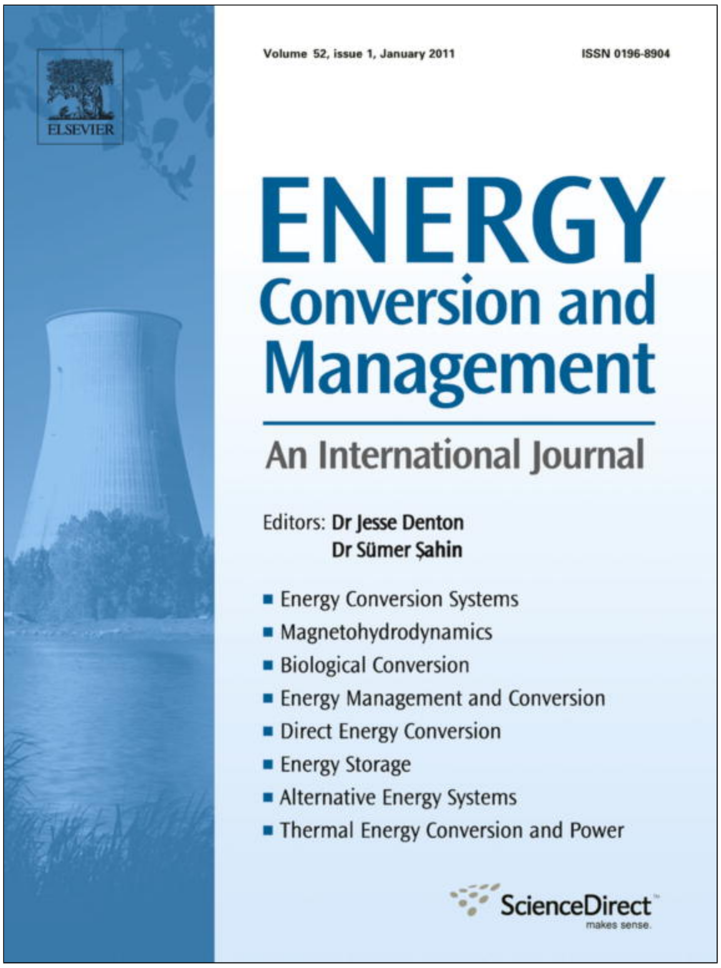

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Observation and calculation of the solar radiation on the Tibetan Plateau

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ABSTRACT

Distribution of solar radiation is vital to locate the most suitable regions for harvesting solar energy, but solar radiation is only observed at few stations due to high costs and difficult maintenance. From 2001 to 2005, a set of pyranometer instruments were set up in Gaize, on the Tibetan Plateau, to test the hypothesis of high solar-radiation levels in this region, and find a suitable method for estimating the radiation. Over the 5-year observation period, the average daily radiation was 21 MJ $m^{-2}day^{-1}$ with maximum daily values of 27 MJ $m^{-2}day^{-1}$ occurring in June and minimum values of 14 MJ $m^{-2}day^{-1}$ in December, which is much higher than those measured in other regions at similar latitudes. The observational data were used to validate a set of radiation models: five sunshine based and three temperature based. The results showed that of the five sunshine-based models, a newly developed "comprehensive" model performed the best, but that the "vapor revised Angstrom model" was recommended to use for its simplicity and easy operation. The temperature-based models performed worse than the sunshine-based ones, where the Wu model is to be preferred if a temperature-based model is the only option. Moreover, it was shown that when estimating the solar radiation based on time-dependent coefficients, consideration of the seasonal variation of the coefficients has little predictive value and is thus unnecessary. Based on the results of this study, a strategy for the calculation of solar radiation on the Tibetan Plateau was made for potential users.

1. Introduction

Solar radiation is considered to be a safe, effective and economic energy resource, having the potential to be one of the major energy sources in the near future [1]. To make full use of solar energy, it is vital to accurately establish its spatial distribution. However, compared to the large number of routine measurements of meteorological parameters, few stations observe solar radiation due to scarcity of instruments and high cost of maintenance. Therefore, it is common practice to calculate solar radiation through basic meteorological variables [2–4].

Based on the relationship between solar radiation and sunshine hours, the Angstrom model was introduced in 1924 [5] and revised in 1940 [6], and is likely the most popular empirical model for estimation of solar radiation when sunshine hours are available e.g. [7–11]. Based on sunshine hours and radiation data from 48 stations, a worldwide radiation model was developed by Bahel et al. [12], which was more complex than the Angstrom model and providing higher accuracy. Having examined the performance of the Angstrom and Bahel models at 48 stations over China, Chen developed a new radiation model considering not only sunshine hours but also air temperature, which was proved to be more accurate than both other models [7,13].

In addition to the sunshine-based models mentioned above, Bristow and Compbell [14], Hargreaves et al. [15], and Allen [16] developed different temperature-based models as exponential and square root expression respectively. Using not only temperature, but also humidity and precipitation, Thornton and Running [17] reformulated the Bristow and Compbell model, and found that the new model produced better results. Adding rainfall and dew point to the Hargreaves model, Wu et al. [13] presented two new models, and the validation results indicated that the model performed better when rainfall was considered, and performed best when both rainfall and dew point were considered. Recently, Li et al. [18] examined the performance of 12 models in Chongqing, China, finding that the model using all selected variables performed the best. Evaluation of the accuracy of several models for estimating solar radiation across Australia also indicated that a model using more variables always performed better [19].

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Several studies have indicated sunshine based models are superior to those temperature based ones [7,13,20], and that models using more variables can always obtained better performance [7,13,17–19]. However, these hypotheses are drawn mostly from the low-elevation regions, but have never been tested on the Tibetan Plateau, especially the non-populated high-altitude region in the western part of the Tibetan Plateau.

Located in the western part of the Tibetan Plateau, Gaize covers 9.74×10^4 km^2, with an averaged altitude of 4700 m above sea level. Average annual sunshine hours is 3168 h, which is far higher than that in low-land regions at the same latitude [21]. Because of the high altitude and sunshine hours, meteorologists have assumed that solar radiation in Gaize would be much higher than that in the plain regions at the similar latitude [22], but as yet no observations have been made to support this theoretical estimate.

