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Radiation calibration of FAO56 Penman–Monteith model to estimate reference crop evapotranspiration in China

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ABSTRACT

The standardized FAO56 Penman–Monteith model, which has been the most reasonable method in both humid and arid climatic conditions, provides reference crop evapotranspiration (ET_o) estimates for planning and efficient use of agricultural water resources. Net radiation is an important and site-specific component to determine ET_o. The empirical radiation estimation in FAO56 Penman–Monteith model was calibrated by observed solar radiation of 81 meteorological stations over China during 1971–2000, and measurements of net longwave radiation in the Tibetan Plateau. Results showed that Ångström formula based on simple annual linear regression coefficients of 0.20 and 0.79 yielded the least error for the preserved 30 validation stations, and are thus recommended for estimating solar radiation in China. The optimal calibration of net longwave radiation was based on Penman estimation combined with the minimum and maximum temperatures. The calibrated net radiation served as the basis to estimate ET_o accurately, which would be overestimated by about 27% if no local calibration is performed on the FAO56 Penman–Monteith model in China. The average ET_o was 769 mm yr^{-1} based on calibrated radiation model in China during 1971–2000.

1. Introduction

The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration and is denoted as ET_o. The reference surface is a hypothetical grass reference crop with specific characteristics. ET_o represents the evaporating rate of atmosphere and an upper bound of actual evapotranspiration rates (Allen et al., 1998). Being an important component of the hydrological cycle, ET_o will affect agricultural water use (Allen, 2000; Hunsaker et al., 2002), ecosystem models (Fisher et al., 2005), aridity/humidity conditions (Wu et al., 2006), and rainfall-runoff estimation.

ET_o can be computed as a function of weather parameters. Numerous methods, such as temperature-based, radiation-based or combined methods, have been used to estimate ET_o (Penman, 1948; Thornthwaite, 1948; Priestley and Taylor, 1972; Hargreaves, 1974; Hargreaves, 1994). However, it causes confusion as to which method to select for ET_o estimation. Therefore, the Food and Agriculture Organization of the United Nations proposed Penman–Monteith model in Irrigation and Drainage Paper No. 56 (hereafter as FAO56-PM) using the hypothesized reference crop (height of 0.12 m, surface resistance of 70 s m^{-1} and albedo of 0.23) as the sole method for determining ET_o (Allen et al., 1998; Walter et al., 2000). The FAO56-PM model, which incorporates thermodynamic and aerodynamic aspects, has proved to be a relatively accurate method in both humid and arid climates. The model has received favorable acceptance and application over much of the world, some researches thereafter took it as standard to

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modify other models, which required less input data (Wright et al., 2000; Temesgen et al., 2005).

The evapotranspiration process is determined by the amount of energy available to vaporize water (Allen et al., 1998). By providing energy, solar radiation R_s plays a key role in the energy balance of the Earth–Atmosphere system (Iziomon and Mayer, 2002), and is a key variable for computing ET_o. The availability of observed R_s measurements has proven to be spatially and temporally inadequate for many applications, leading to researches to focus on the estimation of R_s (Belcher and DeGaetano, 2007). Empirical formulas have been developed to estimate R_s using some normal observations, such as the maximum and minimum temperatures, sunshine hours, cloud, precipitation, latitude, elevation and gradient. Empirical formulas are the most easy and exact method compared with other ways such as remote sensing, random weather model, linear interpolation and net neural network (Trnka et al., 2005).

As for the radiation formula in FAO56-PM model, where no actual solar radiation data are available and no calibration has been carried out for improved empirical coefficients, the FAO recommended values could be used (Allen et al., 1998). Due to the site-specific empirical coefficients, the calibration of radiation in the FAO56-PM model has great impact on planning and efficient use of agricultural water resources. However, most studies applied FAO56-PM model to China without calibration, except some improvements (Niu et al., 2002; Chen et al., 2005). Moreover, net longwave radiation (R_{nl}) has not been studied often because of the lack of measured values. Where measurements of incoming and outgoing longwave radiation are available, calibration of R_{nl} can be carried out (Allen et al., 1998).

