Estimation of instantaneous net surface longwave radiation from MODIS cloud-free data

Bohui Tang a, b, Zhao-Liang Li a, c, *  

a Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China  
b Graduate University of Chinese Academy of Sciences, China  
c TRIO/LSIIT (UMR7005 CNRS)/ENSPS, Bld Sebastien Brant, BP10413, 67412 Illkirch, France

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ABSTRACT

This paper develops a statistical regression method to estimate the instantaneous Downwelling Surface Longwave Radiation (DSLR) for cloud-free skies using only the satellite-based radiances measured at the Top Of The Atmosphere (TOA), and subsequently combines the DSLR with the MODIS land surface temperature/emissivity products (MOD11_L2) to estimate the instantaneous Net Surface Longwave Radiation (NSLR). The proposed method relates the DSLR directly to the TOA radiances in the MODIS Thermal InfraRed (TIR) channels provided that the terrain altitude and the satellite Viewing Zenith Angle (VZA) are known. The simulation analysis shows that the instantaneous DSLR could be estimated by the proposed method with the Root Mean Square Error (RMSE) of 12.4 W/m² for VZA=0° and terrain altitude z=0 km. Similar results are obtained for the other VZAs and altitudes. Considering the MODIS instrumental errors of 0.25 K for the TOA brightness temperatures in channels 28, 33, and 34, and of 0.05 K for channels 29 and 31, and of 0.35 K for channel 36, the overall retrieval accuracy in terms of the RMSE is decreased to 13.1 W/m² for the instantaneous DSLR. Moreover, a comparison of MODIS derived DSLR and NSLR are done with the field measurements made at six sites of the Surface Radiation Budget Network (SURFRAD) in the United States for days with cloud-free conditions at the moment of MODIS overpass in 2006. The results show that the bias, RMSE and the square of the correlation coefficient (R²) between the MODIS derived DSLR with the proposed method and the field measured DSLR are 20.3 W/m², 30.1 W/m² and 0.91 respectively, and bias=11.7 W/m², RMSE=26.1 W/m² and R²=0.94 for NSLR. In addition, the scheme proposed by Bisht et al. [Bisht, G., Venturini, V., Islam, S., & Jiang, L. (2005). Estimation of the net radiation using MODIS (Moderate Resolution Imaging Spectroradiometer) data for clear-sky days. Remote Sensing of Environment, 97, 52–67], which requires the MODIS atmospheric profile product (MOD07) and also the MODIS land surface temperature/emissivity products (MOD11_L2) as inputs, is used to estimate the instantaneous DSLR and NSLR for comparison with the field measurements as well as the MODIS derived DSLR and NSLR using our proposed method. The results of the comparisons show that, at least for our cases, our proposed method for estimating DSLR from the MODIS radiances at the TOA and the resultant NSLR gives results comparable to those estimated with Bisht et al.’s scheme [Bisht, G., Venturini, V., Islam, S., & Jiang, L. (2005). Estimation of the net radiation using MODIS (Moderate Resolution Imaging Spectroradiometer) data for clear-sky days. Remote Sensing of Environment, 97, 52–67].

1. Introduction

The net surface longwave radiation (NSLR, 4.0–100 μm), representing the energy sink lost to the atmosphere through radiative processes, is one of the main components of the Net Surface Radiation (NSR) which is the driving force for the surface energy balance and vitally important for various applications, including climate studies and agricultural meteorology (Suttles & Ohring, 1986; Ramannathan, 1987). The NSLR is defined as the difference between the Downwelling Surface Longwave Radiation (DSLR) resulting from atmospheric absorption, emission and scattering within the entire atmospheric column, and the upwelling surface longwave radiation emitted and reflected by the earth’s surface. It is generally believed that the upwelling surface longwave radiation emitted by the earth’s surface may be accurately calculated using the surface temperature and emissivity, although the estimation of surface temperature and emissivity from satellite over land surfaces is still problematic, whereas the DSLR is more difficult to estimate directly from the radiances measured by satellite instrument because the DSLR is
largely decoupled from the radiation measured at the Top Of The Atmosphere (TOA) and the DSLR comes mainly from the near-surface layers of atmosphere. Consequently, on the basis of the empirical relationships derived from observed radiation fluxes, the clear-sky DSLR is basically determined by the near-surface temperature and humidity fields (Angström, 1918; Brun's, 1932; Swinbank, 1963; Brutsaert, 1975; Idso, 1981; Prata, 1996; Dilley & O'Brien, 1998), and the NSLR is then estimated by combining remote sensing observations with surface and atmospheric data (Diak & Gautier, 1983; Gautier et al., 1980; Gratton et al., 1993; Ma et al., 2002; Nishida et al., 2003). A review of earlier parameterization schemes for the DSLR was given by Ellington (1995). Niemelä et al. (2001) performed a comparison of several downwelling longwave radiation parameterizations with hourly averaged pointwise surface radiation observations made at Sodankylä, Finland, in 1997 and 1999, and pointed out that almost all schemes underestimated the downwelling clear-sky flux, particularly in cold conditions where there existed very strong surface inversions. Duarte et al. (2006) tested several well-known parameterizations of the DSLR for clear-sky days for an experimental site at Ponta Grossa during 279 days in spring, summer, fall and winter (2003/2004), and pointed out that the existing clear-sky parameterizations usually overestimated the measured values. These contradictory findings show that the coefficients of the existing downwelling longwave radiation parameterizations are likely site-specific and need local calibrations. Zhou and Cess (2001), and Zhou et al. (2007) determined the DSLR by using surface upwelling longwave flux and column precipitable water vapor. The surface upwelling longwave flux in their papers, however, was computed from the 2-m air temperature using Stefan–Boltzmann’s law, assuming an emissivity equal to unity. It is well known that almost all of the current parameterization schemes of the DSLR need screen level information such as air temperature or water vapor pressure as model input, which are not suitable for the areas where there exists no ancillary information at the screen level. To this end, Bish et al. (2005) used air and dew point temperatures at vertical pressure level of 1000 hPa, provided by the MODerate resolution Imaging Spectroradiometer (MODIS) atmospheric product MOD07, as surrogate for the temperatures at screen level height to estimate the DSLR and NSLR. However, this scheme needs to further interpolate the MOD07 level data to obtain the screen level temperatures, assuming a hydrostatic atmosphere.