Supported by a joint project between China and Japan, about 5-year of continuous observations were made in Gaize, from 2001 to 2005. The objectives of this study were: (1) to identify if the solar radiation in Gaze is as high as previously estimated, (2) to validate six existing models together with two new developed models to test the hypothesis mentioned above, that sunshine based models are superior to those temperature based models and more variables in the model might lead to a higher accuracy, (3) to provide recommendations for estimation of solar radiation in the western part of the Tibetan Plateau based on the modeling results.

2. Experiment and methodology

2.1. Description of the experimental site

Solar-radiation measurements were conducted at Gaize weather station (32° 30′ N, 84° 06′E, 4420 m above sea level) (Fig. 1). Gaize belongs to the sub semi-arid Alpine Monsoon Climate Zone [21], with annual monthly maximum temperature of 11.9 °C in July and minimum temperature of −12.8 °C in January. The average annual precipitation is 189.6 mm. The soil at the Gaize weather station is composed of clay with a certain amount of sand. Sparse vegetation, mainly consisting of plateau spike-like weeds and desert spike-like weeds, is only present during the rainy season from June to August, only reaching heights of a few centimeters. The ground surface around the weather station is quite flat and homogeneous, without any obstacle within some tens of kilometer distance. The Air density in Gaize is only half of that at sea level, due to the high elevation. Being a non-populated region, Gaize has quite clear air without man-made pollutants.

2.2. Instrument installation and data collection

In October 2000, a MS-80 precision pyranometer for global radiation measurement, was installed at a platform 1.5 meter above ground inside the Gaize weather station, and immediately calibrated. Measurement error of the pyranometer is within ±1.5%. The instrument was subsequently calibrated every year from 2001 to 2005. Solar radiation was measured at every 5 s and averaged every hour to exclude random errors, and the measured values recorded automatically by a microcomputer set beside.

In this study, hourly radiation values were first integrated to daily values, followed by a data-quality control, strictly according to standards, where (1) measured values should be lower than the extra-terrestrial solar radiation, and (2) measured values should not be high in rainy days. Data failing to pass the quality test were to be excluded from the final data set. However, no data failed the quality test. Because of instrument calibration, 30 days of data were missed during the 5-year measurement period, yielding an average of 6 days of missing data per year. Still, this is much better than in datasets routinely recorded at radiation stations in China [23], where the number of missing data usually exceeds 10 per year. In addition, a number of missing data less than 7/year meets the meteorological standard formulated by the China Meteorological Administration (CMA) [23]. Besides solar radiation, routinely observed meteorological data was also measured simultaneously in the Gaize weather station, including sunshine hours (Jordan sunshine recorder) (±5%), daily mean, maximum and minimum temperature (CAWS600) (±0.2 °C), air pressure (CAWS600) (±0.2 hPa), vapor pressure (HPHS) (±2%), wind speed (CAWS) (±0.6 m/s) and precipitation (CAWS) (±4%). Fog was also observed during 2001–2005, although it does not belong to the ordinary meteorological items.

Based on the measured data, a database was established including solar radiation and the corresponding meteorological data routinely observed. Then the database was divided into two data sets. The first set, containing 1085 days from 2001 to 2003, was used to calibrate the coefficients of the models, while the second set, containing 701 days from 2004 to 2005, was used for model validation.

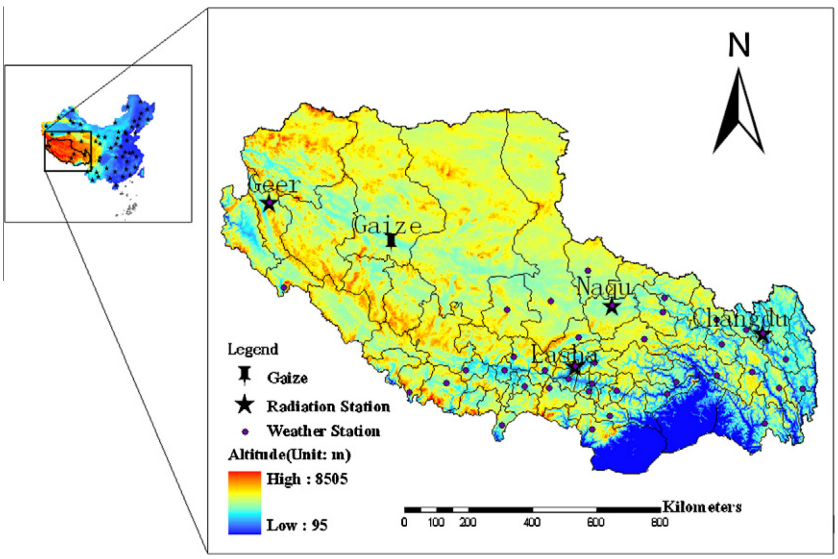

Fig. 1. Distribution of the weather and radiation stations in China and the location of the experimental site in this study.

2.3. Model introduction

There are about 2480 weather stations in China [23], but solar radiation is only observed at 90 of those. However, sunshine hours are routinely measured at the basic weather stations and can be obtained from CMA (website: http://mdss.cma.gov.cn:8080/). In the fact, sunshine hours are treated as a basic ordinary observed item, just the same as temperature, by CMA [23]. Previous studies have indicated that the models based on sunshine hours can provide more accurate estimations of solar radiation than those based on other items such as temperature and precipitation, etc. [7,13,20]. Consequently, this study mainly focused on the sunshine based models. However, models based on temperature and precipitation may be of use in case sunshine data is lacking or cannot be easily obtained. Thus, eight radiation models, including five sunshine-based and three temperature-based, were calibrated and validated against the measured data in Gaize. Brief introductions to the used models are as follows:

Model 1: The Angstrom model. Angstrom suggested this simple model, based on the linear relationship between radiation and sunshine hours, in 1942 [5], and it was modified by Prescott in 1940 [6]. The model can be expressed as

$$R_A = R_E\left[a + b\frac{S}{S_0}\right] \tag{1}$$

where R_A is actual daily solar radiation (MJ m^{-2} day^{-1}), R_E is the daily extra terrestrial solar radiation (MJ m^{-2} day^{-1}), S is the actual sunshine hours and S_0 is the potential sunshine hours.

Model 2: The Bahel model. Based on sunshine hours and global radiation data from 48 stations around the world, Bahel et al. [12] developed this worldwide model as

$$R_A = R_E\left[a + b\left(\frac{S}{S_0}\right) + c\left(\frac{S}{S_0}\right)^2 + d\left(\frac{S}{S_0}\right)^3\right] \tag{2}$$

Model 3: The Chen model. Chen et al. [7] found a new expression of the relationship between R_A/R_E and meteorological variables, and suggested a new model in which both sunshine hours and temperature were included.

$$R_A = R_E\left[a + b\ln(T_{\max} - T_{\min}) + c\left(\frac{S}{S_0}\right)^d\right] \tag{3}$$

Chen et al. [7] validated his model against data in China and found that the results were more accurate than those derived from the Angstrom and Bahel models.

