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Empirical estimation of daytime net radiation from shortwave radiation and ancillary information

Bo Jiang[a,*], Yi Zhang[b], Shunlin Liang[a,b], Georg Wohlfahrt[c], Altaf Arain[d], Alessandro Cescatti[e], Teodoro Georgiadis[f], Kun Jia[a], Gerard Kiely[g], Magnus Lund[h], Leonardo Montagnani[i,j], Vincenzo Magliulo[k], Penelope Serrano Ortiz[l], Walter Oechel[m], Francesco Primo Vaccari[n], Yunjun Yao[a], Xiaotong Zhang[a]

[a] State Key Laboratory of Remote Sensing Science, and School of Geography, Beijing Normal University, Beijing 100875, China
[b] Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA
[c] Institute of Ecology, University of Innsbruck, Innsbruck, Austria
[d] School of Geography and Earth Sciences and McMaster Centre for Climate Change, McMaster University, Hamilton, Ontario L8S4K1, Canada
[e] European Commission, Joint Research Center, Institute for Environment and Sustainability, Ispra, Italy
[f] CNR-Institute of Biometeorology, via Gobetti 101, 40129 Bologna, Italy
[g] Civil and Environmental Engineering, and Environmental Research Institute, University College Cork, Ireland
[h] Arctic Research Centre, Department of Bioscience, Aarhus University, Frederiksborgvej 399, DK-4000 Roskilde, Denmark
[i] Faculty of Science and Technology, Free University of Bolzano, Piazza Università 5, 39100 Bolzano, Italy
[j] Forest Services, Autonomous Province of Bolzano, Via Brennero 6, 39100 Bolzano, Italy
[k] CNR-ISAFOM, Institute for Mediterranean Agricultural and Forest Systems, National Research Council, via Patacca 85, 80040 Ercolano (Napoli), Italy
[l] Dpto. Ecología, Facultad de Ciencias, Universidad de Granada, Spain
[m] Global Change Research Group, San Diego State University, San Diego, CA 92182, USA
[n] IBIMET-CNR Institute of Biometeorology National Research Council, via G. Caproni 8, 50145 Firenze, Italy

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ABSTRACT

All-wave net surface radiation is greatly needed in various scientific research and applications. Satellite data have been used to estimate incident shortwave radiation, but hardly to estimate all-wave net radiation due to the inference of clouds on longwave radiation. A practical solution is to estimate all-wave net radiation empirically from shortwave radiation and other ancillary information. Since existing models were developed using a limited number of ground observations, a comprehensive evaluation of these models using a global network of representative measurements is urgently required. In this study, we developed a new day-time net radiation estimation model and evaluated it against seven commonly used existing models using radiation measurements obtained from 326 sites around the world from 1991 to 2010. MERRA re-analysis products from which the meteorological data were derived and remotely sensed products during the same period were also used. Model evaluations were performed in both global mode (all data were used to fit the models) and conditional mode (the data were divided into four subsets based on the surface albedo and vegetation index, and the models were fitted separately). Besides, the factors (i.e., albedo, air temperature, and NDVI) that may impact the estimation of all-wave net radiation were also extensively explored. Based on these evaluations, the fitting RMSE of the new developed model was approximately 40.0 Wm^{-2} in the global mode and varied between 18.2 and 54.0 Wm^{-2} in the conditional mode. We found that it is better to use net shortwave radiation (including surface albedo) than the incident shortwave radiation nearly in all models. Overall, the new model performed better than other existing linear models.

1. Introduction

All-wave net surface radiation (R_n) constitutes the available radiative energy at the surface, and as such regulates most biological and physical processes, such as evapotranspiration (Lu et al., 2014, 2013; Wang and Liang, 2008), photosynthesis and turbu-

* Corresponding author. Tel.: +86 10 58809071.
E-mail address: bojiang@bnu.edu.cn (B. Jiang).

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lent and conductive heat fluxes. Thus, accurate estimates of R_n are essential for understanding the land surface energy distribution, the formation and transformation of air masses, snow melting calculations (Male and Granger, 1981), modeling crop growth, and addressing water resource management (Bisht and Bras, 2011; Hwang et al., 2012). Estimation of R_n is necessary because it is a key input for land surface process models, and are also used routinely to calculate evapotranspiration (Monteith, 1965), which is a critical component of agricultural, hydrological, and ecological research.

R_n is the difference between the incoming and outgoing shortwave and longwave radiation fluxes at the surface. Mathematically described as:

$$\begin{aligned} R_n &= R_{ns} + R_{nl} \\ R_{ns} &= R_{si} - R_{so} = (1-\alpha)R_{si} \\ R_{nl} &= R_{li} - R_{lo} \end{aligned} \quad (1)$$

where R_{si} is the incoming shortwave radiation (Wm^{-2}), R_{so} is the reflected outgoing shortwave radiation (Wm^{-2}), which is calculated by $R_{so} = \alpha \times R_{si}$, α is the shortwave broadband albedo (dimensionless), thus R_{ns} is the net shortwave radiation, R_{li} is the incoming longwave radiation (Wm^{-2}), R_{lo} is the outgoing longwave radiation (Wm^{-2}), and R_{nl} is the net longwave radiation (Wm^{-2}). R_n is normally positive during the daytime because net shortwave radiation dominates, but negative during the nighttime because net longwave radiation dominates (Allen et al., 1998).