Here we show a regional calibration of both R_s and R_{nl} models using radiation measurements made in China that was done to improve the performance of the FAO56-PM model to estimate reference crop evapotranspiration in China.

2. Materials and methods

2.1. *Materials*

Monthly observations of solar radiation and actual sunshine duration were collected at 111 stations during 1971–2000 (Fig. 1), of which 81 stations were used to calibrate solar radiation by linear regression, and the other 30 stations, representing different climatic regions of China, were preserved to validate an optimum solar radiation model calibration (Table 1). Meteorological data, latitude and elevation of stations were provided by the Climatic Data Center (CDC), National Meteorological Information Center (NMIC) of China Meteorological Administration (CMA). Radiation measurements made at the meteorological stations were validated by CDC using quality control procedures.

The Eppley Precision Infrared Radiometer, Pyrgeometer, was used to measure the net longwave radiation in the Tibetan Plateau in 1979 from May to August, and from August of 1982 to July of 1983. These were the first time such measurements were made in China (Zhou, 1984; Ji, 1985; Zuo, 1991). There exists a general dome heating problem with the use of pyrgeometer as an instrument for measuring downward infrared radiation (Albrecht and Cox, 1977; Udo, 2000). At present, there is some ways but no internationally recognized standard to calibrate pyrgeometers (Philipano et al., 1995; Reda et al., 2002).

A data set of 616 meteorological stations provided by CDC (Fig. 1), with good-quality monthly observations of maximum and minimum air temperature, relative humidity, and sunshine duration at 2 m height, wind speed measured at 10 m height (transformed to wind speed at 2 m height by a logarithmic wind speed profile relationship in FAO56) for the period 1971–2000, was used in this study to simulate ET_o. A few missing data were replaced by average value from other years obtained at the same station.

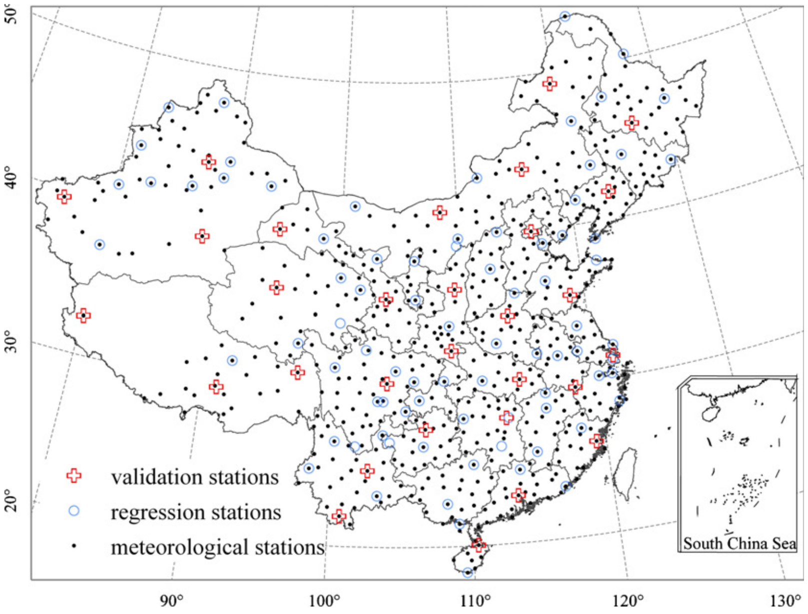

Fig. 1 – The distribution of meteorological stations in China.

