Evaluation of the estimation of shortwave solar radiation in Japan using the Mountain Microclimate Simulation Model

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Abstract

Solar radiation is an essential parameter for ecological, agricultural, and other models. However, the availability of large-scale radiation data is usually limited. The Mountain Microclimate Simulation Model (MTCLIM) can resolve such data insufficiency by estimating missing daily shortwave solar radiation data using simple climatological and topographic parameters. Several studies have found the performance of the MTCLIM to be sufficient for the estimation of solar radiation. However, its performance in the East Asian monsoon zone, which is generally characterized by warm wet summers and cold dry winters, has not been thoroughly evaluated. We assessed the performance of the MTCLIM in Japan located at the East Asian monsoon zone. We estimated daily shortwave solar radiation using daily maximum and minimum temperature and precipitation data recorded over 57 years and topographic parameters including slope angle and direction at 41 meteorological stations. Then, we compared the estimated solar radiation with the solar radiation observed at each meteorological station using a simple linear regression equation. The slope of the regression equation without intercept was 0.96 and the coefficient of determination ($R^2$) was 0.61 for all data. The estimation performance was increased for the monthly mean of daily solar radiation (slope=1.03; $R^2$=0.93). The degree of estimation error showed geographical and seasonal trends; stations located at higher latitudes had larger slopes than those at lower latitudes. The bias was largest (positive) in spring and smallest (negative) in summer. This study confirmed that the MTCLIM performed sufficiently well to estimate solar radiation in Japan. In particular, the model’s high performance for the monthly mean of daily solar radiation suggests that it provides estimates of solar radiation that are sufficiently accurate for ecological, agricultural, and other models in which values of average solar radiation for a given period of time are more meaningful than instantaneous daily solar radiation.

Key words: Atmospheric transmittance, East Asian monsoon zone, Large-scale ecological modeling, MTCLIM

1. Introduction

Solar radiation is an essential factor controlling many ecosystem processes, such as plant growth and survival, and can be an important variable for predicting plant distribution ranges and biomass production in ecological, agricultural, and other models. However, obtaining reasonable solar radiation data for large-scale modeling is usually limited due to the sparse spatial distribution of meteorological stations that record solar radiation compared with those that record only fundamental meteorological variables such as temperature and precipitation (Thornton and Running, 1999). Even though some large-scale re-analysis data of meteorological observations are available (Kalnay et al., 1996; Uppala et al., 2005), the spatial and temporal resolution of these data are usually lower than that required by large-scale plant distribution models. Thus, temperature data have often been used as input data instead of solar radiation.

The Mountain Microclimate Simulation Model (MTCLIM; Running et al., 1987; Hungerford et al., 1989; Thornton and Running, 1999) is a meteorological model that resolves the problem of insufficient solar radiation data. The MTCLIM can be used to calculate daily solar radiation (shortwave solar radiation) at a target point using simple climatological parameters (temperature and precipitation) and some topographic variables. Because the MTCLIM estimates solar radiation based on an empirical relationship between atmospheric transmittance and temperature or precipitation, the calculation effort is lower than in physical models such as the Weather Research and Forecasting model. Thus, the MTCLIM has been widely used to estimate photosynthesis and transpiration processes in ecological and hydrological process modeling (Thornton, 1998).

Several studies have assessed the performance of the MTCLIM for estimating solar radiation at a regional scale, for example, in a subtropical coastal region in Brazil (Almeida and Landsberg, 2003), in a mountainous area in Austria (Thornton et al., 2000) and Pakistan (Sardar et al., 2017), and throughout North America (Thornton and Running, 1999), and at a global scale (Bohn et al., 2013). These studies found acceptable model performance, although they also observed some seasonal and regional
prediction bias. However, the performance of the MTCLIM in the East Asian monsoon zone, where it is warm and wet in summer and cold and dry in winter, has not been thoroughly evaluated.

In Japan, many meteorological stations (about 50) have recorded meteorological data, including air temperature and precipitation that was used in the MTCLIM as input data, in parallel with solar radiation, for a long time. These data make it possible to test the performance of the MTCLIM for estimating solar radiation in the East Asian monsoon zone with high reliability. In this study, we aimed to validate the performance of the MTCLIM for estimating solar radiation in Japan by comparing the model-estimated solar radiation with in situ measurements of solar radiation.