If all four components of Eq. (1) are known, the calculation of R_n is straightforward. Indeed, many radiation measurement towers measure these four components of radiation, thereby allowing us to determine R_n at individual points. Various satellite observations have been used to generate radiation products at regional and global scales (Liang et al., 2010, 2013b; Tang and Li, 2008; Tang et al., 2006; Wang and Liang, 2009b; Zhang et al., 2014). Satellite observations from the visible to near-infrared spectrum have been used for estimating incident solar radiation and surface albedo, and thermal-infrared data for estimating longwave radiation. There are roughly two types of algorithms for estimating radiation (Liang et al., 2010), one calculates radiative quantities from the derived satellite products of all relevant atmospheric and surface variables (e.g., aerosol, cloud, atmospheric temperature profile), and another estimates radiation directly from satellite observed radiance using a regression equation established from extensive radiative transfer simulations.

However, frequent cloud coverage implies that it is extremely difficult to estimate R_n directly from satellite data, particularly longwave radiation component, because clouds block the surface information from reaching the sensors. Since incident shortwave radiation dominates day-time net radiation, methods have been developed to estimate the incident shortwave radiation from satellite data (Liang et al., 2010). Satellite data include information from both atmosphere and surface. From the "clearest" observations (less atmospheric signals) during a temporal window, surface reflectance/albedo can be retrieved, which can be assumed invariant during a short period of time. As long as surface information is known, we can determine the remaining atmospheric component that leads to estimation of incident shortwave radiation (Liang et al., 2006). One of the challenges is the need for multiple observations during a day for estimating day-time radiation but most polar–orbiting satellite sensors, such as MODIS, observe the same surface only a couple of times daily. One solution is to combine both polar–orbiting satellite data with geostationary satellite (Zhang et al., 2014), for example, the Global Land Surface Satellite (GLASS) radiation products at 5 km spatial resolution and 3-h temporal resolution (Liang et al., 2013a,c). Thus, an important research goal presently is to develop robust methods for the empirical estimation of R_n from incident shortwave radiation.

Although important information can be derived from sustained and uninterrupted measurements of R_n over a surface, R_n measurements are only available from a small number of representative radiometric observatories because expensive instruments and constant maintenance are required (Monteith and Unsworth, 1990). To overcome the lack of experimental observations, R_n needs therefore to be estimated from empirical relationships based on physical considerations and meteorological data. From a practical view point, it is important that R_n can be determined from relationships that are not location-dependent so they are more universally applicable and easy to use (Al-Riahi et al., 2003). Consequently, numerous attempts have been made to calculate R_n based on different empirical methods. Two main types of empirical methods can be classified according to previous studies. The first type of methods estimates R_n from incoming shortwave radiation R_{si} and other meteorological variables using simple linear regression (see Section 2.1.1). The second type of methods estimates R_n by calculating the individual components in Eq. (1) separately, where each component is estimated empirically or physically (Allen et al., 2011). The first type of methods is used more widely, while the second one often generates hybrid models with mixed empirical and physical sub- models.

Many of these empirical models were developed based on observational data from specific locations. Thus, evaluating their performance in various environmental conditions is a critical issue. Several studies have been conducted to evaluate the performance of various empirical R_n estimation methods. Iziomon et al. (2000) compared four types of regression models in three sites at different altitudes in the southern Upper Rhine valley between Germany and Switzerland, and defined a model as a "basic regression model" where R_n was only related to R_{si}. The limitations associated with basic regression models were identified and improvements were suggested such as incorporating a clearness index for characterizing the effects of clouds on both shortwave and longwave radiation and air temperature for better estimation of longwave radiation (see Eqs. (4) and (6) below). Alados et al. (2003) also compared the basic regression model with a model that was modified by including albedo and seasonal information for a period of 38 months at a semi-arid region site in Southeastern Spain. They concluded that seasonal information yielded significant improvements for a semi-arid shrubland, but only slight improvements were obtained by incorporating albedo information. Kjaersgaard et al. (2007) tested six commonly used empirical models, including basic regression, multivariate regression, and hybrid models coupled to physical Stefan–Boltzmann relationships, at two independent temperate sites in Denmark for 32 and 7 years. Kjaersgaard et al. (2009) focused mainly on comparisons of three net longwave radiation parameterization models under two climate regimes in Denmark and Spain respectively. Kjaersgaard et al. (2007) showed that various regression models that rely on the local calibration of model coefficients should be derived from a time series that comprises at least 5 years of data, and they also showed that physically-based models are more suitable. They concluded that the performance of these models is generally best in the summertime and worst in the wintertime. Better performance in the summertime and worse performance in the wintertime for various radiation parameterization schemes, both the physical and empirical, are due to the higher signal-to-noise ratio (STNR) for higher magnitudes of radiation in the summertime but lower STNR for lower magnitudes of radiation in the wintertime. Similarly, Sentelhas and Gillespie (2008) evaluated four types of models to estimate the hourly R_n at a grass site in mid-latitudes in Canada for a 58-day period during the growing season in 2003. These models were based on different combinations of R_{si}, meteorological variables (air temperature and relative humidity), and cloud cover information. The results