The objective of the present work is to estimate the DSLR directly from the radiances measured by MODIS TIR channels at the TOA and to subsequently combine the DSLR with the MODIS land surface temperature/emissivity products (MOD11_L2) to estimate the NSLR. MODIS provides comprehensive and frequent global earth imaging in 36 spectral channels and at the spatial resolution with nadir footprints of 1 km for its TIR channels. Although the MODIS instrument is not an atmospheric sounding instrument, it does have many thermal spectral channels to detect the radiances mainly leaving from the atmosphere and the land surface. Taking advantage of the characteristics of the TIR channels in MODIS sensor, this paper aims to develop a statistical synthetic regression method to estimate the instantaneous DSLR directly from the TOA clear-sky radiances in the MODIS TIR channels.

Section 2 presents the methodology and rationale to derive the instantaneous DSLR directly from the radiances at the TOA and subsequently to estimate the instantaneous NSLR. The retrieval errors and other issues related to the proposed method are discussed in Section 3. Section 4 describes the study region and data used in the present study and gives a preliminary validation with the field measurements. Finally, the conclusion is given in Section 5.

2. Methodology

2.1. Radiance measured by TIR channels at the TOA

On the basis of the radiative transfer theory and neglecting the scattering of thermal infrared radiation, in cloud-free skies, the channel radiance $B_i(T_i)$ received at the TOA in a TIR channel $i$ of the sensor onboard the satellite, is approximately the sum of the radiance contributions from the earth’s surface and from all levels in the atmosphere as follows,

$$B_i(T_i) = e_i(T_i)T_i(\theta, \phi, P_i \rightarrow 0) + \int_0^\infty \int_0^\pi \int_0^{2\pi} B_i(T_p) \frac{d\tau_i(\theta', \phi', P - P_i)}{\sin \theta'} \frac{d\theta'}{\sin \theta} \frac{d\phi'}{d\phi} \, dP,$$

where $T_i$ represents the channel brightness temperature observed in channel $i$ at TOA, $e_i$ is the surface emissivity in channel $i$, $T_i$ is the surface temperature, $\tau_i(\theta, \phi, P \rightarrow 0)$ is the total atmospheric transmittance along the target to sensor path in channel $i$, $\theta$ and $\phi$ are respectively the viewing zenith angle and azimuth angle, $P_i$ denotes the atmospheric pressure at ground level, $T_p$ is the air temperature at the level of atmospheric pressure $P$, $\tau_i(\theta, \phi, P \rightarrow 0)$ is the channels transmittance of the atmosphere from the level of atmospheric pressure $P$ to the TOA (pressure $0$), and $\tau_i(\theta, \phi, P \rightarrow P_i)$ is the channels transmittance of the atmosphere from the level of atmospheric pressure $P$ to the ground level $(P_i)$. The second term on the right-hand side of Eq. (1) denotes the sum of the radiance contributions from all the atmospheric levels to the measured radiance, and the third term represents the hemispheric atmospheric downwelling longwave radiation reflected by the surface and then attenuated by the atmosphere along the path from the surface to the sensor. $\frac{d\tau_i}{dP}$ is the channel weighting function which depicts the magnitude of radiance contribution from different atmospheric vertical layer. For a given channel $i$, the atmospheric layer corresponding to the channel maximum weighting function, contributes the maximum magnitude of radiance to the sensor onboard the satellite.

MODIS is a scanning spectroradiometer with 36 spectral channels between 0.405 and 14.385 μm (King et al., 1992) where the TIR channels 28–36 are capable of observing the earth’s atmosphere and surface. Table 1 lists the MODIS TIR channels. Channel 28 is a water vapor absorption channel and also provides information about the atmospheric temperature if there is enough moisture in the atmosphere. Channels 33–36 are CO$_2$ absorption channels providing atmospheric temperature information, and the window channels 29, 31, and 32 also provide some moisture information due to weak water vapor absorption (Seemann et al., 2003). Fig. 1 shows the weighting functions of the MODIS TIR channels 27–36 for a mid-latitude summer atmosphere with horizontal visibility of 23 km. As shown in Fig. 1, each MODIS TIR channel has a different weighting function, which implies that the MODIS thermal infrared channels can detect the information at different altitudes in a vertical atmospheric column. The satellite-based radiances for channel 28 is mainly from the