2. Materials and methods

2.1 Description of the MTCLIM

The MTCLIM is a model which extrapolates the daily maximum and minimum air temperature, precipitation, shortwave solar radiation (hereinafter referred to as solar radiation), vapor pressure (VP), and length of day, for a target point using meteorological data (temperature and precipitation) recorded at a reference point, as well as geographical information (e.g., elevation) for both the reference point and the target point and latitude for the target point. To improve the accuracy of estimations in complex terrain, the MTCLIM utilizes additional geographical information such as slope angle and direction, and slope angle to east and west horizon for the target point as input data.

The daily maximum and minimum temperature at the target point are estimated by correcting for elevation using the general lapse rate from the reference point. The solar radiation is estimated using a function of potential radiation, and clear-sky and cloudy-sky transmittance (Bristow and Campbell, 1984; Thornton et al., 2000) as follows:

\[ R_{\text{sw}} = R_{\text{pot}} \times T_{\text{t,max}} \times T_{\text{c,max}}, \]

where \( R_{\text{sw}} \) is the shortwave solar radiation, \( R_{\text{pot}} \) is the daily total top-of-atmosphere solar radiation on a horizontal surface, \( T_{\text{t,max}} \) is the maximum (cloud-free) daily total transmittance (clear-sky transmittance), and \( T_{\text{c,max}} \) is the cloudy-sky transmittance, which is the proportion (fraction) of solar radiation not absorbed or scattered by clouds in \( R_{\text{sw}} \). The daily total top-of-atmosphere solar radiation depends on the latitude and day of the year. Clear-sky transmittance is expressed by the following function:

\[ T_{\text{c,max}} = \left[ \sum_{s=3}^{s} R_{\text{pot},s} \times T_{\text{0,nadir,dry},s} \left( \frac{P_{0}}{P_{\text{dry}}} \right)^{m_{s}} \sum_{s=3}^{s} R_{\text{pot},s} \right]^{1/2} + (-6.1 e^{-3}) \times VP, \]

where \( R_{\text{pot},s} \) is the instantaneous potential horizontal radiation at solar time \( s \), \( s \) and \( ss \) are times of sunrise and sunset, \( T_{\text{0,nadir,dry}} \) is the instantaneous transmissance at sea level, at nadir, for a dry atmosphere, \( P_{0} \) and \( P_{\text{dry}} \) are the surface air pressures at elevation \( z \) and at sea level, \( m_{s} \) is the optical air mass at solar zenith angle \( \theta \) (Thornton et al., 2000).

Cloudy-sky transmittance is a function of the diurnal temperature range (DTR):

\[ T_{\text{c,max}} = 1.0 - 0.9 \exp (-B \times DTR^{C}), \]

where \( B \) and \( C \) are parameters that describe the effects of the DTR on daily total transmittance through adjustment of \( T_{\text{c,max}} \), and \( DTR \) is the 30-day moving average of the DTR. For days with precipitation, the value of \( T_{\text{c,max}} \) calculated by Eq. 3 was multiplied by 0.75.

In the MTCLIM, solar radiation depends weakly on VP through \( T_{\text{c,max}} \) (Eq. 2); and VP are also affected by solar radiation through potential evapotranspiration (Thornton et al., 2000; Bohn et al., 2013). To estimate radiation and VP simultaneously, the MTCLIM offers two options. If the dewpoint temperature \( T_{\text{dew}} \) can be obtained, VP is computed as the saturation vapor pressure when the air temperature equals \( T_{\text{dew}} \). If \( T_{\text{dew}} \) cannot be obtained, the MTCLIM estimates VP and solar radiation simultaneously using the following procedure. First, VP is estimated by assuming \( T_{\text{dew}} \) equal to the minimum temperature \( T_{\text{min}} \), and solar radiation is estimated from estimations of \( T_{\text{t,max}} \) and \( T_{\text{c,max}} \). The estimated solar radiation is then used to compute potential evapotranspiration. When the ratio of potential evapotranspiration to annual precipitation \( (\text{EP}) \) \( \geq 2.5 \), \( T_{\text{dew}} \) is calculated using a function of EP and DTR as follows (Kimball et al., 1997), in order to correct biases in \( T_{\text{dew}} = T_{\text{min}} \) under arid climates:

\[ T_{\text{dew}} = T_{\text{min}} \times (-0.127+1.211 \times (1.003-1.444 \times EP+12.312 \times EP^{2}-32.766 \times EP^{3})+0.0006 \times DTR), \]

