



On the determination of atmospheric longwave irradiance under all-sky conditions



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ABSTRACT

In this work we review and recalibrate existing models, and present a novel comprehensive model for estimation of the downward atmospheric longwave (LW) radiation for clear and cloudy sky conditions. LW radiation is an essential component of thermal balances in the atmosphere, playing also a substantial role in the design and operation of solar power plants. Unlike solar irradiance, LW irradiance is not measured routinely by meteorological or solar irradiance sensor networks. In most cases, it must be calculated indirectly from meteorological variables using simple parametric models. Under clear skies, fifteen parametric models for calculating LW irradiance are compared and recalibrated. All models achieve higher accuracy after grid search recalibration, and we show that many of the previously proposed LW models collapse into only a few different families of models. A recalibrated Brunt-family model is recommended for future use due to its simplicity and high accuracy (rRMSE = 4.37%). To account for the difference in nighttime and daytime clear-sky emissivities, nighttime and daytime Brunt-type models are proposed. Under all sky conditions, the information of clouds is represented by cloud cover fraction (CF) or cloud modification factor (CMF, available only during daytime). Three parametric models proposed in the bibliography are compared and calibrated, and a new model is proposed to account for the alternation of vertical atmosphere profile by clouds. The proposed all-sky model has 3.8–31.8% lower RMSEs than the other three recalibrated models. If GHI irradiance measurements are available, using CMF as a parameter yields 7.5% lower RMSEs than using CF. For different applications that require LW information during daytime and/or nighttime, coefficients of the proposed models are corrected for diurnal and nocturnal use.

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1. Introduction

The downward atmospheric longwave irradiance flux (LW, W/m²) is an essential component of radiative balance for solar power plants and is of great importance in meteorological and climatic studies, including the forecast of nocturnal temperature variation and cloudiness. It also plays a critical role in the design of radiant cooling systems, as well as in the modeling of weather and climate variability (Alados et al., 2012; Carmona et al., 2014), and on the determination of selective optical properties for photovoltaic panels, photovoltaic-thermal collectors, solar thermoelectricity parabolic disks, etc. (Eicker and Dalibard, 2011; Zaversky et al., 2013).

The downward longwave atmospheric irradiance can be measured directly by pyrgeometers. However, pyrgeometers are not standard irradiance equipment in most weather stations because

pyrgeometers are relatively expensive and require extensive calibration and adjustments to exclude the LW radiation emitted by surrounding obstacles, buildings and vegetation. Spectral (line-by-line) calculations considering the interactions of LW irradiance with atmospheric molecules (such as H₂O, CO₂ and O₃), aerosols and clouds yield reasonable estimates of LW for global calculations, but line-by-line calculations are generally too complex for meteorological or engineering use.

A simple approach to estimate LW relies on parametric modeling of meteorological variables measured routinely at the surface level, such as screening level air temperature and relative humidity. The parametric models imply specific assumptions regarding the vertical structure of the atmosphere (Brunt, 1932; Brutsaert, 1975; Ruckstuhl et al., 1984; Maghrabi and Clay, 2011). These assumptions are either explicit (Brutsaert, 1975), or implicitly included in the parametric models by locally fitting coefficients (Berdahl and Fromberg, 1982; Tang et al., 2004; Ruckstuhl et al.,

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1984; Bilbao and De Miguel, 2007; Maghrabi and Clay, 2011; Carmona et al., 2014).

In this work we review a large number of previous models for determining the downward atmospheric longwave (LW) radiation at the ground level, and propose a novel model for all sky conditions (diurnal and nocturnal, clear or cloudy skies). Section 2 outlines some of the background concepts needed to interpret the dataset and clear sky models used in this work, which are described in Section 3 and in Appendix A. Section 4 discusses and re-calibrates previously proposed models for clear sky conditions, and selects the most accurate model family to be used as a basis for the development of an all-sky condition model, which is evaluated against independent data sets. Conclusions from this work are presented in Section 6.

2. Background

For longwave atmospheric irradiance (4–100 μm), the background atmosphere can be considered as a gray body, and the LW irradiance is approximated as a fraction of a fictional blackbody emissive power evaluated at the surface level air temperature (Mills and Coimbra, 2015). This fraction is called the effective sky emissivity ε_{sky} and is expressed as,

$$\varepsilon_{\text{sky}} = \frac{\text{LW}}{\sigma T_a^4} \quad (1)$$

where $\sigma = 5.6697 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$ is the Stefan-Boltzmann constant (Mills and Coimbra, 2015) and T_a (K) is the air temperature at the surface level. This balance can be used to define an effective sky temperature T_{sky} (K) by approximating the sky as a blackbody,

$$\text{LW} = \sigma T_{\text{sky}}^4 \quad (2)$$

Compare Eqs. (1) and (2), the relationship between T_{sky} and ε_{sky} is,

$$T_{\text{sky}} = \varepsilon_{\text{sky}}^{1/4} T_a \quad (3)$$

Since ε_{sky} ranges from 0 to 1, the effective sky temperature is lower than the surface level air temperature (Mills and Coimbra, 2015).