<table>
<thead>
<tr>
<th>Primary use</th>
<th>Band</th>
<th>Bandwidth (μm)</th>
<th>Spectral radiances (and reference temperature) (K)</th>
<th>Required NEAT (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cirrus clouds/water vapor</td>
<td>27</td>
<td>6.535–6.895</td>
<td>1.16 (240)</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>7.175–7.475</td>
<td>2.18 (250)</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>8.400–8.700</td>
<td>9.58 (300)</td>
<td>0.05</td>
</tr>
<tr>
<td>Ozone</td>
<td>30</td>
<td>9.580–9.880</td>
<td>3.69 (250)</td>
<td>0.25</td>
</tr>
<tr>
<td>Surface temperature</td>
<td>31</td>
<td>10.780–11.280</td>
<td>9.55 (300)</td>
<td>0.05</td>
</tr>
<tr>
<td>Temperature profile</td>
<td>32</td>
<td>11.770–12.270</td>
<td>8.94 (300)</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>13.185–13.485</td>
<td>4.52 (260)</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>13.485–13.785</td>
<td>3.76 (250)</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>13.785–14.085</td>
<td>3.11 (240)</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>14.085–14.385</td>
<td>2.08 (220)</td>
<td>0.35</td>
</tr>
</tbody>
</table>
2.2. Retrieval of the DSLR from the satellite measured radiances

2.2.1. Rationale

The Downwelling Surface Longwave Radiation (DSLR, 4.0–100 μm), for cloud-free conditions, is the result of atmospheric absorption, emission and scattering of the entire atmospheric column, and it depends on the vertical profiles of temperature and gaseous absorbers. However, the DSLR is determined effectively only by the radiation emitted in a shallow layer close to the surface. Nearly 80% of the longwave radiation reaching the surface is emitted within the lowest 500 m of the atmosphere (Schmetz, 1991).

It should be emphasized here that the radiances measured by the TIR channels at the TOA are strongly dependent on the channel weighting functions. In other words, the channel radiances contributed from the surface and each atmospheric layer mainly rely on their weighting functions. From Fig. 1, one can see that the radiances of channels 33 and 34 are mainly from the upwelling radiances of the near-surface atmosphere, and partly from the upwelling radiances of the surface. Channels 28 and 36 can provide the information of the upper layers of the troposphere and stratosphere, respectively, which can be used to correct for theirs in the other TIR channels. Channels 29 and 31 provide mainly the information emitted by the surface and each atmospheric layer at pressure about 590 hPa, and 850 hPa for channel 33, 660 hPa for channel 34, and 320 hPa for channel 36. Channels 29, 31, and 32 are window channels.

\[
\text{DSLR} = a_0(\theta, z) + \sum_{i=1}^{n} a_i(\theta, z)M_i
\]  

(2)

with

\[
M_i = \pi \times L_i(\theta)
\]  

(3)

where \(a_0\) and \(a_i\) are conversion coefficients, which are functions of the satellite Viewing Zenith Angle (VZA) \(\theta\) and the terrain altitude \(z\), and \(L_i\) is the TOA radiance (W/(m² sr μm)) measured by the MODIS TIR channel \(i\).

2.2.2. Retrieval algorithm

The atmospheric radiative transfer model MODTRAN 4 (Berk et al., 1998) is used to simulate the MODIS data measured at the TOA. In our MODTRAN simulations, eight surface emissivity spectra, collected from the ASTER spectral library (http://speclib.jpl.nasa.gov/), are employed, including vegetation canopy, grassland, wetland, and sandy loam, barren-desert, urban, ocean water and fresh snow, their spectral emissivities are shown in Fig. 2. Since there is no spectral emissivity available beyond the wavelength 14 μm, and considering the strong absorption of the atmosphere at the spectra wavelength larger than 14 μm, the surface emissivity used in MODTRAN simulation beyond this wavelength is assumed to be unity in our simulations.

Keeping in mind that a practical DSLR algorithm should accommodate atmospheric variations wide enough to cover all possible real situations, two radiosonde observation databases are considered in our simulation. One is the latest version of the Thermodynamic Initial Guess Retrieval (TIGR) database TIGR2002, which was constructed by the Laboratoire de Météorologie Dynamique (LMD) and represents a worldwide set of atmospheric situations (2311 radiosoundings) from polar to tropical atmosphere with varying water vapor amounts ranging from 0.1 to 8 g/cm², and varying atmospheric surface temperature from 231 K to 315 K (http://ara.lmd.polytechnique.fr/htdocs-public/products/TIGR/TIGR.html). The other is the six standard atmospheric profiles (tropical, mid-latitude summer, mid-latitude winter, sub-arctic summer, sub-arctic winter, and US76) stored in the MODTRAN 4. As we only consider atmospheric variation in clear-sky conditions for DSLR retrieval, the profiles with relative humidity at one of levels greater than 90% in TIGR2002 are discarded since this seldom happens under clear-sky conditions. Therefore, 1413 representative atmospheric situations are extracted from TIGR2002. In total, 1419 atmospheric profiles are used in our simulation.

