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# Estimation of surface upward longwave radiation from MODIS and VIIRS clear-sky data in the Tibetan Plateau

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ABSTRACT

Surface upward longwave radiation (SULR) is one critical component of the surface energy balance and is closely related to the surface temperature fields. The SULR with the moderate spatial resolution and appropriate precision in the Tibetan Plateau, a large and complex cryosphere, can enhance our understanding of the land surface processes, atmospheric circulations and even global climate change. The purpose of this paper is to estimate SULR from top-of-atmosphere (TOA) radiances of Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS). A hybrid method is proposed that combines extensive radiative transfer simulation and the Artificial Neuron Network (ANN) statistical model. For the sake of ensuring the availability of the simulation database, the eligible profiles from MODIS atmospheric profiles product were screened according to five criteria. And then the analyses on the important parameters of the simulation dataset were performed to check the integrality of this dataset. Moreover, the variables' importance was analyzed, and TOA radiances of MODIS channels 29, 31, 32 and 33 (or VIIRS channels M14, M15 and M16) and sensor view zenith angle (VZA) were selected to retrieve SULR. The ANN-based retrieval model was created finally based on this simulation dataset. The evaluation showed good agreements for both MODIS and VIIRS training and testing datasets with $R^2$ greater than 0.98. The MODIS SULR was validated using two-year ground-measured data at seven sites in the Tibetan Plateau with $R^2$ of 0.886, root-mean-square error (RMSE) of 26.985 W $m^{-2}$ and mean bias error (MBE) of 10.812 W $m^{-2}$ as a whole. And the relevance was obvious from the overall trend and distribution though the discrepancy was relatively large when directly comparing SULR from VIIRS and MODIS data. The validation results showed that the ANN model is a good nonlinear model to retrieve SULR with the TOA radiances and VZA.


## 1. Introduction

The Tibetan Plateau, known as the "Third Polar", is the large highland core of Asia with an average elevation of over 4500 m (Qiu, 2008). This complex cryosphere significantly influences climate and environment of the East and South Asia as well as mankind resides there (Wonsick & Pinker, 2013). This unique region is also sensitive to water cycles and global climate changes, thus can be a good indicator to investigate what happened to the system of the Earth (Yang et al., 2014). The surface radiation balance (SRB) is an important component within it (Shi & Liang, 2013; Yang, Koike, Stackhouse, Mikovitz, & Cox, 2006).

Surface radiation balance includes net longwave and shortwave radiative fluxes, which are the critical driving factors in models of numerical weather forecasting, hydrology, ecology, etc. SRB is also the essential parameter in the energy exchanges between the land surface and atmosphere, thus thoroughly impacts climate and land cover changes (Soci, Fischer, & Horányi, 2006). As a significant part of the SRB, surface longwave radiation plays an essential role in the surface material and energy cycle, particularly in the night, high altitude and polar regions. The surface longwave radiation consists of three components: upward, downward and net radiation. Surface upward longwave radiation (SULR) mainly represents the capability of thermal radiation from the Earth's surface and is related to the solar radiation, evapotranspiration, soil moisture, land cover types and topography. Accurate retrieval of SULR is important for investigating the spatiotemporal variability of SULR on regional and global scales, thus has high scientific and practical merits.

SULR (4–100 μm) is the total upward component of the thermal infrared radiative flux at the Earth's surface in W $m^{-2}$, which is the

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sum of surface emitted thermal radiation and the first-order reflected component of surface downward longwave radiation (SDLR) as follows:

$$SULR = \varepsilon\sigma T^4 + (1-\varepsilon)SDLR, \quad (1)$$

where σ is the Stefan–Boltzmann constant; ε is the surface broadband emissivity; and T is the surface skin temperature (K). According to the Kirchhoff's law and conservation of energy, the surface broadband albedo is equal to one minus the broadband emissivity. SDLR is the total downward thermal radiative flux density emitted by the atmosphere and clouds that reaches the earth's surface. SULR is dominated by the thermal inertia of the land or ocean (Mlynczak, Smith, Wilber, & Stackhouse, 2011), and is the main cause of surface cooling in the clear night (Helbig & van Herwijnen, 2012).

SULR can be retrieved according to its definition in Eq. (1), which can be called the temperature-emissivity method (Long, Gao, & Singh, 2010; Wang et al., 2005; Wang, Liang, & Augustine, 2009). The surface skin temperature and emissivity data can be derived from the satellite data, like Moderate Resolution Imaging Spectroradiometer (MODIS) products. SDLR can be obtained from ground-measured data, reanalysis data or results simulated by radiation transfer models (Abramowitz, Pouyanné, & Ajami, 2012; Nussbaumer & Pinker, 2012).

Hybrid method is a physical-based retrieval approach to estimate SULR from satellite data. Firstly, extensive simulation database is established by radiation transfer codes, which includes SULR, top-of-atmosphere (TOA) radiances or brightness temperatures of a multispectral satellite sensor and various key variables associated with the different surface properties (such as surface emissivity, skin temperature) and atmospheric conditions (air temperature, water vapor content etc.). Secondly, SULR is derived using statistical regression analysis, like linear methods (Wang & Liang, 2010; Wang et al., 2009) or nonlinear methods (Wang et al., 2009; Wang, Yan, & Chen, 2012). The results of Wang et al. (2009) shows that the root-mean-square error (RMSE) of the hybrid method using the Artificial Neuron Network (ANN) model is smaller than linear models, indicating the advantage of nonlinear models.

