Development and validation of a general model for estimating global solar radiation from hourly, daily and monthly surface meteorological data

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Abstract: Long-term recorded data at world-widely distributed meteorological stations provides an opportunity to construct historical solar radiation for studies on crop productivity, hydrology, climate change, and solar power-relevant designs The Ångström–Prescott model has been widely used to estimate global solar radiation from measured sunshine duration. However, this model has site-dependent coefficients, which have to be calibrated for different climate zones and elevations, because this model does not explicitly take into account radiative extinction processes in the atmosphere. In this study, we developed a general radiation model available with global data sets for turbidity and ozone from remote sensing. Its development followed the four principles below: (1) it keeps the simple form of Angstrom model while can explicitly and accurately deal with radiative extinction processes in the atmosphere; (2) model inputs are surface meteorological data (sunshine duration, air temperature, and relative humidity) so that the model can be applied easily; (3) under clear skies, the estimated solar radiation is equal to the value calculated by sophisticated spectral models; (4) at the top of atmosphere, the estimated solar radiation is exactly equal to the theoretical value of solar radiation. The model is calibrated with data in Japan, while it is successfully applied to China, Saudi Arab, and America, where have distinct climate zones and elevations. We expect the radiation output of this model could be used for cross-validation with satellite products.

Key words: surface solar radiation, Ångström–Prescott model, general radiation model, turbidity data set, ozone data set.

1. Introduction

Solar radiation reaching the Earth drives most of physical and biological cycle in the Earth system. The surface solar radiation is an indispensable input for many studies on agriculture, hydrology, and climate change. Also, it is a crucial index in designing solar devices. However, direct measurements of solar radiation are still too sparse to support scientific and technological research. The situation is particularly true in remote areas and mountainous areas, where snowmelting and glacier retreat become hot topics in hydrological and climate change studies, due to global warming and water resources crisis. A feasible approach to provide solar radiation for these studies is to estimate it from other surface meteorological data, such as temperature, humidity, precipitation, sunshine duration, and so on. They often have a long record at meteorological and hydrological stations and thus provide a possibility to construct historical solar radiation for relevant studies.

There exist two major methods to estimate global solar radiation from the surface meteorological data. The first one is the so-called Ångström–Prescott model, which estimate surface solar radiation from measured bright sunshine duration. This model has been widely applied to agricultural meteorology and hydrology for nearly one century. However, it does not consider radiative extinction processes in the atmosphere, so model parameters are site-dependent, and have to be calibrated locally. Although a number of studies have focused on how to tune the parameters, but their success is still limited. The second one is so-called Bristow-Campbell model, which uses daily temperature (minimum and maximum) and precipitation records for the estimation. In general, the first method can provide better radiation estimation than the second one. Also, the second cannot be applied to estimate hourly solar radiation.

In this study, we made efforts to develop a more general model for solar radiation estimation from surface meteorological variables and available global data set for turbidity and ozone thickness. This model follows the simple form of Ångström–Prescott approach while it can account for the radiative extinction processes. The input data are sunshine duration, air temperature, and relative humidity. The output are hourly, daily and monthly global solar radiation, depending on the temporal resolution of the input.

The paper is organized as follows: First, we develop a sub-model to calculate solar radiation from surface air temperature and relative humidity under clear skies. Second, several globally covered data sets are introduced into the solar radiation model to calculate Ångström turbidity coefficient and ozone. Third, the global solar radiation under cloudy conditions is scaled by the surface solar radiation under clear skies, rather scaled by than radiation at the extraterrestrial level. Fourth, model parameters are tuned for estimation of hourly, daily, or monthly-mean daily radiation respectively, using data at 53 stations of Japan in 1995. The Ångström–Prescott model is calibrated by the same data sets. Finally, we apply the new model and Ångström–Prescott model to world-widely distributed stations. These stations have distinct climate from humid to dry zones and surface elevation varying from the sea-level to as high as near 4000 m.