Taking into account the angular dependence of the TOA radiance and the maximum MODIS viewing zenith angle (less than 65° from nadir), different viewing zenith angles varying from 0° to 60° are used in MODTRAN simulations to compute simultaneously the TOA radiances of MODIS TIR channels and the DSLR. In addition, different altitude values of surface relative to sea level, ranging from 0 km to 2.5 km, are considered in our investigations. On the basis of the above simulated data pairs of TOA radiances \(L_i\) and the corresponding DSLR, for a given viewing zenith angle and a given altitude value and

![Fig. 1. Weighting functions (dφ/dlnP) for MODIS infrared channels as functions of pressure (hPa), calculated with the mid-latitude summer atmosphere and horizontal visibility of 23 km in MODTRAN 4 using a sensor view angle of 0°.](Image 67x508 to 252x741)

![Fig. 2. Spectral emissivity curves of eight surface types used in MODTRAN simulation.](Image 326x66 to 529x215)
assuming that the earth surface is Lambertian, a linear relationship between the TOA radiances \( L_i \) and the DSLR as described in Eq. (2) can be obtained by a statistical synthetic regression method.

The statistical regression algorithm used here is based on the stepwise regression method in the Statistical Package for the Social Sciences (SPSS) procedure. The MODIS TIR channels are subsequently added as features to a multi-linear model, based on the ability to improve the fit of the model with the data. Keeping in mind that more channels can bring more instrumental errors, the selection of the TIR channels is the result of a trade-off between the number of channels used and the resultant accuracy. In other words, the selection procedure is stopped when improvement in the stepwise regression method in the Statistical Package for the Social Sciences (SPSS) procedure is obtained by a statistical synthetic regression method.

It is well known that longwave radiation is influenced by surface emissivity. In order to see how significant the effect of the surface type on the accuracy of the DSLR retrieval is, the regression coefficients are derived as functions of the surface types. Eq. (3) shows the comparison of the actual DSLRs (i.e. the MODTRAN 4 simulated DSLRs) and those estimated using Eq. (4) with the coefficients \( a_i (i=0, 6) \) derived for different surface types for VZA=0° and \( z=0 \) km. The histograms of the difference of the actual and estimated DSLRs for different surface types are depicted in Fig. 4. As shown in this figure and Table 2, the Root Mean Square Errors (RMSEs), vary from 6.5 W/m² to 12.3 W/m² for different surface types.

On the other hand, we determine the regression coefficients \( a_i (i=0, 6) \) without discriminating the different surface types. But the dataset is divided into two groups randomly. One group with 80% cases is used as independent training dataset to fit the model described by Eq. (4), and another group with remaining 20% cases is used as testing dataset for determination of the quality of our fit. As an example, Figs. 5 and 6 show the comparison of the actual DSLRs (i.e. the MODTRAN 4 simulated DSLRs) and those estimated using Eq. (4) with the coefficients \( a_i (i=0, 6) \) stored in the look-up table for VZA varying from 0° to 60° and for different surface altitudes ranging from 0 km to 2.5 km, is established and will be used in the following calculations.

Note that the TOA radiance of the MODIS TIR channel depends on the variations of the Viewing Zenith Angle (VZA) and the surface altitude, \( z \), a look-up table of regression coefficients \( a_i (i=0, 6) \), for VZA varying from 0° to 60° and for different surface altitudes ranging from 0 km to 2.5 km, is established and will be used in the following calculations.

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Table 2

<table>
<thead>
<tr>
<th>Surface types</th>
<th>Barren desert</th>
<th>Broadleaf</th>
<th>Fresh snow</th>
<th>Grass land</th>
<th>Ocean water</th>
<th>Sand loam</th>
<th>Urban</th>
<th>Wet land</th>
<th>All types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum error (W/m²)</td>
<td>−62.6</td>
<td>−65.4</td>
<td>−79.2</td>
<td>−21.4</td>
<td>−77.8</td>
<td>−29.7</td>
<td>−66.2</td>
<td>−46.1</td>
<td>−81.2</td>
</tr>
<tr>
<td>Maximum error (W/m²)</td>
<td>46.3</td>
<td>57.4</td>
<td>55.5</td>
<td>38.6</td>
<td>55.6</td>
<td>45.1</td>
<td>55.7</td>
<td>58.1</td>
<td>57.8</td>
</tr>
<tr>
<td>RMSE (W/m²)</td>
<td>10.4</td>
<td>12.0</td>
<td>12.3</td>
<td>6.5</td>
<td>12.3</td>
<td>8.3</td>
<td>11.8</td>
<td>11.3</td>
<td>12.4</td>
</tr>
</tbody>
</table>

Fig. 3. Comparison of the actual DSLRs (i.e. the MODTRAN 4 simulated DSLRs) and those estimated using Eq. (4) with the regression coefficients \( a_i (i=0, 6) \) obtained for different surface types.

Fig. 4. Histograms of the differences of the actual and estimated DSLRs for different surface types, for VZA=0° and surface altitude \( z=0 \) km.

Fig. 5. Comparison of the actual downwelling surface longwave radiation for the training dataset, for different types of surfaces and cloud-free conditions, with those estimated using Eqs. (4) and (3) with coefficients \( a_i (i=0, 6) \) stored in the look-up-table for VZA=0° and surface altitude \( z=0 \) km.
the RMSE increases with the increase of the VZA;  
2) the RMSE increases with the increase of the surface altitude if the surface altitude is below about 1 km and the opposite is found for the surface altitude above 1 km, which may be caused by the turning points around 1 km found in most of the atmospheric temperature profiles in the TIGR2002 and the MODTRAN standard atmospheres;  
3) the maximum (16.8 W/m²) and the minimum (11.2 W/m²) of the RMSE are found respectively at VZA=60°, z=1.0 km and VZA=0°, z=2.5 km.

