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Development of a general model to estimate the instantaneous, daily, and daytime net radiation with satellite data on clear-sky days

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ABSTRACT

Net radiation is a key variable in computing evapotranspiration and is a driving force in many other physical and biological processes. Remote sensing techniques provide an unparalleled spatial and temporal coverage of land-surface attributes, and thus several studies have attempted to estimate net radiation by combining remote sensing observations with surface and atmospheric data. However, remote sensing provides instantaneous data, when many applications and models need information at other temporal scales. In this work, a new general methodology is proposed to estimate daily and daytime net radiation and to retrieve the diurnal cycle of net radiation. Four images were acquired on different dates, two corresponding to the TM sensor (Landsat 5) and two from ETM+ (Landsat 7), and ancillary meteorological data covering the Tandil department (Argentina) were collected. The performance of the methodology at both local and regional scales is assessed by comparing the results with ground net radiation measurements. At local scale, estimation errors between ±4 and ±9%, biases close to zero, and good agreement between predicted net radiation values and ground-measured values were obtained. On the other hand, estimation errors between ±2 and ±4% were finally obtained using satellite data. Note that the methodology presented here is not restricted to a latitude, a date, or a time of satellite overpass, and therefore it can be applied to any satellite mission, provided it has visible, infrared, and thermal bands to obtain previously the instantaneous net radiation.

1. Introduction

Net radiation (Rn) represents the sum of incoming and outgoing contributions of shortwave and longwave radiation fluxes at the surface. It is the balance between the energy absorbed, reflected, and emitted by the Earth's surface (Jobson, 1982). Its study is of great relevance, since it is a key parameter in computing evapotranspiration and is a driving force in many other physical and biological processes such as climate monitoring, weather prediction, and agricultural meteorology (Rosenberg, Blad, & Verma, 1983). Rn is normally positive during the daytime and negative during the nighttime. Its daily average value is almost always positive, except in extreme conditions at high latitudes (Allen, Pereira, Raes, & Smith, 1998).

In many physical, agronomical, and biological applications, Rn rather than solar radiation (Rs) is required. However, net radiation data are rarely available due to the technical and economical limitations associated with direct measurements. Even when net radiation measures are available, they are generally limited to a small area and do not represent the spatial variability. For example, the methodology recommended by Allen et al. (1998) for estimating daily net radiation is limited to areas over well-watered grass canopy and cannot be used over other vegetation types or areas with sparse and/or stressed vegetation conditions (Samani, Bawazir, Bleiweiss, et al., 2007).

Thus, several research groups focused their studies on the estimation of Rn at regional scale (Bisht, Venturini, Islam, & Jiang, 2005; Samani et al., 2007; Wang & Liang, 2008; Kjaersgaard & Cuenca, 2009; Ma & Ma X, 2011; Ma, 2012). To map the Rn, it is necessary to combine remote sensing observations with surface and atmospheric data, where the spatial variability is mainly modeled by means of albedo, emissivity, and land surface temperature maps obtained from satellite data. Then, net radiation flux can be obtained according to the following equation:

$$Rn_i = Rs_{\downarrow i}(1-\alpha) + \varepsilon Rl_{\downarrow i} - \varepsilon\sigma T_{Si}^4 \tag{1}$$

where $Rs_\downarrow$ is the incoming shortwave radiation (Wm^{-2}), α is the albedo ($\alpha = Rs_\uparrow/Rs_\downarrow$, with $Rs_\uparrow$ the reflected solar radiation), ε is the surface emissivity, $Rl_\downarrow$ is the incoming longwave radiation (Wm^{-2}), σ is the Stefan-Boltzmann constant (Wm^{-2}K^{-4}), and T_S is the land surface temperature (K). The subscript i represents instantaneous values. Generally,

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α, ε, and T_S are obtained by means of satellite data, while $Rs_\downarrow$ and $Rl_\downarrow$ can be measured at the surface or modeled.

If Eq. (1) is correctly applied, then it is possible map Rn with good accuracy (Carmona, 2014). However, these maps correspond to satellite overpass times, whereas many agricultural applications (e.g. models for estimating evapotranspiration) generally need daily average net radiation (Rn_d) or daytime average net radiation (Rn_D) (also called the diurnal cycle of net radiation) (Bisht et al., 2005). In this sense, there are a limited number of models for extending Rn at both average daily and daytime scales or to retrieve the diurnal cycle of net radiation.

First, Rn_d can be obtained according to the following equation:

$$Rn_d = C_d\, Rn_i = \left[\frac{Rn_d}{Rn_i}\right]_{local} Rn_i \tag{2}$$

where C_d is the ratio between daily and instantaneous net radiation, which can be calculated for each date from the ground-collected net radiation data. Since the ratio C_d has been shown to vary with the time, date, or site latitude, but not with the vegetation type, a constant value can be used for each image (Sánchez, Scavone, Caselles, et al., 2008; Sobrino, Gómez, Jiménez-Muñoz, et al., 2005; Sobrino, Gómez, Jiménez-Muñoz, & Olioso, 2007a; Sobrino, Gomez, Jimenez-Muñoz, & Olioso, 2007b). Fig. 1 shows the scheme for estimating daily net radiation, where although the ratio C_d does not vary, Rn_d and Rn_i have different values in each pixel.