2. Global solar radiation model under clear sky conditions

The global solar radiation is affected by a number of extinction processes in the atmosphere. They are Rayleigh scattering, aerosol extinction, ozone absorption, water vapor absorption and permanent gas absorption. A spectral model can be used for calculating global solar radiation under clear skies:

$$R_{b0} \equiv \sin h \int_{\lambda_{\min}}^{\lambda_{\max}} I_{0i}(\lambda)\tau_{oz}(\lambda)\tau_{w}(\lambda)\tau_{g}(\lambda)\tau_{r}(\lambda)\tau_{a}(\lambda)d\lambda\,, \tag{2.1}$$

$$R_{d0} \equiv 0.5 \sin h \int_{\lambda_{\min}}^{\lambda_{\max}} I_{0i}(\lambda)\tau_{oz}(\lambda)\tau_{w}(\lambda)\tau_{g}(\lambda)[1-\tau_{r}(\lambda)\tau_{a}(\lambda)]d\lambda\,. \tag{2.2}$$

where R_{b0} (W m^{-2}) is solar beam and R_{d0} (W m^{-2}) is solar diffuse radiation at ground level under clear skies.

We then simplify the spectral model as follows

$$R_{b0} = I_0 \overline{\tau_{b0}} \cos Z\,, \tag{2.2a}$$

$$R_{d0} = 0.5 I_0 \overline{\tau_{d0}} \cos Z\,, \tag{2.2b}$$

where

$$\overline{\tau_{b0}} \approx \bar{\tau}_{oz}\bar{\tau}_{w}\bar{\tau}_{g}\bar{\tau}_{r}\bar{\tau}_{a} - 0.013\,, \tag{2.3a}$$

$$\overline{\tau_{d0}} \approx \bar{\tau}_{oz}\bar{\tau}_{g}\bar{\tau}_{w}(1-\bar{\tau}_{a}\bar{\tau}_{r}) + 0.013 \tag{2.3b}$$

$$\bar{\tau}_{oz} = \exp[-0.0365(ml)^{0.7136}]\,, \tag{2.3c}$$

$$\bar{\tau}_{w} = \min[1.0, 0.909 - 0.036\ln(mw)]\,, \tag{2.3d}$$

$$\bar{\tau}_{g} = \exp(-0.0117 m'^{0.3139})\,, \tag{2.3e}$$

$$\bar{\tau}_{r} = \exp(-0.008735 m' \bar{\lambda}_{r}^{-4.08})\,, \tag{2.3f}$$

$$\bar{\tau}_{a} = \exp(-\beta m \bar{\lambda}_{a}^{-1.3})\,, \tag{2.3g}$$

$$\bar{\lambda}_{r} = 0.547 + 0.014m' - 0.00038m'^{2} + 4.6\times10^{-6} m'^{3}\,, \tag{2.3h}$$

$$\bar{\lambda}_{a} = 0.6777 + 0.1464(m\beta_{t}) - 0.00626(m\beta_{t})^{2}\,, \tag{2.3i}$$

$$m = 1/[\sin h + 0.15(57.296h + 3.885)^{-1.253}] \tag{2.3j}$$

$$m' = m\, p / p_0 \tag{2.3k}$$

According to the preceding equations, R_{b0} and R_{d0} can be calculated given surface pressure p, Ångström turbidity β, precipitable water w, and ozone thickness l.

This model was evaluated as one of the best models in calculating surface solar radiation under clear skies (Gueymard, 2003a, 2003b).

For practical application, the precipitable water is calculated from relative humidity (rh, %) and air temperature (T_a, K):

$$w = 0.493\, rh\, T_a^{-1} \exp[26.23 - 5416 T_a^{-1}]\,.$$

3. Global distribution of Angstrom turbidity coefficient and ozone

The aerosol scattering is one of the most important radiation-damping processes. The Ångström turbidity coefficient, a key parameter for the scattering, generally decreases with respect to elevation and also decreases toward to high latitude. Ångström gives a formula to estimates it, but the formula can be questionable in some areas such as India and China because of its high variability in both space and time.

In the new model, we introduce two data sets to calculate the turbidity. First, we follow Hess et al. (1998) and calculate optical depth at wavelength $0.5\,\mu\mathrm{m}$. The optical length is then converted to Ångström turbidity β. This method can provide a global cover, but its spatial resolution ($5^0 \times 5^0$) and temporal resolution (summer and winter) are low, so we use it as a background of turbidity; that is, it is used if no other data sources are available. The second data set is a monthly mean data provided by AVHRR. It has a higher spatial resolution ($1^0 \times 1^0$) and temporal resolution (monthly), but no data is available beyond 70 degrees latitude in both hemispheres.