It should be pointed out here that due to the coarser spatial resolution of MODIS sensors and other factors, accurate classification of surface types is still problematic, and considering the fact that the DSLR could be retrieved with RMSE about 12 W/m² for VZA=0° and z=0 km without discriminating the surface types, and the improvement in the accuracy of DSLR retrieval is not significant if the surface types are taken into account in the retrieval (see Table 2 and Figs. 3 and 4), the coefficients in Eq. (4) corresponding to all the surface types will be used in the following calculations.

2.3. Retrieval of NSLR

The Net Surface Longwave Radiation (NSLR) is defined as the difference between the DSLR and the upwelling surface longwave radiation emitted and reflected by the earth’s surface, i.e.

$$\text{NSLR} = \text{DSLR} - \varepsilon_s T_s^4 - (1 - \varepsilon_s)\text{DSLR}$$

where \(\sigma\) is the Stefan–Boltzmann constant \((5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4})\), \(\varepsilon_s\) is surface emissivity, and \(T_s\) is surface skin temperature (Kelvin). The third term on the right-hand side of Eq. (5) accounts for the reflected radiation by the surface.

From the MODTRAN simulations in Section 2.2.2, we can also obtain the data pairs of TOA radiances and the corresponding NSLR for a given viewing zenith angle and a given altitude value in cloud-free conditions. With the same rationale given in Section 2.2.1, we initially try to estimate the NSLR also directly from the radiances measured at the TOA by the MODIS TIR channels. But unfortunately we have not obtained a good regression model. Consequently, we turn to use Eq. (5) to estimate the NSLR with the DSLR retrieved using our proposed algorithm developed in Section 2.2.2 and \(T_s\), \(\varepsilon_s\) extracted from the MODIS land surface temperature/emissivity products.

3. Sensitivity analysis

Note that the accuracy of the DSLR retrieval depends also on the instrument calibration, navigation, and co-registration in the infrared channels. Several sources of error must be taken into account. The MODIS instrument detector noise and calibration error can have an impact on the retrieval accuracy. Detector-to-detector differences in the spectral response functions within a channel have been shown to produce 0.5%–1.0% difference in radiance measurements in the TIR channel (Seemann et al., 2003). This is seen as detector striping within a scene.

Note that the DSLR is not actually linear to MODIS channel radiances at the TOA as formulated in Eq. (1). The proposed method of retrieval DSLR using Eq. (4) is just for simplicity and time efficiency. Consequently, we calculate the retrieval error transferred by our proposed model. Calculating the partial derivative of Eq. (4) leads to

$$\delta\text{DSLR} = \sum_{i=1}^{n} a_i^2 \delta M_i^2$$

Considering the MODIS instrument error of 0.25 K for the TOA brightness temperatures in channels 28, 33 and 34, and of 0.05 K for channels 29 and 31, and of 0.35 K for channel 36 (see the last column in Table 1), the corresponding radiation error \(\delta M\) at the TOA for channels 28, 33 and 34 are 0.05, 0.06, 0.05, and for channels 29 and 31
are 0.03, 0.02, and for channel 36 is 0.05 \( \text{W/(m}^2 \ \mu\text{m}) \), respectively. Combining the conversion coefficients \( a_i \ (i=1, 6) \) for \( VZA=0^\circ \) and \( z=0 \ \text{km} \), for example, we can get the retrieval error, transferred by our proposed model, of 4.3 \( \text{W/m}^2 \) for the DSLR. The total error of the present algorithm is, therefore, written as

\[
\delta\text{DSLR}_{\text{tot}} = \sqrt{\delta\text{DSLR}^2 + \text{RMSE}_{\text{DSLR}}^2}
\]

where \( \delta\text{DSLR} \) is the error related to the instrumental noise, and \( \text{RMSE}_{\text{DSLR}} \) is the error caused by the proposed model itself. Finally, the overall error of the retrieval, for \( VZA=0^\circ \) and \( z=0 \ \text{km} \), is 13.1 \( \text{W/m}^2 \) for the DSLR.

It should be pointed out that the error is dominated by the model error, as the contribution of the instrumental uncertainty to the overall error is comparatively small: the square of 4.3 is much smaller than the square of 12 (only about 10%).