Then VP and solar radiation are calculated using the corrected \( T_{\text{dew}} \) values. If \( EP < 2.5 \), the initial estimated solar radiation using the assumption of \( T_{\text{dew}} = T_{\text{min}} \) was retained.

2.2 Meteorological data

Meteorological data used in this study were maximum and minimum daily temperature, daily precipitation, hourly dewpoint temperature, and daily solar radiation recorded at 41 meteorological stations and provided by the Japan Meteorological Agency. The data covered the period from 1961 to 2017 (57 years), with the exception of dewpoint temperature, which was recorded only between 1991 and 2017. Information for each surface observation station is listed in Table 1 and the geographical location of each station is indicated in Fig. 1.

The MTCLIM requires continuous data (i.e., no missing values) for any given year. Thus, we used only data for years without missing data.

2.3 Evaluation of MTCLIM performance

In this study, the reference and target points in the MTCLIM were set as the same meteorological station, to validate the accuracy of the MTCLIM. We compared values of daily solar radiation estimated by MTCLIM ver. 4.3 (Thornton et al., 2000) with values of daily solar radiation observed at the same geographical position. For meteorological input data for the MTCLIM, we used maximum and minimum daily temperature data and daily and annual precipitation data from each meteorological station from 1961 to 2017. For geographical information, we used the latitude and elevation data for each meteorological station as input data; these were used to
estimate daylength and the instantaneous transmittance in Eq. 2. Additionally, we prepared topographic variables, slope angle and direction, and slope to east and west horizontal for each station using Digital Elevation Model (DEM; appropriate 1 km resolution) data from the National Land Information provided by the Japanese Ministry of Land, Infrastructure, Transport and Tourism.

We also compared the performance of the MTCLIM with and without $T_{\text{ave}}$ temperature as input data, because obtaining the observed $T_{\text{ave}}$ temperature data would often be difficult when applying this model. For this evaluation, we used meteorological data from 1991 to 2017.

The accuracy of the model estimation was validated using the slope and coefficient of determination ($R^2$) of a simple linear regression equation with estimated radiation as the dependent variable and observed radiation as the independent variable. The root-mean-square error (RMSE), mean absolute error (MAE), and bias between the observed and estimated solar radiation were also used as indexes of model accuracy. Bias was calculated as the daily difference between the predicted and observed radiation values. Moreover, to assess the geographic trend of the estimation accuracy, we compared the slope of the regression equations and the RMSE among all stations. The temporal variation of the estimation accuracy was also investigated for monthly and yearly trends. The monthly trend of the model accuracy was evaluated using the variation of monthly RMSE and bias. To evaluate yearly trends, the slopes of the regression equations and the RMSE were assessed for data from all meteorological stations calculated over each five-year period. For the evaluation of the yearly trend, observed solar radiation was used as the dependent variable and model-estimated radiation was used as the independent variable.

### 3. Results

#### 3.1 General performance of the MTCLIM in estimating solar radiation

To validate the accuracy of the solar radiation estimated by the MTCLIM, we compared observed and estimated daily solar radiation values for all meteorological stations and years (Fig. 2). For the regression equation without intercept ($\text{intercept} = 0.0$), the slope was 0.96 and $R^2$ was 0.61. When we considered both slope and intercept, the slope was 0.73, the intercept was 3.81, and $R^2$ was 0.70. The slope was lower and $R^2$ was slightly higher in the equation with intercept than in the equation without intercept. The RMSE was 3.93 MJ m$^{-2}$ day$^{-1}$ and the MAE was 3.02 MJ m$^{-2}$ day$^{-1}$.