Model 4: The "Vapor revised Angstrom" model. Considering the important role of vapor in solar radiation, we suggested a new empirical model as:

$$R_A = R_E\left[a + \left(b + c\frac{1}{E}\right)\frac{S}{S_0}\right] \tag{4}$$

in which E is the daily vapor pressure (hPa).

Model 5: The "Comprehensive" model. This model is based on the Chen model and the new developed vapor revised Angstrom model, resulting in a comprehensive model involving both temperature difference and the vapor pressure, and can be expressed as:

$$R_A = R_E\left[a + b\ln(T_{\max} - T_{\min}) + \left(c + d\frac{1}{E}\right)\frac{S}{S_0}\right] \tag{5}$$

Model 6: The Hargreaves model. This model can be used easily with only temperature as input variable [15], which is more readily obtained compared to other variables:

$$R_A = R_E(a + b\sqrt{T_{\max} - T_{\min}}) \tag{6}$$

where $T_{\max}$ is the maximum temperature and $T_{\min}$ is the minimum temperature. When the coefficient a equals 0, it becomes the Allen model [16]. So, the Allen model can be referred to as a special type of the Hargreaves model.

Model 7: The Bristow and Campbell model. This model also uses temperature as input variables [14], and expressed the relationship between solar radiation and temperature difference as an exponential form:

$$R_A = R_E a\{1 - \exp[-b(T_{\max} - T_{\min})^c]\} \tag{7}$$

Model 8: The Wu Model. Wu et al. [13] developed a model considering both temperature and precipitation, which proved to be better than the Bristow and Campbell model:

$$R_A = R_E(a + b\sqrt{T_{\max} - T_{\min}} + cT_a + dP_t) \tag{8}$$

where T_a is the daily average temperature (°C), and P_t is the transformed rainfall data, which was defined as $P_t = 1$ if $P > 0$; $P_t = 0$ if $P = 0$, where P is the daily total precipitation (mm).

Additional temperature based models [e.g. [18]] have also been developed, but they were not used in this study due to their input variables, e.g. the dew point and fog, etc., not being routinely observed [23]. The daily extra-terrestrial solar radiation was calculated according to the equations described by Allen et al. [24] and the coefficient was fitted by numerical iteration methods [25].

2.4. Model evaluation

Three statistics, the Nash–Sutcliffe Equation (NSE), the Mean Absolute Percentage Error (MAPE), and the Root Mean Squared Error (RMSE), were used as evaluation criteria in this study, and can be calculated as follows respectively:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Yo_i - Ys_i)^2}{\sum_{i=1}^{n}(Yo_i - \overline{Yo})^2} \tag{9}$$

$$MAPE = \frac{\sum_{i=1}^{n}\frac{|Yo_i - Ys_i|}{Yo_i} \times 100}{n} \tag{10}$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(Yo_i - Ys_i)^2\right]^{\frac{1}{2}} \tag{11}$$

where Yo_i is the observed value, Ys_i is the simulated value, $\bar{Yo}$ is the average value of the observed radiation, and n is the number of data. NSE was suggested by Nash et al. [26] in 1970 and is currently widely used as a criterion to evaluate model performance in different scientific domains, e.g. hydrology [27], energy [7], and agronomy [28]. The value of *NSE* indicates the model efficiency, i.e. the variation in measured values accounted for by the model, and a higher *NSE* value means a more efficient model. *RSME* is one of the global statistics, where a small value indicates high accuracy of the model prediction. *NSE* was used as the evaluation criterion for model calibration. As for the assessment of the prediction, *RSME* was used as the main indicator for validation, together with other criteria such as *NSE*, *intercept*, and *slope*.

The *t*-statistic is used to identify significant differences between and within the sunshine based models and the temperature based ones, and the t value can be calculated as [29–31]:

$$t = \sqrt{\frac{(n-1) \times MBE^2}{(RMSE^2 - MBE^2)}} \tag{12}$$

where *MBE* is the mean bias error:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(Ys_i - Yo_i) \tag{13}$$

When the calculated $|t| \geqslant t_{0.05}$ (critical value), the two groups of data differ significantly, and vice versa [29–31].

3. Results

3.1. Primary statistical analysis of the routinely observed meteorological variables

The routinely observed meteorological variables, including sunshine hours, rainy days, temperature, air pressure, vapor pressure and wind speed, were analyzed from 2001 to 2005. Averaged monthly mean values of the meteorological variables are shown in Fig. 2. Sunshine hours were high in Gaize, with an annual mean daily value of 8.8 h. Minimum averaged monthly mean daily sunshine hours occurred in January, while the maximum occurred in May, yielding a pattern similar to that of potential sunshine hours (see Fig. 2a). However, the observed sunshine hours decreased in June while the potential sunshine hours increased to its maximum value. Observed sunshine hours in July and August were also lower than those in May and April, respectively. This phenomenon could be attributed to the increase in rainy days from June to August, coinciding with the rainy season in Gaize (Fig. 2b). Under the influence of the Alpine Monsoon climate [21], Gaize has the obvious alternation of dry and wet climate conditions. In the dry season, from October to April the next year, the averaged monthly rainy days never exceeded 2 days. However, the averaged monthly rainy days increased to more than 10 days in the rainy season from June to August, with the highest values of about 14 days found in July and August. Temperatures in Gaize are low (Fig. 2c) with the lowest monthly mean temperature of −11.9 °C in January and the highest value of 12.9 °C in July. The diurnal temperature variation, i.e. the difference between maximum and minimum temperature, is more than 15 °C throughout the year. The averaged monthly mean air pressure in Gaize is low, never exceeding 600 hPa. The averaged monthly vapor in Gaize (Fig. 2e), follows the same seasonal variation as in rainy days and temperature, with the lowest value of about 0.7 hPa found in January and the highest value of 7.3 hPa found in August. The maximum in averaged monthly wind speed was 4.1 ms^{-1} in February and decreased to the minimum value of 2.3 ms^{-1} in October. Fog days were also analyzed but are not shown due to its small values. In fact, there were only five fog days recorded during the consecutive five years of measure-

