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A METHOD TO ESTIMATE SPECTRAL RADIATION COMPONENTS FROM SURFACE NET RADIATION, USING LONG-TERM CLOUD OBSERVATIONS

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1. Introduction

Land surface net radiation, the total radiative energy absorbed by the land surface, is the major forcing that drives the land surface processes of water, energy, and biology. Spectral components of surface net radiation, such as solar (short-wave) and thermal (long-wave) radiations possess different functions in these processes. However, measurements of all four components are scarce (20% among ground observation sites that are participating in AmeriFlux), which hinders current investigations of radiative energy balance at the land surface. This poses a challenge to decompose the net radiation data into corresponding spectral components, so that the network data can be utilized more effectively in the land surface models (LSMs), remote sensing and many other studies.

Many research efforts are being made to tackle accurate estimates of spectral radiative components at the land surface. Atmospheric radiation modeling continues following the approaches of improving cloud parameterizations, radiative transfer models, and cloud microphysics models. On the other hand, measurements of land surface radiations are enhanced by using satellite remote sensing to retrieve surface radiations and monitor cloud variability, and also by building ground networks to collect long-term continuous field observations (such as the global FLUXNET project and the U.S. Department of Energy Atmospheric Radiation measurement (ARM) program).

Meanwhile, the efforts to validate the current land surface process descriptions has been limited to only a few ground observation sites where we can obtain sufficient model forcing which includes spectral components of incoming radiations at the land surface.

This study intends to enhance the utilization of field observation network data for the validation of land surface process descriptions. As a part of the land surface modeling study, a statistical approach was developed to partition surface net radiation measurements into the solar and thermal, upward and downward, clear-sky and cloud radiant components.

2. DATA

This study is based on field observations from the AmeriFlux network, which is a regional network of the global micrometeorological flux measurement project (FLUXNET). These networks intend to measure the exchange of carbon dioxide, water vapor, energy and momentum between the biosphere and the atmosphere on a long-term (multiple years) and continuous (hourly time series) basis (Baldocchi et al. 2001). The AmeriFlux network funded by the U.S. Department of Energy, NASA, NOAA, and NSF covers diverse biomes and climates (Baldocchi et al. 2001), currently including 167 sites (115 in United States) equipped with instrument towers making measurements inside and above the canopy. The

AmeriFlux data were obtained online through the Oak Ridge National Lab (http://public.ornl.gov/ameriflux/). The surface spectral radiation data of field observations are from four AmeriFlux sites in United States implemented with Kipp and Zonen CNR1 radiometers. Table 1 summarizes information of four sites used in this study. The analysis was performed initially for the Willow Creek observations, and then data from the other three sites were obtained to examine whether the relationship found in this study is consistent over different locations. Another major reason for the selection for these four sites is the availability of measured radiations of all four spectral components as well as air temperature and humidity.

Table 1: Site description

Site	Land Class	Location	Data Period
Willow Creek, WI.	Hardwood	45°48´21"N 90º05´48"W	01/01/98 - 08/23/04
Niwot Ridge, CO.	Mixed forest	40º01´58"N 105º32´7"W	01/01/99 - 02/31/03
Fort Peck, MT.	Flat grassland	48º18´28"N 105º 06´02"W	01/01/00 - 06/25/05
Audubon, AZ.	Semi-arid desert	31º35´27"N 110º30´37"W	06/07/02 - 03/05/05

3. Method

This method estimates downward longwave radiation when we have measured net radiation, air temperature and humidity.

3.1 Estimation of Ground Upward Longwave Radiation

Ground upward radiation ($L_g^{\uparrow}$) —the emission of ground surface is described by the Stefan-Boltzmann Law:

$$L_g^{\uparrow} = \varepsilon_g \sigma T_g^4 \quad (1)$$

Where $\varepsilon_g \approx 0.95 \sim 1.0$ is the surface bulk emissivity, σ is the Stefan-Boltzmann constant, and T_g is the surface skin temperature. In LSMs, the skin temperature is calculated as the equivalent (effective) temperature responsible for the long-wave emission from a heterogeneous land surface. It can be measured by radiometers mounted on towers or estimated by satellite remote sensing. Only at a few AmeriFlux sites provide skin temperature measurement, therefore, surface air temperature (T_a) is often used as the substitute of T_g. The ground upwelling radiation calculated from the surface air temperature above the canopy appears close to the observations. Over the grassland of Fort Peck, the use of skin temperature or surface air temperature does not show any significant difference in the ground thermal radiation estimation. However, over the areas with low fraction of vegetation coverage such as the semi-arid area of Audubon, AZ., use of surface air temperature resulted in serious underestimations of ground upward thermal radiations in particular, over the high range.