For the monthly mean of daily solar radiation at each station, the slope of the regression equation between observed and daily solar radiation values without intercept was 1.03 and $R^2$ was 0.93 (Fig. 3). In the equation with intercept, the slope was 1.04, the
intercept was $-0.13$, and $R^2$ was 0.93 (Fig. 3). The slope and $R^2$ in the regression equation with intercept were extremely close to those in the equation without intercept. The RMSE was 1.20 MJ m$^{-2}$ day$^{-1}$ and the MAE was 0.95 MJ m$^{-2}$ day$^{-1}$.

In comparison of the solar radiations estimated by the MTCLIM with and without dewpoint temperature as input data, two estimation values showed good agreement (Fig. 4). The slope of the regression equation without intercept was 1.02, and $R^2$ was 0.997. In the equation with intercept, the slope was 1.02, the intercept was $-0.08$, and $R^2$ was 0.997. The RMSE was 0.41 MJ m$^{-2}$ day$^{-1}$.

As shown in Fig. 5, the diurnal fluctuation of solar radiation estimated by the MTCLIM indicated that DTR and precipitation significantly influence the estimation of solar radiation. The timing of the increase and decrease of the estimated radiation matched well with the observational data.

### 3.2 Geographical variation in the performance of the MTCLIM

The accuracy of the MTCLIM-estimated solar radiation differed between meteorological stations (Table 2). For the regression equations with intercept, the slope ranged from 0.56 to 0.90, and for the equations without intercept, the slope ranged from 0.83 to 1.09. The RMSE ranged from 3.23 to 4.97 MJ m$^{-2}$ day$^{-1}$, MAE ranged from 2.47 to 3.93 MJ m$^{-2}$ day$^{-1}$, and the bias ranged from $-1.23$ to 1.86 MJ m$^{-2}$ day$^{-1}$ (Table 2). Stations located at higher latitudes showed larger slopes than those at lower latitudes, both in the equations with and without intercept (Fig. 6a and b). No geographical trends were observed for RMSE (Fig. 6c). At the Choshi station, the smallest slope for the equation with and without intercept, the largest MAE and RMSE, and the largest negative bias were observed.

The mean of DTR for each meteorological station did not show a clear geographical trend (Fig. 6d). In contrast, the mean of the MTCLIM-estimated vapor pressure deficit (VPD) for each station showed a clear geographical trend which decreased with increasing latitude (Fig. 6e).

### 3.3 Seasonal variation in the performance of the MTCLIM

The mean estimation errors showed seasonal trends for all meteorological stations (Fig. 7). The highest RMSE occurred in April (spring; 5.11 MJ m$^{-2}$ day$^{-1}$) and the lowest RMSE was observed in December (winter; 2.31 MJ m$^{-2}$ day$^{-1}$). The ratio of the RMSE to the monthly mean of observed daily solar radiation was lowest in August (summer; 0.26) and highest in January (winter; 0.34). Bias was highest in April (1.66 MJ m$^{-2}$ day$^{-1}$) and lowest in August ($-0.93$ MJ m$^{-2}$ day$^{-1}$). Bias was close to zero from September to January. The DTR was highest in April (9.63 °C) and lowest in July (7.43 °C). The VPD estimated by MTCLIM was highest in August (10.96 hPa) and lowest in January (2.88 hPa).

**Fig. 2.** Relationship between observed and estimated daily shortwave solar radiation for all meteorological stations and years (1961–2017).

**Fig. 3.** Relationship between the monthly means of observed and estimated daily shortwave solar radiation for each meteorological station from 1961 to 2017.

**Fig. 4.** Comparison of daily shortwave solar radiation estimated by the Mountain Microclimate Simulation Model (MTCLIM) with and without dewpoint temperature as input data for all meteorological stations between 1991 and 2017.
3.4 Long-term variation in the performance of the MTCLIM

The accuracy of the MTCLIM was found to follow a clear long-term trend (Fig. 8). The slope of the regression equations with intercept for data over each five-year period was low for 1965 (0.86) and 1970 (0.89), after which values increased. For 2000, the slope of the regression equations was 1.01, and increased to about 1.07 in 2015. The highest RMSE was observed for 1960 (4.36 MJ m⁻² day⁻¹); subsequently, values decreased until 1985 (3.76 MJ m⁻² day⁻¹). After 1985, RMSE remained at a low level (3.83–3.92 MJ m⁻² day⁻¹).