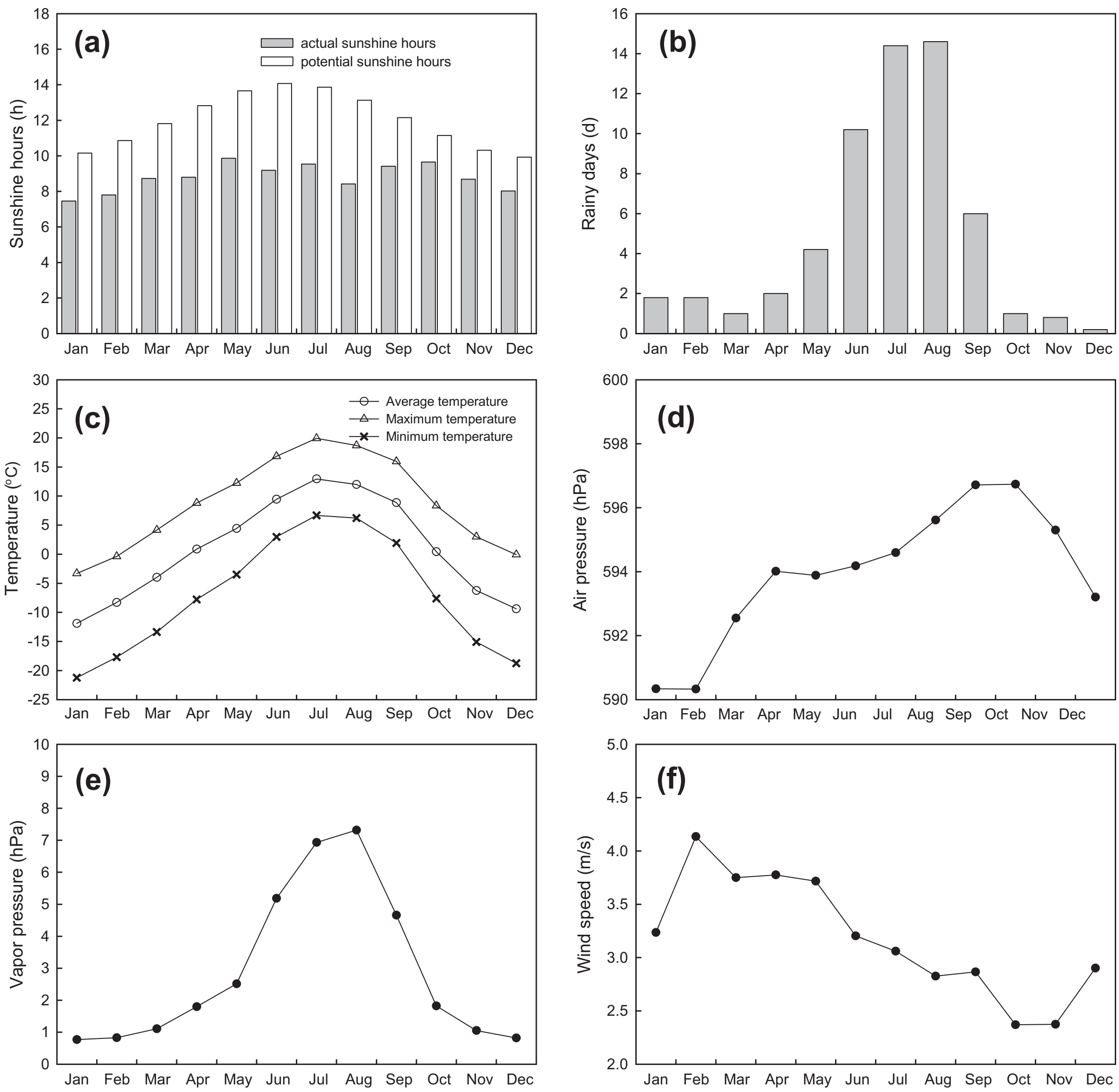

Fig. 2. Distribution of routinely observed meteorological items in Gaize from 2001 to 2005. (a) Sunshine hours, (b) rainy days, (c) temperature, (d) air pressure, (e) vapor pressure, and (f) wind speed.

ments, and this can be attributed to the cold temperature, low vapor pressure and the high wind speed in this highland region.

3.2. Distribution of solar radiation

The averaged diurnal variations of solar radiation in different seasons are given in Fig. 3.a. The variation patterns in different seasons were similar, with a maximum at noon. The lowest solar radiation value at noon, 649.8 $Jm^{-2}\,s^{-1}$, was recorded in winter, while the highest value, 884.6 $Jm^{-2}\,s^{-1}$, was recorded in spring. The solar radiation at noon in summer was 883.6 $Jm^{-2}\,s^{-1}$, just slightly less than that in spring. Five-year averaged daily radiation changed greatly from the lowest value of 9.6 MJ m^{-2} day^{-1} (January) to the highest value of 31.0 MJ m^{-2} day^{-1} (July) (Fig. 3b). The distribution of the 5-year averaged monthly daily solar radiation is shown in Fig. 3c, displaying a clear seasonal variation, with a minimum value of 13.6 MJ m^{-2} day^{-1} in December and a maximum value of 26.9 MJ m^{-2} day^{-1} in June. The curves showing the diurnal variations of solar radiation (Fig. 3a) are not symmetrical because of the lower radiation in August in contrast with the higher radiation in June, due to more rainy days in August. The interannual solar-radiation variation is given in Fig. 3d. The averaged 5-year daily solar radiation was 20.9 MJ m^{-2} day^{-1}, with the lowest value of 20.5 MJ m^{-2} day^{-1} in 2005 and the highest value of 21.3 MJ m^{-2} day^{-1} in 2001. During the 5-year measurement period, the annual daily solar radiation had a small coefficient of variance (0.013), indicating that the annual solar radiation is quite stable in Gaize.

3.3. Seasonal variation in the clear sky index

Further investigation was made to identify the sky conditions in Gaize in different seasons. The clear sky index, *Kt*, which is the ratio of the actual solar radiation to the extra-terrestrial solar radiation, was used as the criterion for sky conditions in this study [32].

The monthly mean clear sky index averaged over five years are shown in Table 1. The index was high in Gaize without any value lower than 0.6 in any season of the year. The higher index occurred from October to March next year, corresponding to the lower rainy days at the same period (Fig. 2b).