3.2 Downward clear-sky longwave radiation

Incoming clear-sky radiation ($L_{sky}^{\downarrow}$) is the surface-received, long-wave radiation emitted by the atmospheric compounds excluding clouds. Many previous studies in the literatures have attempted to estimate the clear-sky (or atmospheric) radiation using surface air temperature and vapor pressure (see the review in Iziomon et al. 2003). Eight pre-existing models were tested at the four AmeriFlux sites where the total downward long-wave radiation

($L^{\downarrow} = L^{\downarrow}_{sky} + L^{\downarrow}_{cld}$) is measured. The test (Fig. 1) shows that, all models produce similar variation patterns according to the variations of air temperature and vapor pressure, but with significant differences in quantity. These empirical models are regression models that are based on specific observational datasets, so the model biases vary with time and location. This implies that the empirical models need to be calibrated for each site, even though pre-existing empirical models could capture diurnal pattern of downward clear-sky radiation. Two methods (two coefficients regression method and UA-SCE method) were used in order to further capture the accurate magnitude of downward thermal radiation.

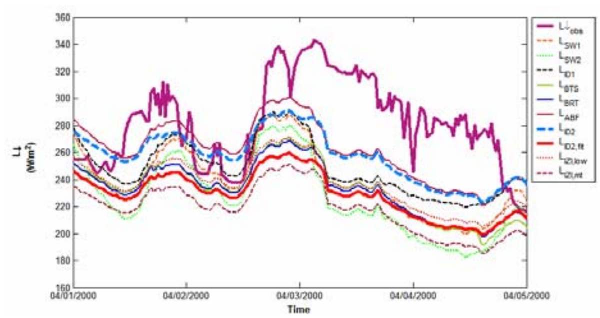

Figure 1: Time series of observed total downward long-wave radiation ($L^{\downarrow}$) and the clear-sky downward long-wave radiation ($L^{\downarrow}_{sky}$) estimated from 9 empirical models (eight models without calibration and the calibrated Idso model) at Willow Creek, Wisconsin, during 04/01-04/05/2000.

Idso model (Idso, 1981) was used for clear-sky radiation estimation:

$$L^{\downarrow}_{sky} = \sigma T_a^4 [A + B \cdot eExp(1500 / T_a)] \quad (2)$$

where, T_a and e are surface air temperature and vapor pressure, respectively; σ is the Stefan-Boltzmann constant; A and B are model parameters. Idso model was selected for this study simply because it has been adopted by several LSMs, such as the recently developed Common Land Model.

We consider that, clear-sky downward radiation ($L^{\downarrow}_{sky}$) has the lowest value in the total downward long-wave radiation observations ($L^{\downarrow} = L^{\downarrow}_{sky} + L^{\downarrow}_{cld}$) corresponding to the same (T_a, e) under various weather (cloud) conditions.

The regression model with two coefficients is capable of finding lowest clear-sky plane. However, the calibrated Idso model can fit the "observed" $L^{\downarrow}_{sky}$ data even better if the exponential factor 1500 in Eq. 2 is also taken as an additional model parameter. The optimization scheme of Shuffled Complex Evolution (Duan et al. 1993) was used for the later case.

3.3 Decomposition of Net Radiation

In this study, instead of testing various empirical models, the cloud thermal radiation was estimated through the surface radiative energy balance. First, a dimensionless, integrated factor (C_f) which represents the relative quantity of clouds in the sky was defined based on the multi-layer cloud radiation model (Kimball et al. 1982),

$$C_f = \frac{L^{\downarrow}_{cld}}{\tau_8 f_8 \sigma T_c^4} \quad (3)$$

where the denominator ($\tau_8 f_8 \sigma T_c^4$) is adopted from the Kimball model (1982).

Analysis using the tower observation shows that there is an empirical relationship among R_n, C_f, and S_n (Fig. 2). In Fig. 2, the long-term observed spectral radiation component data at Willow Creek are plotted using their R_n, S_n, and C_f (obtained from $L_{cld}^{\downarrow} = L^{\downarrow} - L_{sky}^{\downarrow}$) values.

The distribution of the data points illustrates some patterns worth aware:

(1) The data points along the horizontal bottom line at $C_f = 0$ represent the clear-sky data.

(2) The left border of the data collection is the nighttime data ($S_n = 0$).

(3) The data points with equal net solar radiation (S_n = constant) are gathering on lines parallel to the left border. In other words, (2) is a special case of (3) when $S_n = 0$.

(4) The triangle shape of the data collection indicates that large net radiation data are observed under clear-sky or less-cloudy sky conditions and they were dominated by the high net solar radiation.