The thickness of ozone is provided by a NASA global dataset with a $1^0 \times 1^0$ spatial resolution and monthly temporal resolution.

4. Framework to develop a new general model

The traditional Ångström–Prescott model assumes that globe solar radiation can be scaled by the solar radiation at the top of the atmosphere. That is

$$R = (a + b\,S + c\,S^2)R_0 \tag{4.1}$$

However, the new model assumes that the globe solar radiation can be scaled by its value under clear skies.

$$R = (a + b\,S + (1 - a - b)\,S^2)(R_b + R_d) \tag{4.2}$$

The new model has four features: (1) it has a simple form as Ångström–Prescott model; (2) model inputs are surface meteorological data (sunshine duration, air temperature, and relative humidity) so that the model can be applied easily; (2) under clear skies, the estimated solar radiation is equal to the value calculated by sophisticated spectral models. (3) At the top of atmosphere, the estimated solar radiation is exactly equal to the theoretical value of solar radiation. Hereafter, it is called hybrid model.

5. Model calibration

We calibrated the two models using the data at 53 stations in Japan. The maximum surface elevation is less than 300 m, and the humidity is relative high. The models are calibrated for hourly, daily and monthly solar radiation estimation

6. Model validation

We compare the two models at a number of stations by three indices: mean bias error (MBE), root mean square errors (RMSE), and correlation coefficient (R^2). The following only shows the major index RMSE in USA and Saudi Arabia.

(1) In USA.