3.4. Model performance with fixed coefficients

The data set from 2001 to 2003 was used to calibrate the coefficients of the eight models, and the fitted coefficients, together with respective values of *MAPE* and *NSE*, are listed in Table 2. There was a distinguished difference between the *NSE* values of the sunshine-based models (models 1–5) compared to those of the temperature-based models (models 6–8). All sunshine-based models had *NSE* values higher than 0.9, while none of the temperature-based models had *NSE* values exceeding 0.8. A comparison of the *NSE* values from the sunshine-based models indicted that the comprehensive model (model 5), with a *NSE* value of 0.928, performed the best among all selected models. However, it should be noted that the differences in model performance among the five models were very small (a difference of 0.007 in *NSE* values between the “best” and “worst” performing models). The performances of all temperature-based models were poorer than the sunshine-based ones, with the best performing temperature-based model being the Wu model (model 8) yielding a *NSE* value of 0.752. The difference among the temperature-based models was 0.02, much larger than the sunshine based ones.

Subsequently, the calibrated coefficients were used to drive the second data set from 2004 to 2005 for model validation. Fig. 4 shows the validation results with values of *RMSE* and *NSE* for each

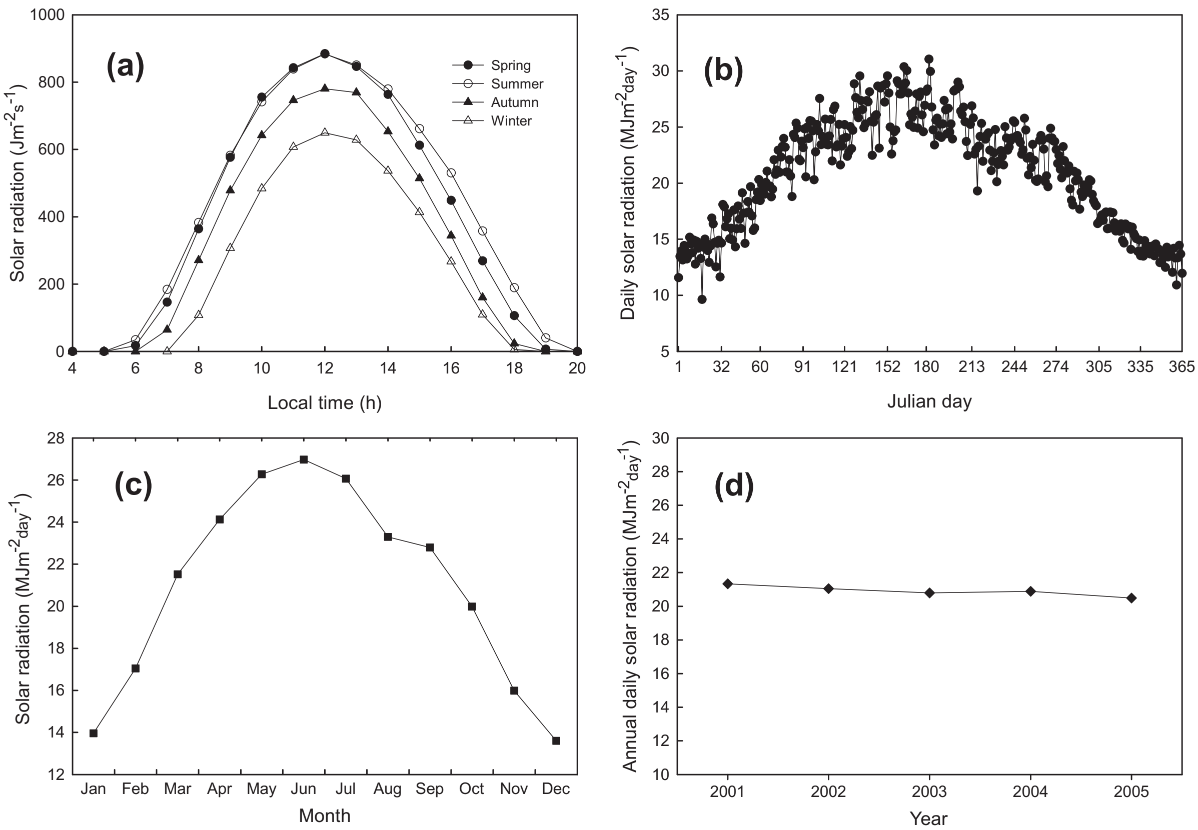

Fig. 3. Distribution of solar radiation in Gaize from 2001 to 2005. (a) Diurnal variation, (b) daily variation, (c) monthly variation, and (d) annual variation.

Table 1
Monthly mean clear sky index *Kt* from 2001 to 2005.

Month	January	February	March	April	May	June	July	August	September	October	November	December
Kt	0.696	0.690	0.698	0.663	0.655	0.653	0.643	0.621	0.702	0.761	0.763	0.732

Table 2
Coefficients and evaluation indicators of the model calibrated with the data from 2001 to 2003.

Model no.	*a*	*b*	*c*	*d*	*MAPE*	*NSE*
1	0.321	0.503	–	–	5.952	0.921
2	0.331	0.567	−0.284	0.228	5.921	0.922
3	0.215	0.062	0.433	1.137	5.774	0.927
4	0.329	0.479	0.020	–	5.856	0.924
5	0.208	0.055	0.449	0.011	5.772	0.928
6	0.172	0.130	–	–	12.405	0.732
7	0.794	0.073	1.234	–	12.059	0.745
8	0.243	0.115	0.001	−0.067	11.960	0.752

model respectively. The results of the validation were quite similar to those of the model calibration. It can be clearly seen from Fig. 4, that all sunshine-based models performed better than the temperature-based models, indicated by lower *RMSE* and higher *NSE* values. Among the sunshine based models, the new comprehensive model, considering both temperature and vapor, performed the best (Fig. 4e). The Chen model performed (Fig. 4c) only slightly worse than the comprehensive model. The new vapor revised Angstrom model was slightly less accurate than the comprehensive and Chen models (Fig. 4d). The Angstrom and Bahel models performed worse than the previous three models with little prediction difference. Similar to the calibration, the validation results clearly showed that the temperature-based models performed worse than the sunshine-based models. The Wu model (model 8) showed the best performance with a *RMSE* value of 3.054 and a *NSE* value of 0.736, much better than those of the other temperature-based models. This result is consistent with those from Wu et al. [13]. The intercept and slope in Fig. 4, used as indicators to describe the agreement between observed and simulated values, also support the advantage of sunshine-based over temperature-based ones.