4. Application to actual MODIS data

4.1. Data

4.1.1. MODIS satellite data

The MODIS instrument is operating on both the Terra and Aqua spacecraft. It has a viewing swath width of 2330 km and views the entire surface of the earth every one to two days. MODIS provides, currently, about 44 data products and they are divided into following five sections—calibration, atmosphere, land, cryosphere and ocean—which renders scientists a new opportunity for global monitoring of terrestrial ecosystems. The MODIS datasets used for the present study consist of MOD021KM, MOD03 and MOD35_L2, which are available in Hierarchical Data Format (HDF) and provided by NASA Goddard Space Flight Center (GSFC) Level 1 and Atmosphere Archive and Distribution System (LAADS) (http://ladsweb.nci.nasa.gov/data/). The MOD021KM data, calibrated Earth View data at 1 km resolution by the MODIS Characterization and Support Team (MCST), are TOA radiances and reflectances. The radiances of six thermal infrared channels 28, 29, 31, 33, 34 and 36 in MOD021KM listed in Table 1 are used in this study. The geolocation dataset, MOD03, provides latitude, longitude, ground elevation, solar zenith and azimuth angles, and satellite zenith and azimuth angles for each 1 km sample. The satellite zenith angle is used to compute DSLR in this work. The MOD35_L2 is a cloud mask product which gives a clear-sky confidence level (clear, probably clear, uncertain, cloudy) to each IFOV.

In addition, in order to compare with the results obtained using the scheme proposed by Bisht et al. (2005), the MODIS atmospheric profile product MOD07, providing air and dew temperature profiles with spatial resolution of 5 km at 20 vertical atmospheric pressure levels (5, 10, 20, 30, 50, 70, 100, 150, 200, 250, 300, 400, 500, 620, 700, 780, 850, 920, 950, 1000 hPa corresponding approximately to surface altitudes of 36, 32, 27, 24, 21, 19, 15.8, 14, 12.1, 10.8, 9.5, 7.5, 5.8, 3.9, 3.1, 2.2, 1.5, 0.8, 0.55, 0.1 km, respectively), is also used to calculate the DSLR. Moreover, for the comparison of the NSLR estimated with the

<table>
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<td>IGBP class</td>
<td>Natural Vegetation</td>
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Fig. 9. Location of the six study sites in the United States.

Fig. 10. Number of days with cloud-free conditions at the moment of MODIS overpass in 2006 for the six studied sites.
method (Eq. (5)), the MODIS Land Surface Temperature (LST) and emissivity data, MOD11_L2, providing LST retrieved by the generalized split-window algorithm (Wan and Dozier, 1996) and emissivities in bands 31 and 32 estimated by the classification-based emissivity method (Snyder and Wan, 1998), at 1 km spatial resolution, are used to estimate the upwelling surface longwave radiation in our study.

4.1.2. The Surface Radiation Budget Network (SURFRAD) data
The Surface Radiation Budget Network (SURFRAD) was established in 1993 through the support of NOAA’s Office of Global Programs. Its primary mission is to support climate research with accurate, continuous, long-term measurements of the surface radiation budget over the United States. The primary measurements of SURFRAD are upwelling and downwelling solar and infrared radiations, direct and diffuse solar radiations, photosynthetically active radiation, ultraviolet radiation (UV-B, 290 nm–320 nm), and meteorological parameters. SURFRAD data are available in daily files of three-minute data [http://www.srrb.noaa.gov/surfrad/surfpage0.html]. The outgoing and incoming longwave radiations are measured with the Precision Infrared Radiometer (PIR) that is sensitive to the spectra range from 3.0 to 50 μm and has the instrumental error within 11 W/m² [http://www.srrb.noaa.gov/surfrad/surfpage4.html]. The downwelling thermal infrared radiation and net infrared radiation are used to preliminarily validate the retrievals of the DSLR and the NSLR from MODIS TIR data using our proposed methods (Eqs. (4) and (5)).

4.2. Study regions of the United States
The SURFRAD sites include Bondille, Illinois; Boulder, Colorado; Desert Rock, Nevada; Fort Peck, Montana; Goodwin Creek, Mississippi; Penn State, Pennsylvania; and Sioux Falls, South Dakota [http://www.srrb.noaa.gov/surfrad/sitepage.html]. The radiation data provided by Bondille, Boulder, Desert Rock, Goodwin Creek, Penn State, and Sioux Falls, whose locations are illustrated in Fig. 9, are used in the

![Fig. 11. Comparison between the DSLRs estimated respectively using the proposed method and Bisht et al.’s (2005) scheme, and those measured in-situ at the six studied sites for cloud-free conditions at the moment of MODIS overpass in 2006 (R² is the square of the correlation coefficient).]
present study. Since there were not many days with cloud-free conditions at the moment of MODIS overpass in 2006 for site Fort Peck, this site is not selected in this study. The detailed information of these six selected locations is given in Table 3. The land cover types given in this table are based on the MODIS/Terra Land Cover Types Yearly L3 Global 0.05Deg CMG product, MOD12C1, providing IGBP classification schemes at a 0.05° (~5600 m) spatial resolution (http://edcdaac.usgs.gov/modis/mod12c1v4.asp).

4.3. MODIS data processing

Based on the clear-sky confidence level (clear, probably clear, uncertain, cloudy) assigned to each pixel in the MODIS cloud mask product, MOD35, clear and probably clear pixels are taken as clear, and uncertain and cloudy pixels are taken as cloudy in our study. The cloudy pixels are then screened out in our retrieval procedures of the DSLR and the NSLR.

4.4. Results and validations

4.4.1. Results of the DSLR

One of the objectives of the present work is to estimate the instantaneous DSLR using the method proposed in Section 2.2. To validate our proposed method, the in-situ measurements of SURFRAD data are chosen in this study. Fig. 10 illustrates the total numbers of days with cloud-free conditions at the moment of MODIS overpass in 2006 for the six studied sites.