Table 1 – Preserved validation stations used in the study

No.	Station	Latitude (°N)	Longitude (°E)	Elevation (m)	Observed solar radiation ($MJ\ m^{-2}\ yr^{-1}$)	Observed period
1	Ankang	32.72	109.03	291	4323	1993–2000
2	Beijing	39.93	116.28	54	5185	1971–2000
3	Chamdo	31.15	97.17	3306	6027	1971–2000
4	Changsha	28.22	112.92	68	3980	1987–2000
5	Chengdu	30.67	104.02	506	3440	1971–2000
6	Dunhuang	40.15	94.68	1139	6372	1971–2000
7	Fuzhou	26.08	119.28	84	4354	1971–2000
8	Ge'er	32.50	80.08	4278	7362	1972–1999
9	Golmud	36.42	94.90	2808	7033	1971–2000
10	Guangzhou	23.13	113.32	7	4112	1971–2000
11	Haikou	20.03	110.35	14	4922	1971–2000
12	Hailaer	49.22	119.75	610	5071	1972–2000
13	Hailiutu	41.57	108.52	1288	6119	1992–2000
14	Harbin	45.75	126.77	142	4743	1971–2000
15	Jinghong	22.00	100.80	553	5561	1971–2000
16	Juxian	35.58	118.83	107	5132	1990–2000
17	Kashi	39.47	75.98	1289	5702	1971–2000
18	Kunming	25.02	102.68	1891	5369	1971–2000
19	Lanzhou	36.05	103.88	1517	5236	1971–2000
20	Lhasa	29.67	91.13	3649	7251	1971–2000
21	Ruoqiang	39.03	88.17	888	6173	1971–2000
22	Shanghai	31.40	121.48	4	4583	1991–2000
23	Shenyang	41.73	123.45	43	4792	1971–2000
24	Tunxi	29.72	118.28	143	4318	1992–2000
25	Urumuqi	43.78	87.62	918	5082	1971–2000
26	Wuhan	30.62	114.13	23	4227	1971–2000
27	Xilinhot	43.95	116.07	990	5518	1990–2000
28	Yan'an	36.60	109.50	959	4970	1990–2000
29	Zhengzhou	34.72	113.65	110	4934	1971–2000
30	Zunyi	27.68	106.92	849	3239	1971–1990

2.2. *Calibration methods*

Reference crop evapotranspiration according to FAO56-PM model is (Allen et al., 1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma(900/(T + 273))U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where ET_o is the reference crop evapotranspiration ($mm\ d^{-1}$), Δ is the slope of saturation vapor pressure versus air temperature curve ($kPa\ {}^{\circ}C^{-1}$), R_n is the net solar radiation at the crop surface ($MJ\ m^{-2}\ d^{-1}$), G is the soil heat flux ($MJ\ m^{-2}\ d^{-1}$), γ is the psychrometric constant ($kPa\ {}^{\circ}C^{-1}$), T is the mean air temperature at 2 m height (°C), U_2 is the wind speed at 2 m height ($m\ s^{-1}$), e_s is the saturation vapor pressure (kPa), and e_a is the actual vapor pressure (kPa).

The key radiation part of the FAO56-PM model can be calculated using the following equations:

$$R_n = R_{ns} - R_{nl} \quad (2)$$

$$R_{ns} = (1 - \alpha)R_s \quad (3)$$

$$R_s = \left(a + b\left(\frac{n}{N}\right)\right)R_a \quad (4)$$

$$R_{nl} = \sigma\left(\frac{(T_{x,k}^4 + T_{n,k}^4)}{2}\right)(c + d\sqrt{e_a})\left(e\left(\frac{R_s}{R_{so}}\right) + f\right) \quad (5)$$

where R_n is the net solar radiation ($MJ\ m^{-2}\ d^{-1}$), R_{ns} is the net shortwave radiation, R_{nl} is the net longwave radiation, α is the albedo, R_s is the solar radiation, n is the actual sunshine duration (hour), N is the maximum possible sunshine duration, n/N is the relative sunshine duration, R_a is the extraterrestrial radiation, σ is the Stefan–Boltzmann constant ($4.903 \times 10^{-9}\ MJ\ K^{-4}\ m^{-2}\ d^{-1}$), $T_{x,k}$ is the maximum absolute temperature during the 24-h period (K), $T_{n,k}$ is the minimum absolute temperature during the 24-h period, R_{so} is the clear-sky solar radiation, a–f are empirical coefficients. N, R_a and R_{so} were calculated by solar constant, latitude, elevation and the number of the day in the year according to the FAO56 report. The FAO56 recommended the coefficients of $a = 0.25$, $b = 0.50$, $c = 0.34$, $d = -0.14$, $e = 1.35$ and $f = -0.35$ to be used in regions where no actual R_s data are available and no calibration has been carried out (Allen et al., 1998).In FAO56-PM model, R_s is calculated according to Ångström method which has been widely applied over the years for its simple and reasonable character. Depending on atmospheric conditions (humidity, dust) and solar declination (latitude and month), the Ångström values a and b will vary (Allen et al., 1998). Therefore, many researchers studied the tempo-spatial regularity of a and b, and tried to parameterized them. The coefficients had no obvious regularity although they changed because of complicated impact factors (Rietveld, 1978; Martinez-Lozano et al., 1984; Gueymard et al., 1995). Values of 0.2170 and 0.5453 were recommend to estimate global solar radiation in Spain (Almorox and Hontoria, 2004). For the Chinese case studies, the daily global radiation may be estimated accurately using