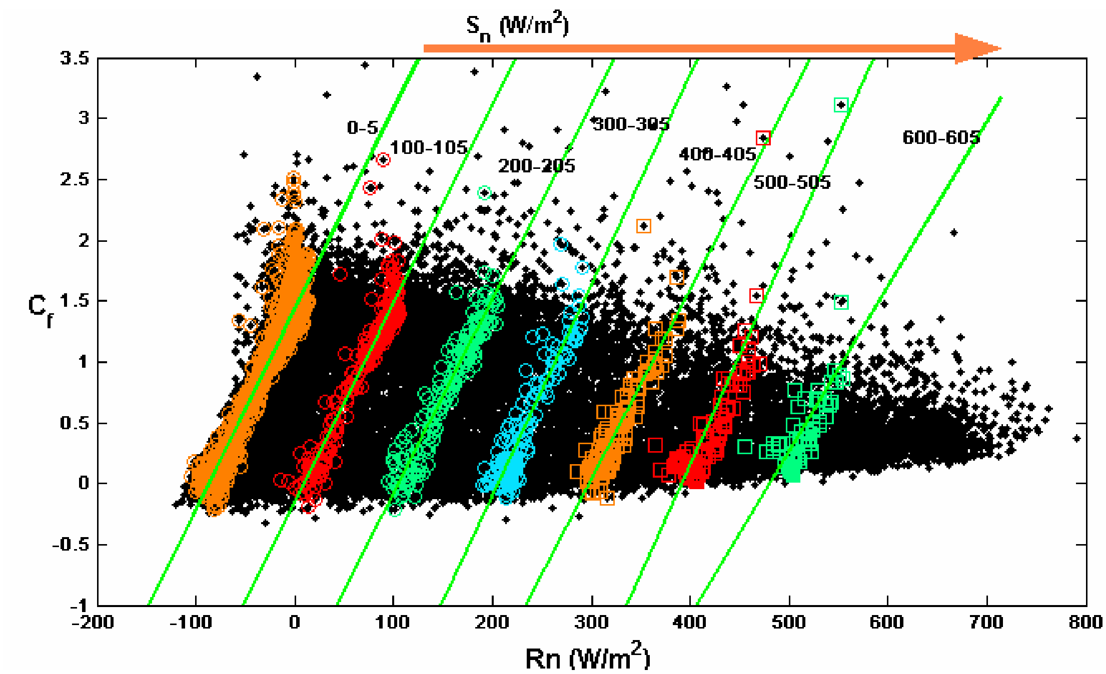

Figure 2: The linear relation between R_n, C_f, and S_n shown by the observed spectral radiation data at Willow Creek, Wisconsin during 01/01/98-08/23/04.

The above features indicate the existence of a linear relation among R_n, C_f, and S_n, which can be represented as follows:

$$C_f = a \cdot R_n + b + c \cdot S_n \quad (4)$$

where *a*, *b*, and *c* are the parameters to be determined by radiation observations. According to (2), *a* and *b* (i.e. the slope and intercept of the left border in Fig. 2) can be calculated from the nighttime ($S_n = 0$) net radiation observation data together with the estimated $L_g^{\uparrow}$ and $L_{sky}^{\downarrow}$ (using $L_{cld}^{\downarrow} (= R_n + L_g^{\uparrow} - L_{sky}^{\downarrow})$ and Eqs. 5). After the determination of *a* and *b*, parameter *c* is calculated using Eqs. 5 with the clear-sky ($C_f = 0$) data (i.e., the horizontal bottom line in Fig. 2):

$$C_f = 0 = a \cdot R_n + b + c \cdot S_n$$
$$R_n = S_n + L_{sky}^{\downarrow} - L_g^{\uparrow} \quad (5)$$

Eq. 4 indicates that given any two variables of R_n, C_f , and S_n, the third one can be determined. Because during nighttime S_n = 0, from any given R_n observations, the corresponding cloudiness of C_f can be obtained from Eq. 4 which is pre-determined from the long-term observation data (described above). In order to decompose daytime net radiation, we propose a scheme to estimate the daytime C_f from two "critical" nighttime C_f values. The scheme includes two steps:

(1) Calculate the C_f values at early morning (before sunrise) and later afternoon (after sunset) when S_n is zero. That is to use the nighttime net radiation $R_n \ (= L_{cld}^{\downarrow} + L_{sky}^{\downarrow} - L_g^{\uparrow})$ and estimated $L_g^{\uparrow}$ and $L_{sky}^{\downarrow}$ to calculate $L_{cld}^{\downarrow}$ and C_f.

(2) Calculate the daytime hourly C_f by interpolating the C_f values at early morning and later afternoon proportionally to the daytime variation of ($\tau_8 f_8 \sigma T_c^4$). Notice that, as mentioned before, the term ($\tau_8 f_8 \sigma T_c^4$) includes the major factors that affect the cloud downward emission in the Kimball's model.