Fig. 11 gives the comparison between the DSLRs estimated from MODIS TIR data using Eq. (4) and the observed SURFRAD data from studied locations A, B, C, D, E and F, respectively, for all days with cloud-free conditions at the moment of MODIS overpass in 2006. The three-minute means of ground observed SURFRAD data are used. Moreover, taking into account that a pyrgeometer actually often sees more than a 1×1 km region of the sky, the mean value of instantaneous estimated DSLRs for 3×3 pixels with 1 km resolution of MODIS data is used in this comparison. This figure shows that the Root Mean Square Errors (RMSE) of the DSLRs between two different measurements (ground and our satellite-based method) are 29.4, 39.3, 25.7, 36.6, 23.6, and 27.6 W/m² for sites A, B, C, D, E and F, respectively. In addition, Table 4 also lists the bias, RMSE and the square of the correlation coefficients between the in-situ measured DSLRs and those estimated using satellite data. One can see that the DSLRs estimated using our proposed method are highly correlated with the in-situ measured DSLRs with the square of the correlation coefficients ($R^2$) larger than 0.90 for the six studied sites.

In order to compare the DSLR estimated using our proposed method (Eq. (4)) with the DSLR estimated using the existing scheme proposed by Bisht et al. (2005), the DSLRs of the six selected SURFRAD sites for all days in 2006 with cloud-free conditions at the moment of MODIS overpass, are estimated once again using Prata’s (1996) scheme, i.e.

$$\text{DSLIR} = \sigma_a T_a^4$$  \(8\)

where $\sigma$ is the Stefan–Boltzmann constant ($5.67\times10^{-8}$ W m$^{-2}$ K$^{-4}$), $T_a$ is the air temperature (K) at screen level, $\sigma_a$ is the effective air emissivity which can be estimated by

$$\sigma_a = 1 - (1 + \zeta)\exp\left(-1.2 + 3.0\zeta^{1/2}\right)$$  \(9\)

in which $\epsilon_0$ is the water vapor pressure (hPa) at screen level, which can be computed using the dew point temperature according to the Clausius–Clapeyron equation as:

$$\epsilon_0 = 6.11\exp\left[L_v \left(\frac{1}{T_0} - \frac{1}{T_d}\right)\right]$$  \(10\)

where $L_v$ is the latent heat of vaporization ($2.5\times10^6$ J kg$^{-1}$), $R_v$ is the gas constant for water vapor (461 J kg$^{-1}$ K$^{-1}$), $T_0=273$ K and $T_d$ is the dew point temperature (K) at screen level.

Bisht et al. (2005) proposed to use the air and dew point temperatures at vertical pressure level of 1000 hPa given by the MODIS atmospheric profile product MOD07 as surrogates for the temperatures at screen level height. However, since the earth’s terrain altitude changes from one place to another, it may be not appropriate to use a constant pressure level (1000 hPa) for all pixels. Therefore, in order to take into account the terrain altitude, the air and dew point temperatures are obtained by interpolating the MOD07 level data to the screen level height, assuming a hydrostatic atmosphere in this study.

![Fig. 12. Comparison between the DSLRs estimated respectively using the proposed method and Bisht et al.’s (2005) scheme, and those measured in-situ for cloud-free conditions at the moment of MODIS overpass in 2006 for all sites ($R^2$ is the square of the correlation coefficient).](image-url)
for each study site. The DSLRs estimated using Bisht et al.’s (2005) scheme with MOD07 data at screen level height are also showed in Fig. 11 for the comparison, and the bias, RMSE and the square of the correlation coefficients between the in-situ measured DSLRs and those estimated using Bisht et al.’s scheme are also listed in Table 4. Moreover, the actual DSLRs and those estimated with different methods for all sites are displayed in Fig. 12, and the bias and RMSE for all of these sites are also included in the last column of Table 4. From this figure and Table 4, we can see that the bias, RMSE and the square of the correlation coefficient ($R^2$) between the MODIS derived DSLR with the proposed method and the field measured DSLRs, are 20.3 W/m², 30.1 W/m² and 0.91 respectively. From Figs. 11, 12 and Table 4, we notice also that our proposed method (Eq. (4)) for estimating DSLR from the MODIS radiances at the TOA gives results comparable, at least for our cases, to those estimated with Bisht et al.’s (2005) scheme. One should also keep in mind that the ground data measured at six SURFRAD sites are point-based scale, while the

retrievals with MODIS data using our proposed method (Eq. (4)) and Bisht et al.’s scheme correspond to the spatial resolution of 3 km and 5 km, respectively. The data measured at ground level are assumed to represent the same spatial scale as that derived from MODIS data, which may lead to large discrepancies if the ground stations are located in a heterogeneous area. Furthermore, the instrumental error within 11 W/m² for pyrgeometer associated with the ground measurements should also be kept in mind when the comparison is performed. Taking the above mentioned sources of error into account, the DSLRs obtained by our proposed method (Eq. (4)) directly from the MODIS TIR data are in agreement with the ground measured DSLRs and comparable to the DSLRs obtained by Bisht et al.’s scheme.

