan Plateau are attributed to BC emissions from surrounding regions (He et al., 2014).

Publications Acknowledging the DOE Grant Support

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