Generally, all of the biases and limits of data products affect the final SULR. Temperature-emissivity method requires data products of surface skin temperature, emissivity and SDLR. However, the state-of-art products estimated from remotely sensed data still have great uncertainty (Wang & Liang, 2009). Narrowband emissivity data have to be converted to the broadband emissivity (Ren, Liang, Yan, & Cheng, 2013; Wang et al., 2005). The anisotropy of the surface emissivity retrieved from satellite images can further aggravate this uncertainty (Ren, Yan, Chen, & Li, 2011; Ren et al., 2014). In addition, SDLR is not a ready-made data: ground-measured data usually mismatch with satellite data; and reanalysis data always have coarser spatial resolution. There are many input parameters in Wang's model which used the hybrid method, such as air and dew point temperature profiles (Wang et al., 2012). These parameters may bring in more uncertainties than the increased accuracy to the estimated SULR. Therefore, more input variables don't always mean higher accuracy.

**Table 1**
The band characteristics of MODIS and VIIRS data.

| Sensor | Band number | Band range (μm) | NEΔT (K) | Nadir resolution (m) |
|---|---|---|---|---|
| MODIS | 29 | 8.400–8.700 | 0.05 | 1000 |
| | 31 | 10.780–11.280 | 0.05 | |
| | 32 | 11.770–12.270 | 0.05 | |
| | 33 | 13.185–13.485 | 0.25 | |
| VIIRS | M14 | 8.4–8.7 | 0.091 (270 K) | 750 |
| | M15 | 10.26–11.26 | 0.070 (300 K) | |
| | M16 | 11.54–12.49 | 0.072 (300 K) | |

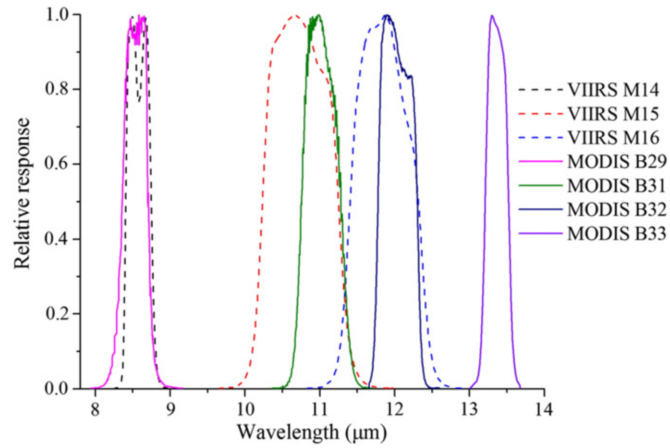


**Fig. 1.** The spectral response functions of MODIS channels 29, 31, 32 and 33, and VIIRS channels M14, M15 and M16.

Currently, there are various global surface longwave radiation products retrieved from remote sensing data, such as International Satellite Cloud Climatology Project dataset (ISCCP-FD) (Zhang, Rossow, Lacis, Oinas, & Mishchenko, 2004), Global Energy and Water Exchanges Project (GEWEX) surface radiation budget dataset (Pinker & Laszlo, 1992), Clouds and Earth's Radiant Energy System (CERES) dataset (Kato et al., 2013) and the Satellite Application Facility on Climate Monitoring (CM-SAF) (Schulz et al., 2009) data products of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). In addition, there are many reanalysis products including SULR, like Climate Forecast System Reanalysis (CFSR) of the National Centers for Environmental Prediction (NCEP), NASA's Modern Era Retrospective Analysis for Research and Application (MERRA), Interim Reanalysis (ERA-Interim), and Japanese 55-year Reanalysis (JRA-55). These available products are designed for large-scale models, which always have high temporal resolution (1–3 h), but generally low spatial resolution (38 km to 2.5°). So they cannot satisfy the requirements of many applications, like high-resolution (about 1–5 km) forecast systems, mesoscale land surface or environmental models (Guan, Tremblay, Isaac, Strawbridge, & Banic, 2000; Masson, Champeaux, Chauvin, Meriguet, & Lacaze, 2003). In heterogeneous areas or mountainous terrains, the surface longwave radiation is more significantly variable and the high-resolution (about 1 km) radiation data are preferred. Furthermore, acceptable precision of the retrieved instantaneous surface radiation from satellite data is less than 20 W $m^{-2}$, monthly mean value is less

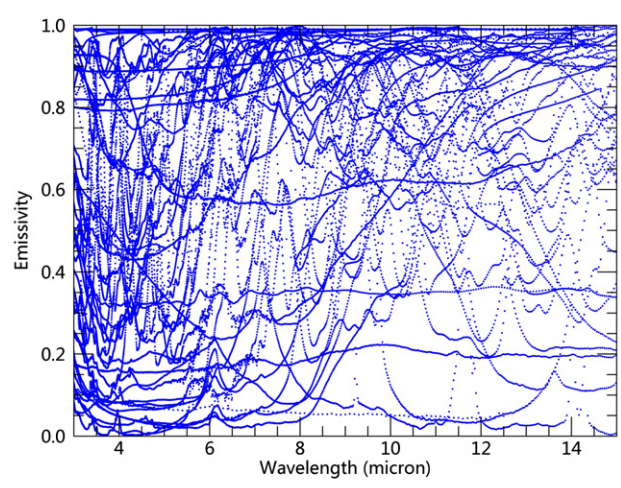


**Fig. 2.** Spectral emissivity curves used in the MODTRAN simulation from ASTER, UCSB and MODTRAN spectral libraries.