Parameterization of Solar Fluxes over Mountain Surfaces for Application to Climate Models

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1. Introduction

Surface fluxes over a complex terrain are strongly affected by variation in the elevation, slope, and albedo. However, these factors are generally neglected in most of the existing radiative transfer schemes which assume that the lower boundary is flat and homogeneous. As shown in Liou et al. (2007), the domain–averaged surface solar flux over a regional modeling scale comprising intense topography can deviate from the smoothed surface by 10–50 W/m^2. Thus, it is critically important to incorporate the inhomogeneous terrain effect on the evaluation of surface radiation balance in GCMs and/or regional climate models.

On the basis of simulations from a 3D Monte Carlo photon tracing program (Chen et al. 2006; Lee 2008), we developed a parameterization by means of multiple linear regression with the topographic information, including elevation, sky view factor, and terrain configuration factor, as independent variables.

2. Model description

In the present Monte Carlo approach, the facet in each pixel is formed based on elevation, slope, and orientation, where the latter two can be calculated from the digital elevation model (DEM). The elevation of a facet center is equal to the real elevation, while the normal vector of a facet is given by the slope and orientation. Therefore, the facet is inclined, and the projection of the edge of a facet lies on the boundary of the pixel, as shown in Figure 1. However, there are usually gaps between adjacent facets. In order to avoid the leaking of photon, vertical planes are added at the gaps to build a seamless land surface.

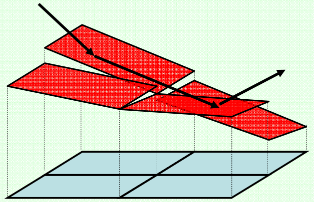


Figure 1. The surface configuration in the current Monte Carlo model as a rectangular grid of inclined quadrilateral facets.

Photons enter the domain as the moving direction determined by the position of the sun. Photons may encounter scattering in the atmosphere due to air molecules or particles, and the moving direction of the scattered photon is determined by the local phase function. When photons hit the land surface, which is assumed as Lambertian surface, the probability that photons are reflected or absorbed is decided by surface albedo. All photons are traced until they are absorbed by the land surface or leave the top of the atmosphere.

As shown in Figure 2, the surface fluxes can be categorized into five components according to the photon's sun-to-surface path: **(1) direct flux**, **(2) diffuse flux**, **(3) direct-reflected flux**, **(4) diffuse-reflected flux**, and **(5) coupled flux**.

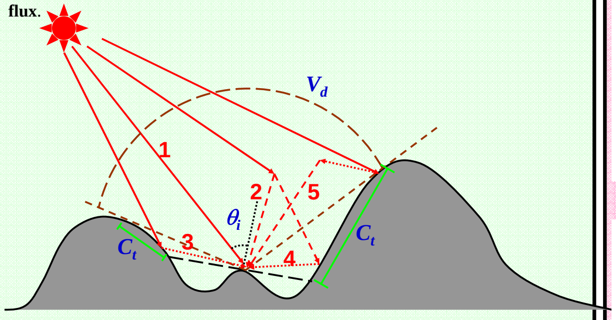


Figure 2. A schematic representation of flux components received by the target on an inclined surface in a mountainous area: (1) direct flux, (2) diffuse flux, (3) direct-reflected flux, (4) diffuse-reflected flux, and (5) coupled flux. The solar incident angle θ_i, sky view factor V_d and the terrain configuration factor C_t are also shown.

3. Input for regression

A mountainous area located at the northern Washington State in the United States with a 1 km^2 resolution was selected as the experiment sample. Figure 3 shows the maps of elevation and slope in this area, which is divided into 81 20×20 km^2 domains. To reduce the edge effect, only the topographic information and surface radiative fluxes in the central 10×10 km^2 areas were used for parameterization. Since this study is to investigate the mountain effect, variation in the surface albedo is neglected, and a uniform value of 0.2 is assumed. In current climate models, unresolved mountains are treated as a flat surface with a mean elevation using the conventional radiative transfer scheme. For this reason, it is not necessary to include mean elevation in parameterization. We also find that difference in the mean elevation of a domain is one of the most dominant factors for surface solar fluxes (results not shown). To eliminate variation in surface fluxes due to the elevation difference, we adjust the heights of all 81 experiment domains so that the mean elevations of the central 10×10 km^2 areas are the same, while other topographic information such as slope and aspect remains unchanged.

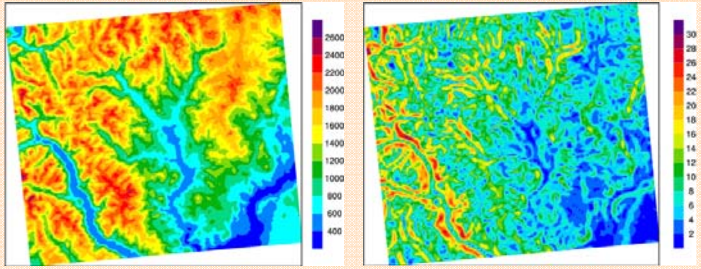


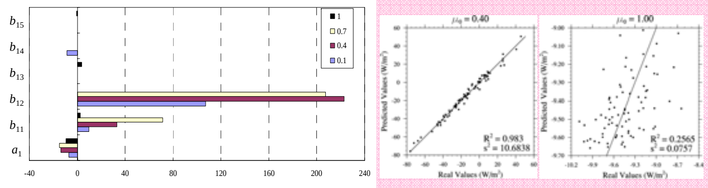
Figure 3. Maps of surface elevation (left panel, in meter) and slope (right panel, in degree) with a 1 km^2 resolution. Data was taken from the HYDRO1k geographic database.