The strict application of this method is limited due to the absence of net radiometers in conventional weather stations. Thus, several methods have been proposed to estimate C_d (Seguin & Itier, 1983; Bisht, 2005; Sobrino et al., 2007a).

Seguin and Itier (1983) analyzed the range of variation of C_d, restricting their discussion to clear summer days. From the analysis of three years of data (for the summer months in Avignon, France), they found a value of $C_d = 0.30 \pm 0.03$, considering instantaneous values at midday (12:00 solar time). This value has been used in several studies since then, often without regard to its local, temporary, and seasonal nature. For instantaneous values that are not acquired at midday in summer, the ratio C_d needs to be recalculated (Sobrino et al., 2007a; Sobrino et al., 2007b; Wassenaar, Olioso, Hasager, et al., 2002).

In order to map Rn_d during the whole year, Rivas and Carmona (2013) proposed to use a linear equation. From the analysis of three years of net radiation flux measurements collected at different campaigns carried out in Tandil (37° 19′ S, 59° 05′ W, 214 m) between March 2007 and December 2009, it was shown that the ratio of net radiation fluxes varies along the year and can be obtained as $C_d = 0.43–54/Rn_i$, where Rn_i is the instantaneous net radiation estimated from satellite data. Meanwhile, Sobrino et al. (2007a); Sobrino et al. (2007b) proposed to calculate C_d with a second degree polynomial equation. They found relationships between the ratio C_d and the day of the year for different times, using net radiation fluxes measured at the meteorological station of the El Saler area, located on the east coast of the Iberian Peninsula (Valencia, 39° 21′ N, 0° 19′ W).

On the other hand, some researchers focused their studies on the estimation of Rn_D because they only think it necessary to consider daytime data as the main driving force for evapotranspiration and other physiological activities (Samani, Nolin, Bleiweiss, & Skaggs, 2005; Samani, Bawazir, Bleiweiss, et al., 2009). In this case, Rn_D can be obtained according to the following similar equation:

$$Rn_D = C_D\, Rn_i = \left[\frac{Rn_D}{Rn_i}\right]_{local} Rn_i \tag{3}$$

where C_D is the ratio between daytime and instantaneous net radiation. Samani et al. (2005) proposed to calculate C_D as the ratio between the daily and instantaneous incoming shortwave radiation, assuming that the positive net radiation received during the daytime is directly proportional to the shortwave solar radiation. Samani et al. (2007) proved this concept using data measured in New Mexico (32° 36′ N, 106° 41′ W, 1145 m), considering instantaneous radiation values at 11:00 a.m. Mountain Standard Times. In some cases, they observed overestimations of the Rn_D as a result of disparity between instantaneous and daily temperatures. Consequently, they presented a modified form of the equation by introducing the effect of the air temperature on Rn_D prediction.

Furthermore, Bisht et al. (2005) proposed a sinusoidal model for estimating both daytime net radiation and the diurnal cycle of net radiation. This sinusoidal model has the advantage of requiring only one satellite observation (Terra–MODIS) to reconstruct the diurnal variation for clear sky days, and was validated using ground data from the Southern Great Plains (37° N, 97° W). This approach presents an interesting methodology; however the results showed significant errors in the retrieval of the diurnal cycle of radiation and average daytime value, Rn_D, with overestimation in both cases.

In summary, when measures of net radiation are not available, existing models show some limitations related to the application site (latitude), the date, or the time of satellite overpass, or simply are not general enough to meet the different needs that arise in practice. Therefore, we understand that it is necessary to have a *general model* for estimating the net radiation from satellite data, which will in turn be easy to implement. In this sense, the main objective of this work is to develop a new model to estimate daily and daytime net radiation and also to retrieve the diurnal variation of net radiation by means of meteorological and satellite data. The specific goals of this study are: (*a*) to develop a general physical model for estimating regional net radiation, (*b*) to adjust its parameters, and (*c*) to evaluate its performance with meteorological and satellite data.

The paper is organized as follows. Section 2 presents the proposed model for estimating net radiation at a regional scale. Section 3 describes the experimental sites and field measurements, the remote sensing data used for the model application, and the calibration and validation methodology. Section 4 presents the results and discussion. Finally Section 5 summarizes the main conclusions drawn from the study.

2. Model

The model description is basically divided into three parts. First, we present the methodology for estimating daily net radiation, where efforts are focused on the estimation of the ratio C_d considering a known hypothetical surface. Then, a similar approach that makes it possible to calculate the daytime average net radiation and, finally, to retrieve the diurnal cycle of net radiation is presented. The model presented

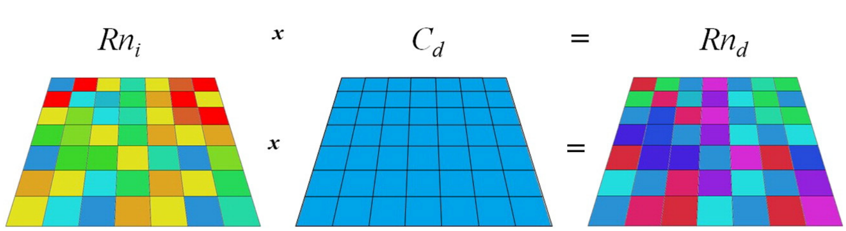

Fig. 1. Scheme for mapping Rn_d with satellite data.