The result of the *t*-test between and within the sunshine-based models and the temperature-based ones can be seen in Fig. 5. The *t*-test value between sunshine and temperature-based models is higher than the critical value of $t_{0.05}$, which means that difference between the sunshine and temperature based models is significant. However, the result of the *t*-test among the five sunshine based models indicates that all of the *t* values are much lower than the critical value, showing that the differences between different sunshine-based models are not significant. A similar result can also been seen among the three temperature-based models.

3.5. Model performance with time-dependent coefficients

Further investigation was made to identify the influence of the calibration timescale on the results of the predictions. The original calibration dataset was divided into four groups according to 3-month seasons in the year. Spring was defined as March to May, summer as June to August, autumn as September to November, and winter as December to February. Thus, four seasonal datasets were created for time-dependent coefficient calibration. The seasonal datasets for validation were developed in the same way.

First, the coefficients of the models were calibrated (Table 3), and then the calibrated coefficients were used to drive the different seasonal data sets for validation from 2004 to 2005. Finally, the seasonal coefficients were also used to drive the original annual dataset as validation. The *MAPE*, *RMSE* and *NSE* values for the validation are given in Table 3 for the evaluation of the predictions. All models performed the best in autumn, yielding the lowest *MAPE* and *RMSE* values and the highest *NSE* values. A comparison of Table 3 with Fig. 4 indicates that predictions using seasonal solar-radiation coefficients do not necessarily provide better results than if fixed annual ones are used. Regarding the sunshine-based models, the Angstrom model and the vapor revised Angstrom model performed slightly better when the seasonal coefficients were used rather than the fixed ones. However, the values of *RMSE* of the other three sunshine based models increased slightly, along with deceasing values of *NSE*, showing the negative effects of the time-dependent coefficients. When making predictions with seasonal coefficients, all temperature-based models performed a slightly better, indicating again that the effect of the time-dependent coefficients on the results of the prediction was rather small.

4. Discussion

Compared to studies of solar radiation simulations based on routine observations [2,7,13,19,18,33–35], the lengths of radiation datasets based on microclimatic observations are much shorter [36,37], largely due to the expensive cost of such experiments. Even a 48-month observation has been considered to be a long period for solar-radiation observations using the microclimate method [37]. However, in this work we present a solar-radiation dataset based on five consecutive years of measurements, where 1786 daily samples were collected, making statistical analysis of solar radiation more reliable. The length of this data set was even longer than the 4-year long time series used by Chen et al. [7] for model validation with routinely observed radiation values in China.

Results from solar radiation studies from different parts of China along the similar latitude as our study site, were used to contrast with the observation results of this work. Shanghai (31°20′N, 121°43′E, 19 m above sea level), which is the biggest city located in the east part of China, has an average annual mean daily solar radiation of 12.8 MJ m^{-2} day^{-1} [38] which is only about 60% of that in Gaize. Wuhan (30°62′N, 114°13′E, 27 m above sea level), the capital of the Hubei Province in the central part of China, has an average annual mean daily solar radiation of 13.2 MJ m^{-2} day^{-1} [39], which is also much more lower than that in Gaize. Situated in the transitional area between the Tibetan Plateau and the plain on middle and lower reaches of the Yangtze River, Chongqing has a monthly mean daily solar radiation ranging from a maximum of 15.1 MJ m^{-2} day^{-1} to a minimum of 3.0 MJ m^{-2} day^{-1} [18]. The maximum is only 55% of that in Gaize and the minimum is only 22% of that in Gaize, respectively. Looking outside China, the results from Tibet can be compared to those from Shiraz (29°36′N, 52°32′E, 1500 m above sea level), which received the top rating among 30 sunny locations in Iran as the most favorable candidate for a thermal power plant site [40]. In Shiraz the average annual daily solar radiation is 19.3 MJ m^{-2} day^{-1} [36], still lower than that at the Gaize station.

Solar radiation at the surface of the Earth is effected by many environmental factors including aerosols and meteorological variables such as sunshine hours, vapor, and precipitation. The low aerosol optical depth (AOD) on the Tibetan Plateau [41] means less attenuation of solar radiation, due to the clear air in this non-polluted area. Higher sunshine and clear-sky indices compared to