Table 2 – Methods to calculate Ångström solar radiation

Expression	Source of a and b	Based radiation R
$R_{s,fao}$	$a = 0.25$, $b = 0.5$ (Allen et al., 1998)	Extraterrestrial radiation
$R_{s,zuo}$	$a = 0.248$, $b = 0.752$ (Zuo et al., 1963)	Clear-sky radiation
$R_{s,ra}$	Simple annual regression coefficients a and b	Extraterrestrial radiation
$R_{s,rso}$	Simple annual regression coefficients a and b	Clear-sky radiation
$R_{s,ram}$	Monthly regression coefficients a and b	Extraterrestrial radiation
$R_{s,rsom}$	Monthly regression coefficients a and b	Clear-sky radiation
$R_{s,ram}$	Single-station regression coefficients a and b	Extraterrestrial radiation
$R_{s,rsom}$	Single-station regression coefficients a and b	Clear-sky radiation

Linear regression was performed by R_s/R as dependent and n/N as independent where solar radiation and actual duration of sunshine are observations, and extraterrestrial radiation or clear-sky radiation were calculated according to procedures described in FAO56 report.

sunshine based models compared with air temperature based models, and the simple Ångström model can provide good results (Chen et al., 2004). Ångström coefficients of 0.248 and 0.752 based on R_{so} were suitable for China (Zuo et al., 1963). While some studies used R_a to obtain regional or seasonal empirical coefficients since R_{so} was difficult to obtain (Zhu, 1982a,b; Ju et al., 2005). Different distribution of coefficients a and b have been reported for China, such as a from 0.1 to 0.3, b from 0.4 to 0.7 (Ju et al., 2005), and a from 0.12 to 0.3, b from 0.45 to 0.68 (Chen et al., 2004).

For Ångström methods, based on either R_{so} or R_a, several regression techniques were explored to determine empirical coefficients. According to the coefficients, eight different solar radiation calculations were to be compared with observations, including $R_{s,fao}$, $R_{s,zuo}$, $R_{s,ra}$, $R_{s,rso}$, $R_{s,ram}$, $R_{s,rsom}$, $R_{s,ram}$ and $R_{s,rsom}$ defined in Table 2. The regression techniques included the following:

(1) Aggregate all months during the year to derive one set of simple annual regression coefficients for all stations.
(2) Analyze 12 months separately to derive monthly regression coefficients.
(3) Analyze each station separately to derive single-station regression coefficients.

Single-station linear regression values were interpolated to the other places using the Spline method in ArcGIS.R_{nl} was based on Ångström–Brunt method and used to calculate evaporation by Penman (Penman, 1948) as:

$$R_{nl} = \sigma T_k^4 (c + d\sqrt{e_a})\left(e + f\left(\frac{n}{N}\right)\right) \quad (6)$$

where T_k is the absolute temperature (K), $\sigma T_k^4(a + b\sqrt{e_a})$ means the clear-sky longwave radiation. The empirical constants varied in different studies (Penman, 1948, 1963; Wright and Jensen, 1972; Doorenbos and Pruitt, 1977; Allen et al., 1998). (Wright, 1982) applied equation (5) to calculate R_{nl}.