3.4 Downward cloud-sky thermal radiation

Downward cloud-sky thermal radiation is calculated as the sum of clear-sky thermal radiation and cloud thermal radiation. The cloud radiation is obtained by multiplying C_f, which is interpolated during daytime, to $\tau_8 f_8 \sigma T_c^4$, each of which is estimated from the empirical equations.

3.5 Solar radiation

Once all components of longwave radiation were determined, surface net solar radiation was estimated as the residual term from the net radiation and its longwave components ($S_n = R_n - L_{sky}^{\downarrow} - L_{cld}^{\downarrow} + L_g^{\uparrow}$). Downward solar radiation and upward solar radiation can be further separated, if we know the albedo of the land surface. This means that we can have incoming solar radiation that can provide realistic net solar radiation, even when we use the wrong albedo specified in the land surface models.

4. RESULTS

The estimated data of total downward long-wave radiation at Willow Creek during 09/22-10/02, 2000 were compared with the observations (Fig. 3). The results indicated that using the interpolation scheme, the daytime variation of total downward longwave radiation traces the observation reasonably well.

Fig. 4 shows the scatter plots and statistical errors between the estimated and observed downward long-wave radiation data at the four sites during the long-term study periods.

The comparisons between estimated and observed net solar radiation at the four sites are shown in Fig. 5. Notice that, when the long-wave radiations are estimated, the observed net solar radiation data have not been used. Therefore, the error in net solar radiation estimation reflects the integral uncertainty by using the proposed estimation schemes.

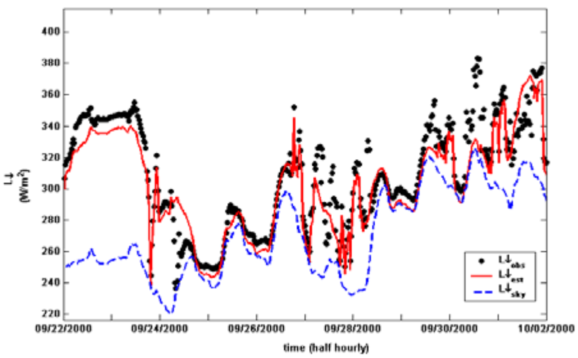

Figure 3: Comparison of estimated downward longwave radiation ($L^{\downarrow} = L^{\downarrow}_{sky} + L^{\downarrow}_{cld}$) with observations at Willow Creek, Wisconsin during 09/22/2000-10/02/2000.

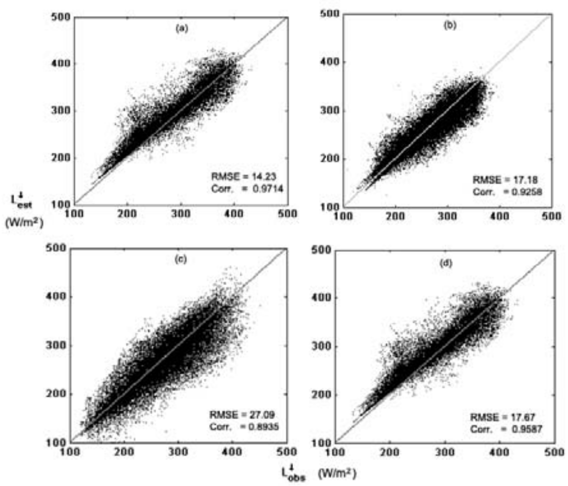

Figure 4: Scatter plots of estimated and observed downward long-wave radiation at (a) Willow Creek, WI, (b) Niwot Ridge, CO., (c) Fort Peck, MT., (d) Audubon, AZ (Unit in W/m^2).

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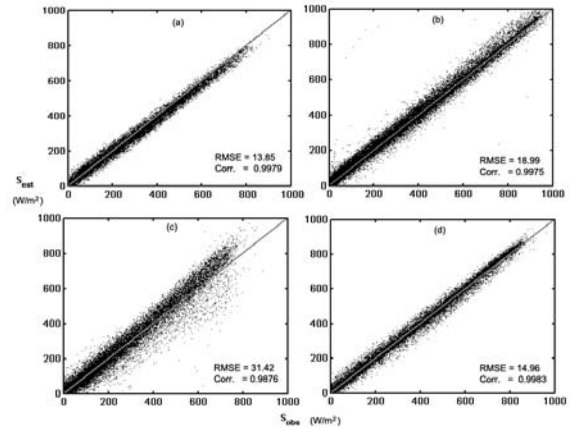

Figure 5: Scatter plots of estimated and observed net solar radiation at (a) Willow Creek, WI, (b) Niwot Ridge, CO., (c) Fort Peck, MT., (d) Audubon, AZ (Unit in W/m^2).

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