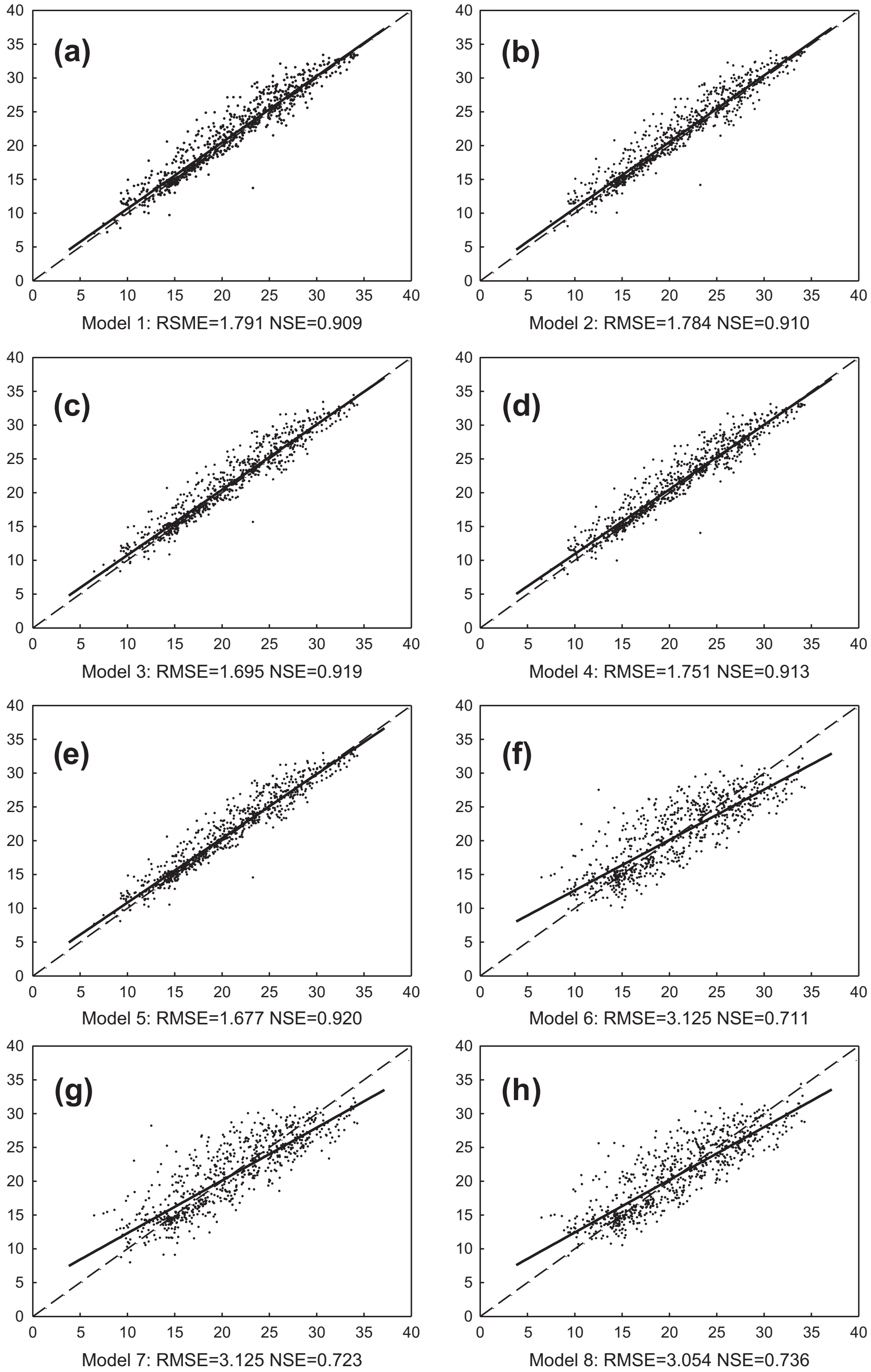

Fig. 4. Model validation. Measured (the horizontal axis) vs. the predicted (the vertical axis) values of solar radiation from 2004 to 2005. (unit: MJ m^{-2} day^{-1}).

other regions [e.g. [18,36]] are also important reasons for higher radiation in this highland region. In addition, the high radiation in Gaize also resulted from the lower vapor pressure and very few fog days compared to other regions [e.g. [18]].

The *a* coefficients for the Angstrom model in Gaize is slightly higher than that in Lhasa [7], but much higher than in other regions in China, reflecting that the effect of type and thickness of prevailing clouds on the Tibetan Plateau is quite different from those in the lowland plain regions [7]. The *b* coefficients for the Angstrom model in Gaize showed no obvious difference to those used in other regions [7], including Lhasa. This clear difference in *a* coefficient between Tibetan Plateau and other regions suggest that further investigations should be made in different areas of Tibetan Plateau to provide a more detailed distribution of the coefficients in this special region. The results from both the calibrations and the validations of the models clearly showed that values of *NSE* for the five sunshine-based models were much higher than those of the temperature-based models, supporting the conclusions made by other studies [7,13,20] that sunshine-based models generally has advantages over temperature-based ones.

Among the five selected sunshine-based models, the Chen model (model 3) performed well in estimating solar radiation in Gaize, only slightly worse than the comprehensive model (model 5). Although slightly less accurate than the Chen model, the vapor

Table 3
Coefficients and evaluation indicators of the models in different seasons.

Model no.	Season	*a*	*b*	*c*	*d*	*MAPE*	*NSE*	*RMSE*	*n*
1	Spring	0.319	0.514	–	–	9.171	0.688	2.439	154
	Summer	0.332	0.474	–	–	7.126	0.806	2.124	184
	Autumn	0.317	0.511	–	–	5.233	0.933	1.250	182
	Winter	0.323	0.514	–	–	5.264	0.875	1.026	181
	Year					6.603	0.910	1.780	701
2	Spring	0.283	0.834	−0.703	0.442	9.257	0.682	2.465	154
	Summer	0.281	0.950	−1.081	0.693	6.960	0.801	2.147	184
	Autumn	0.433	−0.041	0.720	−0.277	5.435	0.930	1.281	182
	Winter	0.401	−0.198	1.467	−0.851	5.465	0.867	1.057	181
	Year					6.683	0.908	1.805	701
3	Spring	0.187	0.061	0.465	1.038	8.707	0.719	2.316	154
	Summer	0.103	0.099	0.421	0.904	6.850	0.825	2.013	184
	Autumn	0.310	0.048	0.391	1.509	5.254	0.930	1.280	182
	Winter	0.274	0.035	0.464	1.183	5.356	0.886	0.978	181
	Year					6.458	0.917	1.707	701
4	Spring	0.329	0.477	0.034	–	9.310	0.693	2.422	154
	Summer	0.346	0.407	0.245	–	6.764	0.818	2.057	184
	Autumn	0.324	0.492	0.014	–	5.206	0.935	1.237	182
	Winter	0.329	0.486	0.012	–	5.174	0.882	0.997	181
	Year					6.508	0.914	1.747	701
5	Spring	0.207	0.052	0.452	0.025	8.990	0.710	2.352	154
	Summer	0.184	0.075	0.376	0.169	6.655	0.831	1.982	184
	Autumn	0.226	0.049	0.458	0.006	5.095	0.934	1.240	182
	Winter	0.254	0.031	0.473	0.009	5.216	0.888	0.972	181
	Year					6.391	0.918	1.700	701
6	Spring	0.210	0.116	–	–	12.839	0.414	3.345	154
	Summer	−0.076	0.198	–	–	11.620	0.485	3.456	184
	Autumn	0.231	0.128	–	–	12.206	0.660	2.822	182
	Winter	0.296	0.097	–	–	12.644	0.420	2.208	181
	Year					12.304	0.747	2.987	701
7	Spring	0.845	0.144	0.879	–	12.736	0.427	3.308	154
	Summer	0.835	0.053	1.302	–	11.681	0.487	3.451	184
	Autumn	0.807	0.028	1.702	–	11.168	0.692	2.684	182
	Winter	1.451	0.217	0.392	–	12.618	0.419	2.211	181
	Year					12.021	0.755	2.943	701
8	Spring	0.251	0.107	0.000	−0.043	12.886	0.418	3.332	154
	Summer	0.040	0.168	0.001	−0.055	11.030	0.535	3.286	184
	Autumn	0.358	0.099	0.000	−0.107	11.462	0.697	2.663	182
	Winter	0.317	0.091	0.000	−0.036	12.748	0.422	2.205	181
	Year					11.993	0.763	2.893	701