In the parametric modeling, the clear-sky effective emissivity of the atmosphere can be expressed as a function of screening level air temperature T_a (K), relative humidity ϕ (%) and/or other meteorological variables, including screening level partial pressure of water vapor P_w (Pa), dew point temperature T_d (K) and moisture content d (g/(kg dry air)),

$$\varepsilon_{\text{sky},c} = f(T_a, \phi, P_w, T_d, d) \quad (4)$$

The partial pressure of water vapor P_w (Pa) and dew point temperature T_d (K) can be expressed as a function of T_a and ϕ by the Magnus expressions (Alduchov and Eskridge, 1996),

$$P_w = 610.94 \left(\frac{\phi}{100} \right) \exp \left(\frac{17.625(T_a - 273.15)}{T_a - 30.11} \right) \quad (5)$$

$$T_d = \frac{243.04 \ln(P_w/610.94)}{17.625 - \ln(P_w/610.94)} + 273.15. \quad (6)$$

And the moisture content d (kg/(kg dry air)) can be expressed as,

$$d = \frac{P_w}{P_a - P_w} \frac{R_a}{R_w} = \frac{0.622 P_w}{P_a - P_w}. \quad (7)$$

where P_a is the air pressure (Pa). In Section 4 of this work, fifteen different forms of Eq. (4) are compared and calibrated using measurements from seven stations across the contiguous United States, and the most accurate formula is proposed.

The presence of clouds substantially modifies the LW because the radiation emitted by water vapor and other gases in the lower atmosphere is supplemented by the emission from clouds. Therefore, under cloudy conditions, the effective sky emissivity is higher compared to clear-sky value. Parametric models can also be used to estimate all-sky condition LW with the consideration of cloud contribution,

$$\text{LW} = f(\text{LW}_c, \text{CF}, \text{CMF}) \quad (8)$$

where LW_c (W/m^2) is the corresponding clear-sky LW, CF (%) is the cloud cover fraction in the sky dome and CMF is a cloud modification factor,

$$\text{CMF} = 1 - \frac{\text{GHI}}{\text{GHI}_c} \quad (9)$$

where GHI (W/m^2) is the global horizontal solar radiation and GHI_c (W/m^2) is the clear-sky GHI. Note that CMF only has values during the daytime. In Section 5, three different forms of Eq. (8) are compared and calibrated, and a new model is proposed to achieve higher accuracy.

Therefore, we propose and validate a new parametric modeling of LW for clear- and all-sky conditions applicable to both daytime and nighttime. We validate the model with data from seven stations over the contiguous United States, for which cloud cover fraction data is available in nearby weather stations. A detailed description of the dataset is presented in Section 3.

3. Preparation of dataset

3.1. Observational data

The comparison and calibration of parametric models in Sections 4 and 5 are performed and validated using the radiation and meteorological measurements from the SURFRAD (Surface Radiation Budget Network) and ASOS (Automated Surface Observing System) operated by NOAA (National Oceanic and Atmospheric Administration). Currently seven SURFRAD stations are operating in climatologically diverse regions over the contiguous United States as shown in Fig. 1 (National Oceanic and Atmospheric Administration, 2015). Our fitting and validation datasets include measurements of year 2012 and year 2013 that are collected in all seven stations. Data from years 2014 and 2015 are not selected to avoid the influence of El Niño and La Niña years (Golden Gate Weather Service, 2016).

The seven stations, Bondville (in Illinois), Boulder (in Colorado), Desert Rock (in Nevada), Fort Peck (in Montana), Goodwin Creek (in Mississippi), Penn State University (in Pennsylvania) and Sioux Falls (in South Dakota) represent the climatological diversities, as shown in Table 1. Fort Peck and Sioux Falls have a cold and humid climate with annual averaged temperature and relative humidity around 7.0 °C and 70%. Bondville and Penn State are cool and humid with annual averaged temperature around 11.0 °C and relative humidity around 71%. Boulder has a mild climate with annual averaged temperature and relative humidity of 12.2 °C and 44.7%. Goodwin Creek is warm and humid with annual averaged temperature of 16.8 °C and relative humidity of 71.9%. Desert Rock has a hot and dry climate with annual averaged temperature and relative humidity of 18.8 °C and 27.5%. The seven sites also covers a large altitude span that ranges from 98 m to 1689 m.

The utilized SURFRAD measurements include 1-min averaged downwelling thermal infrared (IR, W/m^2), direct normal solar radiation (DNI, W/m^2), global horizontal solar radiation (GHI, W/m^2), screen level air temperature (T_a , K) and relative humidity of the air (ϕ , %). The Eppley Precision Infrared Radiometer (PIR) measures the downwelling IR from the atmosphere. The spectral range of the

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