4. Discussion

4.1 General performance of the MTCLIM for the estimation of solar radiation

Our results confirmed that the MTCLIM performed well enough to estimate daily solar radiation in Japan. In the equation without intercept, the slope of the regression equation for the relationship between estimated and observed solar radiation was close to 1.0 (Fig. 2). The degree of prediction error (MAE = 3.02 MJ m⁻² day⁻¹) was similar to that found in other regions—namely, in Austria (2.52 MJ m⁻² day⁻¹; Thornton et al., 2000) and throughout North America (2.39 MJ m⁻² day⁻¹; Thornton and Running, 1999, 3.45 MJ m⁻² day⁻¹; Ball et al., 2004)—and globally (2.32 MJ m⁻² day⁻¹; Bohn et al., 2013). The performance of the MTCLIM for Japan has been shown to be equivalent to that for other parts of the world.

Comparison between the solar radiations estimated by the MTCLIM with and without dewpoint temperature as input data showed good agreement of these two estimations. Obtaining the dewpoint temperature data is difficult in some cases when applying the MTCLIM. In such cases, option in MTCLIM using minimum daily temperature as dewpoint temperature would work well in Japan.

The accuracy of the MTCLIM for the estimation of monthly mean daily solar radiation was fairly high (Fig. 3). It suggests the usefulness of its output for various ecological, agricultural, and other models. In some models that predict plant occurrence and survival based on environmental conditions, cumulative radiation values for a given time period are often more meaningful than instantaneous daily radiation values. The MTCLIM can estimate missing solar radiation data for such models.

4.2 Geographical variation of MTCLIM performance

We found that the slope of the regression equation for the relationship between estimated and observed solar radiation increased with latitude. The model tends to underestimate higher radiation values in southern regions of Japan (Fig. 6). Previous studies also observed a geographical gradient of estimation error (large in coastal regions; Bohn et al., 2013; large in tropical regions; Thornton and Running, 1999), which suggests that this observation might be due to the estimation algorithm for atmospheric transmittance in the MTCLIM (Bohn et al., 2013). In the MTCLIM algorithm, the amount of solar radiation is estimated using the attenuation of potential radiation by both cloud-free daily total transmittance (clear-sky transmittance) and fraction of solar radiation penetrated through cloud (cloudy-sky transmittance). Clear-sky transmittance is influenced by daily mean water vapor pressure and decreases under high vapor pressure (Eq. 2).
results, VPD values estimated by the MTCLIM were higher in southern stations than in northern stations, although DTR values did not differ with latitude (Fig. 6). This suggests that low clear-sky transmittances caused by high VPD can have a large influence on the estimation of solar radiation in southern regions. Consequently, the estimation of higher solar radiation, which might be susceptible to estimation uncertainty related to clear-sky transmittances, might tend to be underestimated in southern regions.

The largest negative bias of estimated solar radiation and the smallest slopes of regression equations were found at the Choshi station, although its latitude was not so low. Underestimation of solar radiation by the MTCLIM have been found at the coastal stations by previous studies (Bohn et al., 2013). Bohn et al. (2013) discussed that under-prediction of $T_{\text{max}}$ due to the moderating influence of ocean on DTR could over-predict the effects of cloud. The Choshi station is located at the tip of the small peninsula surrounded by the ocean (No. 18 in Fig. 1). Such geographical conditions of this station might result in the largest estimation error at this station.