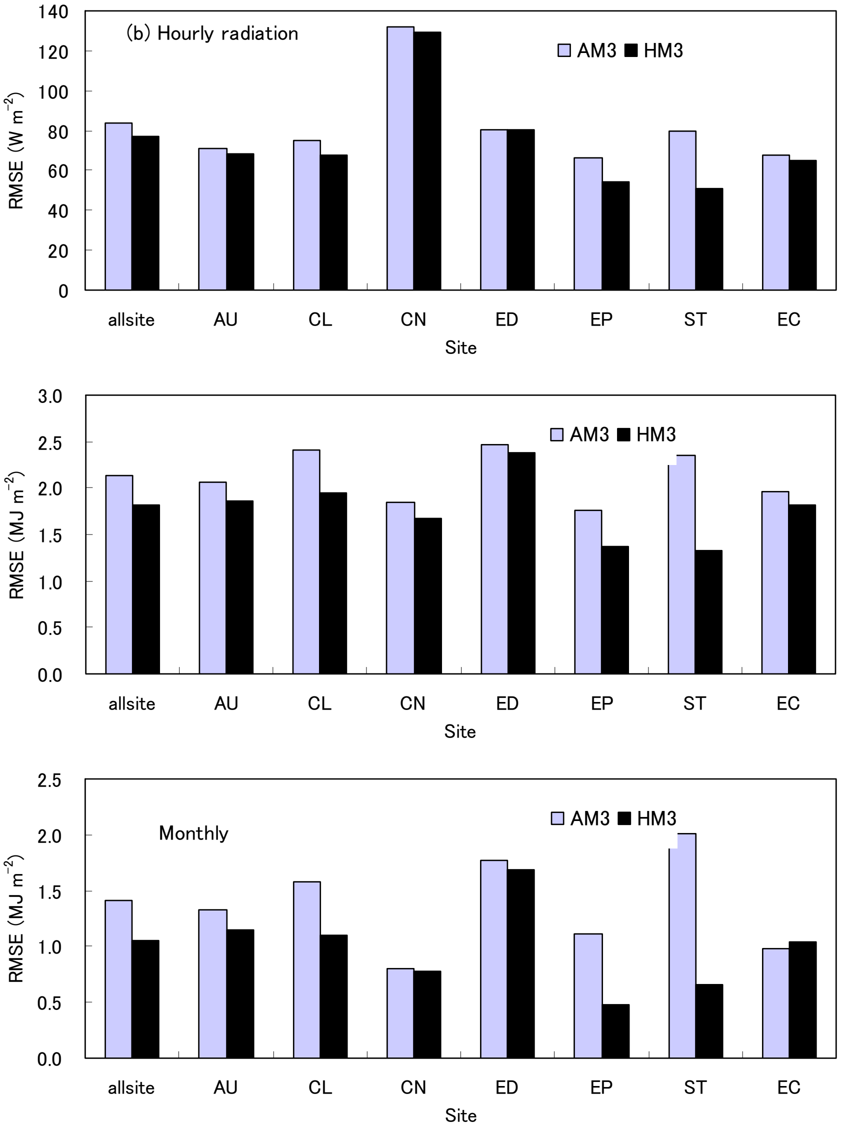

Figure 1 Validation in USA. AM: Ångström–Prescott model; HM: Hybrid model. Upper panel, hourly data; Middle panel: daily data; Lower panel: monthly-mean daily data

(2) In Saudi Arabia.

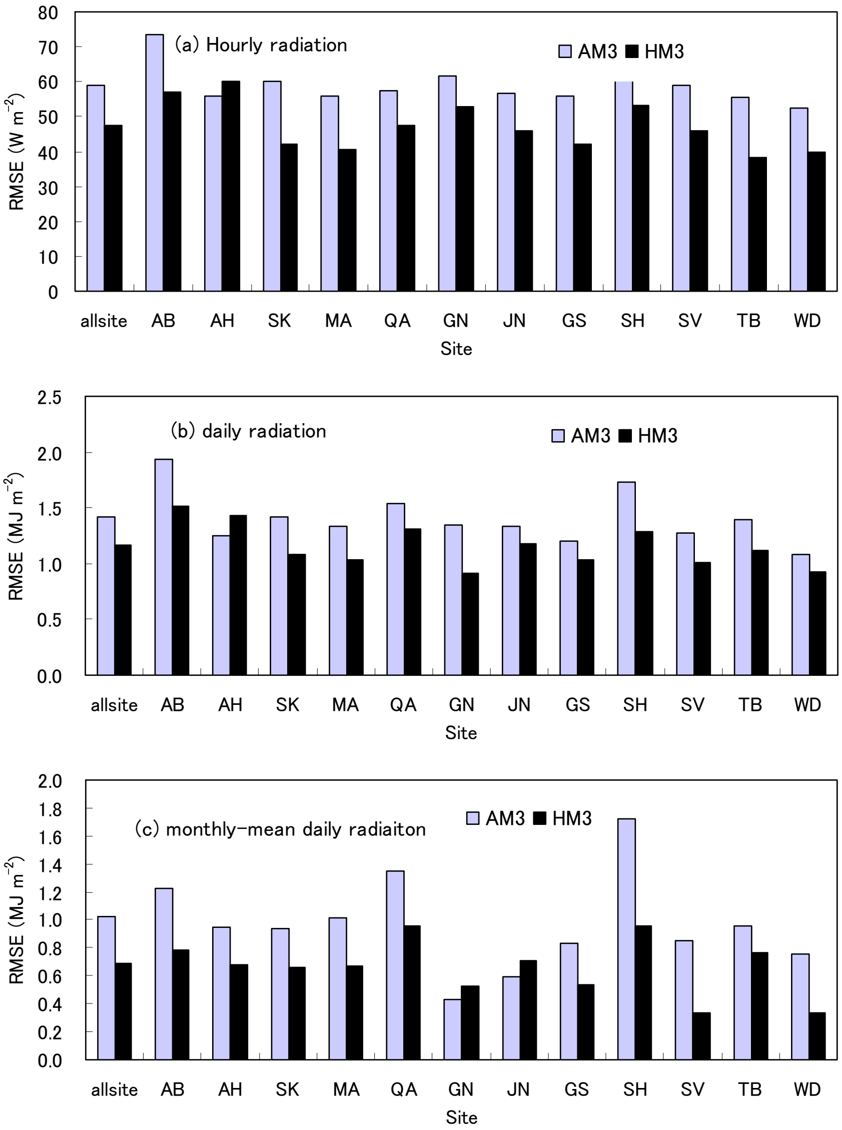

Figure 2 Validation in Saudi Arabia. AM: Ångström–Prescott model; HM: Hybrid model. Upper panel, hourly data; Middle panel: daily data; Lower panel: monthly-mean daily data

7. Conclusion

We develop a new model. The new model much improved the estimation for solar radiation from surface meteorological data compared to the traditional Ångström–Prescott model.