4.4.2. Results of the NSLR

In order to reduce the sources of error for estimating the Net Surface Longwave Radiation (NSLR), we proposed to estimate the NSLR using Eq. (5) with the DSLR estimated using our proposed method

![Fig. 13. Comparison between the NSLRs estimated respectively using the proposed method and Bisht et al.’s (2005) scheme, and those measured in-situ at the six studied sites for cloud-free conditions at the moment of MODIS overpass in 2006 ($R^2$ is the square of the correlation coefficient).]
(Eq. (4)). The land surface skin temperature (Kelvin) \( T_s \) is extracted from MODIS Land Surface Temperature (LST) and emissivity products, MOD11_L2. The land surface emissivity \( \varepsilon_s \) is calculated from MOD11_L2 data by using a nonlinear formula (Li, 2004) as

\[
\varepsilon_s = 0.273 + 1.778\varepsilon_{31} - 1.807\varepsilon_{31}\varepsilon_{32} - 1.037\varepsilon_{32} + 1.774\varepsilon_{32}^2
\]

where \( \varepsilon_{31} \) is the emissivity in MODIS channel 31, and \( \varepsilon_{32} \) is the emissivity in MODIS channel 32.

A preliminary validation of our proposed method (Eqs. (4) and (5)) is performed for the six studied sites with cloud-free conditions at the moment of MODIS overpass in 2006. The comparisons of the NSLRs between the ground measurements from SURFRAD data and those estimated from the MODIS TIR data are shown in Fig. 13. As shown in this figure, the Root Mean Square Errors (RMSE) of the NSLR between two different measurements (ground and our satellite-based method) are 22.3, 32.6, 25.4, 25.8, 18.6, and 26.8 W/m² for sites A, B, C, D, E, and F, respectively. The corresponding bias, RMSE, and the square of the correlation coefficients \( R^2 \) are also listed in the last column of Table 4.

In addition, in order to compare the NSLR estimated using our proposed method with the NSLR estimated using the existing scheme proposed by Bisht et al. (2005), the NSLRs of the six selected SURFRAD sites for all the days with cloud-free conditions at the moment of MODIS overpass in 2006 are estimated once again using Bisht et al.’s scheme, according to Eq. (5). The DSLR is computed by Eq. (8) with the air and dew point temperatures interpolated by the MOD07 level data to the screen level height assuming a hydrostatic atmosphere.

The comparisons of NSLRs between the field measurements and those estimated using Bisht et al.’s scheme with the emissivity and land surface temperature extracted from MOD11_L2 product, for the six studied sites in 2006, are also showed in Fig. 13. In addition, the actual NSLRs and those estimated with different methods for all sites are displayed in Fig. 14 and the bias and RMSE for all of these sites are also included in the last column of Table 4. From Fig. 14 and Table 4, we can see that the bias, RMSE and the square of the correlation coefficient \( R^2 \) between the MODIS derived DSLR with the proposed method and the field measured NSLR are 11.7 W/m², 26.1 W/m² and 0.94 respectively. From Figs. 13, 14 and Table 4, we notice also that, at least for our cases, the two methods give the comparable NSLRs.

It should be pointed out here that all the SURFRAD sites used are limited to a range from 34 to 44° North, thus only one climate region. Also, as there are no other ground measurements available to us, no validation is done over snow/desert/sea surface. A further validation to take all these issues into account will be worked on in the future.

5. Conclusions

In this work, we have developed a simple statistical regression method to estimate instantaneous Downwelling Surface Longwave Radiation (DSLR) directly from the TOA radiances of MODIS TIR data for cloud-free conditions. The simulation analysis showed that the instantaneous DSLR could be estimated by the proposed method with the Root Mean Square Error (RMSE) of 12.4 W/m² for VZA=0° and terrain altitude z=0 km. Similar results were obtained for the other VZAs and altitudes.

In order to show the retrieval accuracy of the proposed method, the field measurements made at six sites of the Surface Radiation Budget Network (SURFRAD) in the United States for days with cloud-free conditions at the moment of MODIS overpass in 2006, have been used to validate preliminarily the resultant DSLR and NSLR estimated using the proposed method with MODIS data. The results showed that the bias, RMSE and the square of the correlation coefficient \( R^2 \) between the MODIS derived DSLR with the proposed method and the field measured DSLR are 20.3 W/m², 30.1 W/m² and 0.91 respectively, and bias=11.7 W/m², RMSE=26.1 W/m² and \( R^2 = 0.94 \) for the NSLR.

In addition, to further demonstrate the proposed method, the scheme proposed by Bisht et al. (2005), which requires the MODIS atmospheric profile product (MOD07) and the MODIS land surface temperature/emissivity products (MOD11_L2) as inputs, has also been used to estimate the instantaneous DSLR and NSLR for comparison with the field measurements as well as the MODIS derived DSLR and NSLR using our proposed method. The results of the comparisons showed that, at least for our cases, the proposed method for estimating DSLR and NSLR gives results comparable to those estimated with Bisht et al.’s (2005) scheme. However, the proposed method is more simple and time efficient than that of the Bisht et al.’s scheme.

We acknowledge that the proposed method adopts only a statistical synthetic regression method. Nonetheless, the proposed linear model has been obtained from off-line simulations done with a complex atmospheric radiative transfer model. Moreover, the methodology attempts to overcome the shortcomings of the conventional models which need ground meteorology data as model input.

Digital values of the coefficients of the linear regression coefficients for estimating the DSLR can be requested via electronic mail to lizl@igsnrr.ac.cn.

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