| No | Station name | $y = ax + b$ | $\text{MAE (MJ m}^{-2} \text{day}^{-1}\text{)}$ | $\text{RMSE (MJ m}^{-2} \text{day}^{-1}\text{)}$ | Bias |
|----|--------------|-------------|---------------------------------|---------------------------------|-------|
| 1  | Wakanai      | 0.94 0.60   | 0.73 3.37 0.68 3.27 4.37 0.44 |
| 2  | Asahikawa    | 1.09 0.71   | 0.90 2.99 0.75 3.09 4.13 1.86 |
| 3  | Sapporo      | 1.00 0.67   | 0.82 2.98 0.71 3.04 4.01 0.75 |
| 4  | Abashiri     | 0.92 0.62   | 0.77 2.64 0.66 3.17 4.27 0.30 |
| 5  | Obihara      | 1.00 0.72   | 0.87 2.18 0.74 2.79 3.71 0.50 |
| 6  | Muroran      | 0.89 0.72   | 0.76 2.19 0.75 3.01 3.86 0.69 |
| 7  | Hakodate     | 1.01 0.67   | 0.82 3.02 0.72 2.95 3.86 0.82 |
| 8  | Aomori       | 1.00 0.69   | 0.82 3.06 0.74 2.90 3.85 0.83 |
| 9  | Akita        | 0.96 0.66   | 0.75 3.39 0.73 3.04 3.99 0.48 |
| 10 | Morioka      | 1.00 0.70   | 0.82 2.95 0.75 2.81 3.66 0.74 |
| 11 | Sendai       | 0.98 0.60   | 0.74 3.85 0.70 3.04 3.91 0.70 |
| 12 | Yamagata     | 1.01 0.75   | 0.85 2.59 0.78 2.57 3.40 0.76 |
| 13 | Fukushima    | 1.05 0.63   | 0.80 3.56 0.70 2.10 3.98 1.13 |
| 14 | Tsukuba      | 0.99 0.64   | 0.76 3.76 0.72 2.79 3.66 0.63 |
| 15 | Utsunomiya   | 1.01 0.66   | 0.79 3.45 0.73 2.66 3.46 0.82 |
| 16 | Maebashi     | 0.99 0.65   | 0.77 3.56 0.72 2.78 3.53 0.56 |
| 17 | Tokyo        | 1.00 0.45   | 0.68 4.98 0.64 3.16 4.06 1.13 |
| 18 | Choshi       | 0.83 0.39   | 0.56 4.66 0.57 3.93 4.97 0.13 |
| 19 | Nagano       | 0.93 0.73   | 0.78 2.61 0.76 2.67 3.48 0.52 |
| 20 | Kofu         | 0.97 0.72   | 0.79 3.14 0.77 2.47 3.23 0.11 |
| 21 | Shizuoka     | 0.92 0.58   | 0.67 4.34 0.70 2.91 3.75 0.22 |
| 22 | Nagoya       | 0.96 0.65   | 0.74 3.72 0.73 2.80 3.54 0.23 |
| 23 | Niigata      | 0.93 0.60   | 0.70 3.90 0.71 3.19 4.13 0.23 |
| 24 | Toyama       | 0.98 0.59   | 0.73 4.13 0.70 3.09 4.08 0.89 |
| 25 | Fukui        | 0.97 0.65   | 0.74 3.79 0.74 2.94 3.85 0.62 |
| 26 | Hakone       | 0.93 0.61   | 0.71 3.78 0.70 3.10 4.03 0.01 |
| 27 | Osaka        | 1.00 0.54   | 0.71 4.62 0.68 2.99 3.83 0.94 |
| 28 | Nara         | 1.04 0.66   | 0.80 3.92 0.75 2.77 3.58 1.31 |
| 29 | Hiroshima    | 0.96 0.69   | 0.74 3.66 0.76 2.63 3.36 0.18 |
| 30 | Matsue       | 0.94 0.62   | 0.72 3.71 0.71 3.09 4.04 0.13 |
| 31 | Takamatsu    | 0.95 0.66   | 0.73 3.70 0.74 2.76 3.56 0.04 |
| 32 | Matsuyama    | 0.93 0.57   | 0.67 4.59 0.71 3.04 3.89 0.07 |
| 33 | Kochi        | 0.91 0.60   | 0.68 4.16 0.71 3.05 3.82 0.43 |
| 34 | Shimonomori  | 0.89 0.51   | 0.62 4.56 0.66 3.33 4.29 0.39 |
| 35 | Fukukawa     | 0.93 0.47   | 0.64 5.02 0.65 3.38 4.30 0.32 |
| 36 | Oita         | 0.99 0.55   | 0.72 4.51 0.68 3.09 3.99 0.78 |
| 37 | Naganoseki   | 0.85 0.49   | 0.60 4.46 0.64 3.63 4.57 1.07 |
| 38 | Saga         | 0.99 0.59   | 0.73 4.37 0.71 2.98 3.82 0.86 |
| 39 | Kamamoto     | 0.97 0.59   | 0.71 4.53 0.71 2.94 3.79 0.54 |
| 40 | Miyazaki     | 0.89 0.48   | 0.61 5.05 0.65 3.43 4.32 0.58 |
| 41 | Kagoshima    | 0.92 0.48   | 0.64 4.92 0.64 3.31 4.23 0.06 |