The dependent variables are deviations of the five components of surface solar fluxes on mountains from those on a flat surface with a mean elevation. The independent variables for multiple linear regression include the mean of the slope $\langle s\rangle$, the mean of the sky view factor $\langle V_d\rangle$, the mean of the terrain configuration factor $\langle C_t\rangle$, and the mean of the cosine of the solar incident angle $\langle \mu_i\rangle$. The standard deviation of height $\sigma(h)$, slope $\sigma(s)$, sky view factor $\sigma(V_d)$, and terrain configuration factor $\sigma(C_t)$, and the skewness of these variables $\gamma(h)$, $\gamma(s)$, $\gamma(V_d)$, and $\gamma(C_t)$ are also used in regression analysis. However, because some independent variables have very high correlation with others, we use C_p statistics to select proper independent variables for the most preferable regression models.

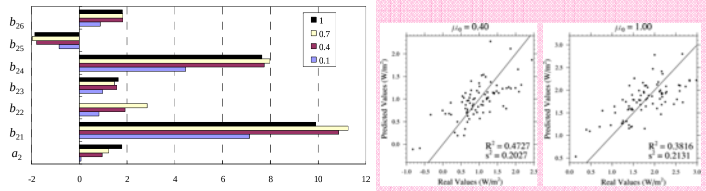
4. Results

With the multiple linear regression, the deviation in surface fluxes can be expressed as the simple linear functions of topographic parameters.

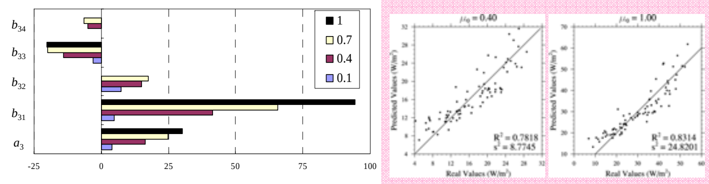
Direct Flux: $f_{dir} = a_1 + b_{11}\langle V_d\rangle + b_{12}\langle \mu_i\rangle + b_{13}\sigma(s) + b_{14}\gamma(h) + b_{15}\gamma(C_t)$



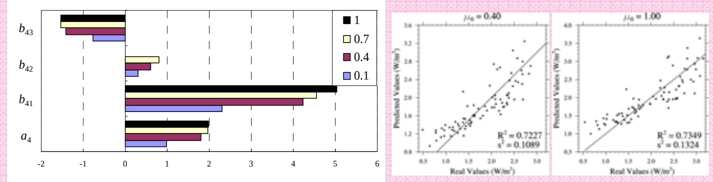
Diffuse Flux: $f_{dif} = a_2 + b_{21}\langle V_d\rangle + b_{22}\langle \mu_i\rangle + b_{23}\sigma(h) + b_{24}\sigma(s) + b_{25}\gamma(h) + b_{26}\gamma(s)$



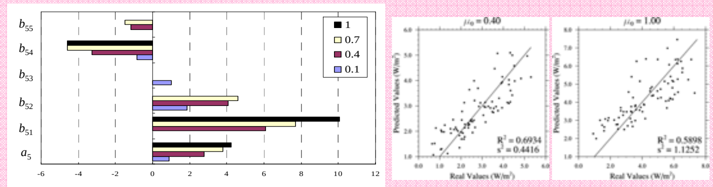
Direct-reflected Flux: $f_{rdir} = a_3 + b_{31}\langle C_t\rangle + b_{32}\langle \mu_i\rangle + b_{33}\gamma(h) + b_{34}\gamma(C_t)$



Diffuse-reflected Flux: $f_{rdif} = a_4 + b_{41}\langle C_t\rangle + b_{42}\langle \mu_i\rangle + b_{43}\gamma(h)$



Coupled Flux: $f_c = a_5 + b_{51}\langle C_t\rangle + b_{52}\langle \mu_i\rangle + b_{53}\sigma(h) + b_{54}\gamma(h) + b_{55}\gamma(C_t)$



5. Concluding remarks

For the direct flux, R^2 are generally larger than 0.95, except that R^2 is only 0.26 when the sun is at zenith. However, it should be noted that the variation in this case is only about 1.5 W/m^2. Comparing to the total incoming flux on the order 1000 W/m^2, random fluctuation from the Monte Carlo simulation may result in poor regression. The most important factor determining the direct flux is the mean solar incident angle, while the mean sky view factor also has a strong impact since it is an indicator of the shading effect.

For the diffuse flux, R^2 are only on the order of 0.5. However, it should be noted that variation in the diffuse radiation is only about 3.5 W/m^2. The most important factor is the sky view factor consistent with the assumption made in most of the surface flux calculations. The second most important factor is the standard deviation of slope. Contributions from the mean solar incident angle, the skewness of height, and the skewness of slope are about the same.

For the direct-reflected flux, variation is generally on the order of 30-60 W/m^2. Therefore, neglecting this variation can cause a significant error in the evaluation of surface energy balance. For the diffuse-reflected and coupled fluxes, variations are about 2.5 and 7 W/m^2, respectively. The dominant factors for these reflected-related fluxes is the terrain configuration factor, followed by the skewness of elevation.

In this study, the surface albedo is assumed to be uniform. However, a high albedo can significantly increase the reflected fluxes. Also, the direct- and diffuse-reflected fluxes are proportional to the surface albedo since photons can only undergo reflection once. In addition, the relationship between the coupled fluxes and albedo is nonlinear. These are subjects that require further simulation and parameterization studies.

References

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