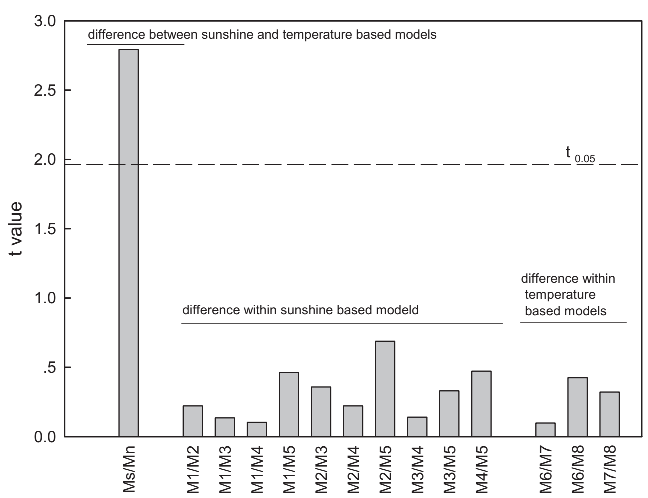

Fig. 5. Values of *t*-statistic comparing predictions between and within the sunshine and temperature based models. *M* denotes "model", s denotes "sunshine based models", *n* denotes "temperature based models", and the digital numbers are those of the models from 1 to 8.

revised Angstrom model (model 4) has the advantage of easy operation because of its simplicity. Also, calibration of coefficients with models involving exponential functions, as in the Chen model, always means more difficult work for the potential users. The vapor revised Angstrom model can be referred to as another form of the Angstrom model, in which the effect of the vapor on the transmission characteristics of cloud free atmosphere was considered by involvement of the vapor pressure. Due to this reason, its coefficient *a* was nearly the same as that of the original Angstrom model [see Table 2]. The coefficient *b* of the Angstrom model was expressed as a linear relationship between *b* and vapor pressure in the revised model, through which the effect of variations in vapor pressure on the transmission of cloud free atmosphere was separated from the coefficient *b* and reasonable considered. Vapor is one of the most important meteorological factors seriously influencing the transmission of solar radiation [42], but few empirical models have considered this parameter. Wang et al. [43] introduced vapor pressure into an empirical model for estimating the national distribution of solar radiation in China, and found that the model performed well with an improvement of the applicability of the model. Despite that the extra-terrestrial radiation in this study was different from the ideal atmosphere radiation used in the Wang model [43], our results support the conclusions made by Wang et al. that the introduction of vapor pressure could make the model perform better. Since the aerosol content is quite low on the Tibetan Plateau because of its non-polluted atmosphere, vapor plays a very important role in the transmission of solar radiation under cloud free conditions. Despite the low vapor pressure on the Tibetan Plateau, it has an obvious daily variation, which had already been proved by GPS measurements [44]. So, adding vapor pressure to coefficient *b* meant that the variation of the vapor pressure was considered reasonably, which led to a better calculation result. When both temperature and vapor pressure were considered in the sunshine-based models, the comprehensive model (model 5) performed the best, which is in agreement with previous results [7,13,17–19] that the more variables considered in the model, the better performance could be shown in the validation. This is further supported by the comparison of the validation results between the three temperature based models (Table 2 and Fig. 4).

In the view of the statistical analyses, the *RMSE* values became smaller when the calibrations were made with seasonal coefficients rather than fixed annual ones, as the values of the *RMSE* in each season would decrease to the minimum according to the least square method [25]. However, a better calibration does not necessarily mean a better validation/prediction in radiation calculations [4,45]. Thus, estimations of solar radiation with seasonal coefficients might not necessarily have an advantage over those based on fixed ones, which is in agreement with the findings of Liu et al. [35] in a recent study on the calculation of solar radiation in North China. Validation of the models with seasonal coefficients in this work supports the conclusions mentioned above, that consideration of the seasonal variations of the coefficients has little predictive value and is thus unnecessary.

Models mentioned in the study, especially the newly developed "vapor revised Angstrom model" and the "comprehensive sunshine based model", can be used to predict the daily solar radiation at weather stations in the western part of the Tibetan Plateau under Alpine Monsoon climate conditions. We cautiously envisage that the models can also be used in the other regions under similar climate conditions, but only after the successful calibration of the parameters and validation against the observations. It should be kept in mind that sunshine hours are not observed in all of the weather stations in this alpine area, which will surely limit the popularization of sunshine based models. Moreover, even temperatures are not observed in a few stations due to tough living and working conditions, which means that precipitation is the only meteorological factor available. So, precipitation based models should be developed and validated in the future studies to make sure that daily solar radiation can be calculated at all weather stations in the western part of the Tibetan Plateau.

5. Summary and conclusions

Observations of solar radiation in Gaize, the Tibetan Plateau, were made during five consecutive years from 2001 to 2005. Statistical analysis of the measured data indicated that the average annual mean daily solar radiation in Gaize was 21 MJ m^{-2} day^{-1}, which is much higher than in other regions at similar latitudes. The high solar radiation was mainly attributed to low atmospheric aerosol content, lower vapor pressure, higher clear-sky index, and very few fog days in this Alpine Monsoon climate region. Estimation of solar radiation clearly indicated that sunshine-based models performed better than temperature-based ones. A newly developed "comprehensive sunshine-based model", including both temperature and vapor pressure, showed the best performance, closely followed by the Chen model. The performance of the newly developed "vapor revised Angstrom model" was slightly worse than that of the former two models, but it can be recommended to use for its simplicity and easy operation. Among the three temperature-based models, the Wu model performed the best. Further investigation on estimation of solar radiation with time-dependent coefficients showed that consideration of seasonal variation of the coefficients has little predictive value and is thus unnecessary.

Based on the results of the present study, the following strategy is recommended for calculating solar radiation on the Tibetan Plateau: (1) fixed annual coefficients rather than the seasonal ones should be used for calibration when the daily solar radiation is to be estimated on the Tibetan Plateau; (2) when sunshine hours, temperature and vapor pressure are available, newly developed comprehensive model should be preferred; (3) when both sunshine hours and temperature are available, the Chen model is sufficient to make accurate estimates; (4) when both sunshine hours and vapor pressure are available, the newly developed vapor revised Angstrom model should be used; (5) when only sunshine hours are available, both the Angstrom and the Bahel model can be selected with little difference in the prediction accuracy; (6) when only the ordinary routinely observation meteorological data can be obtained, the Wu model should be favored.

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