Fig. 6. Geographical variation in (a) the slope of the regression equations for the relationship between observed and estimated shortwave solar radiation with intercept, (b) the slope of the regression equations without intercept, (c) root-mean-square error (RMSE), (d) diurnal temperature range (DTR), and (e) vapor pressure deficit (VPD) estimated by the MTCLIM at all meteorological station.
4.3 Seasonal variation of MTCLIM performance

Differences between observed and estimated solar radiation (bias) was largest positive in spring and smallest negative in summer (Fig. 7). Similar trends have been found in previous studies (Thornton and Running 1999; Thornton et al., 2000), and these are also likely to have been caused by the estimation uncertainty related to transmittance in the MTCLIM algorithm. In the MTCLIM, total daily transmittance ($T_{\text{t,max}} \times T_{\text{f,max}}$) becomes low when DTR is small (Bristow and Campbell; 1984), and Clear-sky transmittance is low under high VP (see Section 4.2). Thus, the large DTR observed in spring (Fig. 7) can lead to the estimation of high total daily transmittance, and high VP and small DTR in summer (Fig. 7) can result in the estimation of low clear-sky transmittance and low total daily transmittance. These climatic conditions may be the cause of the positive bias observed in spring and the negative bias observed in summer in our results.

The seasonal variation that was observed in the ratio of RMSE to mean daily solar radiation showed a trend that is opposite to that of the absolute RMSE, with the former having the highest value in winter and the lowest value in summer. A high absolute error observed in summer could simply be due to the large amount of solar radiation at this time (Thornton and Running, 1999). The potential effects of error in summer are unlikely to substantially affect the data’s usefulness for input in ecological and other models.

4.4 Long-term variation in the performance of the MTCLIM

The yearly trend of the performance of the MTCLIM suggests the importance of considering the estimation period for solar radiation in Japan in the MTCLIM. Previous studies showed that, both in
Japan and globally, atmospheric transmission and solar radiation decreased between the 1950s and 1980s and have been increasing since the 1990s (Wild et al., 2005; Nakamura and Mitani, 2014, 2018). These global trends in solar radiation may affect the temporal variation in the relationships between observed and estimated solar radiation in the present study. Furthermore, Japan entered a period of high economic growth in the 1950s, and atmospheric pollution due to this economic activity became a serious problem until the 1970s. The increasing performance of the MTCLIM after the 1980s (Fig. 8a and b) may reflect the subsequent recovery of atmospheric transmission.

On the other hand, DTR also showed a yearly trend, being larger in the 1960s and 1970s and decreasing after 1970s (Fig. 8c). These trends of meteorological input data may also cause the yearly trend of estimation error. However, the intra-year difference in RMSE was smaller than the seasonal differences in RMSE. Thus, the yearly variation in MTCLIM performance would not seriously affect the suitability of these radiation data for use in ecological and agricultural modeling.

5. Conclusions

This evaluation of the performance of the MTCLIM for the prediction of solar radiation in Japan confirmed that the model performed reasonably well for estimating the humid monsoon climate of East Asia. In particular, the high performance of the model for estimating mean monthly solar radiation suggests that the MTCLIM provides acceptable radiation data for ecological, agricultural, and other modeling in which monthly solar radiation is meaningful rather than daily solar radiation. Although some geographical and seasonal variation was found in the model performance, our regression equation results for each meteorological station may prove useful for correcting biases in the MTCLIM output for Japan.

Even if no measured data are available, the MTCLIM can provide solar radiation datasets with low computational resources. For instance, around 1300 Automated Meteorological Data Acquisition Systems (AMeDAS) record daily temperature and precipitation data in Japan but they have not recorded solar radiation for a long period. Using the MTCLIM to estimate solar radiation with these temperature and precipitation data as inputs allows us to directly evaluate the effects of solar radiation on plant growth and survival in large-scale ecological, agricultural, and other models.

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