In this study, three popularized formulas to estimate R_{nl} were collected including Penman (Penman, 1948), FAO24 (Doorenbos and Pruitt, 1977) and FAO56-PM (Allen et al., 1998). The unit of e_a was converted to kPa and the minimum and maximum temperatures were used for Penman and FAO24 equations for comparison.

$$\text{Penman modification}: \quad R_{nl} = \sigma\left(\frac{(T_{x,k}^4 + T_{n,k}^4)}{2}\right)(0.56 - 0.25\sqrt{e_a}) \times \left(0.1 + 0.9\left(\frac{n}{N}\right)\right) \quad (7)$$

$$\text{FAO24 modification}: \quad R_{nl} = \sigma\left(\frac{(T_{x,k}^4 + T_{n,k}^4)}{2}\right)(0.34 - 0.14\sqrt{e_a}) \times \left(0.1 + 0.9\left(\frac{n}{N}\right)\right) \quad (8)$$

$$\text{FAO56-PM}: \quad R_{nl} = \sigma\left(\frac{(T_{x,k}^4 + T_{n,k}^4)}{2}\right)(0.34 - 0.14\sqrt{e_a}) \times \left(1.35\left(\frac{R_s}{R_{so}}\right) - 0.35\right) \quad (9)$$

2.3. *Analysis methods*

The performance of the calibration methods reported here were adjudged by the root mean-square error (RMSE), mean bias error (MBE) and correlation coefficient (R) of their estimates to measured values. RMSE could reflect the estimated sensitivity and extreme effect of samples, smaller value means more accuracy. MBE could reflect estimation error, positive means higher and negative means lower estimation, the smaller value of absolute MBE, the more accuracy of a calibration method (Stone, 1993; Jacovides and Kontoyiannis, 1995; He et al., 2003; Itenfisu et al., 2003). RMSE and MBE were given by:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{n}} \quad (10)$$

$$\text{MBE} = \frac{\sum_{i=1}^{n}(y_i - x_i)}{n} \quad (11)$$

where x_i and y_i are two methods of the ith sample; n is the number of samples, and x is usually observation.

3. Results and discussion

3.1. *Sensitivity of ET_o to radiation empirical coefficients*

The relative change of annual FAO56-PM ET_o due to relative change of the empirical coefficients a–f was presented as sensitivity curve in Fig. 2. A 10% increase in coefficients a, b, d and f results in a 2.7, 2.6, 2.2 and 1.5% increase in ET_o, respectively. While ET_o showed an opposite response to coefficients c and e. A 10% increase in c and e results in a 4.5 and 3.8% decrease in ET_o, respectively. ET_o was more sensitive

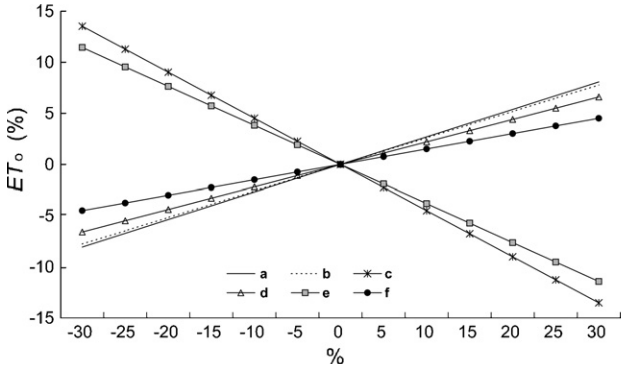

Fig. 2 – Sensitivity of reference crop evapotranspiration to radiation empirical coefficients.

to the change of *c* and *e* in comparison with the other coefficients. Therefore, empirical coefficients in determine radiation, especially net longwave radiation, could have large effects on ET_o.

3.2. Calibration of solar radiation

Results showed that the simple annual linear regression coefficients *a* and *b* of observed monthly R_s/R_{so} to n/N of 81 meteorological stations were 0.20 and 0.79 (0.15 and 0.61 for R_s/R_a). If calibrated *a* and *b* based on $R_{s,ra}$ was applied respectively, ET_o would deviate −11.1 or 5.9% from FAO56-PM result. Monthly regression coefficient *a* was higher in summer and lower in winter, while *b* was contrary to that whether based on R_{so} or R_a (Table 3). Zuo's coefficients (insert citation) were between the monthly regression coefficients based on R_{so}; however, FAO's coefficients were out the range of monthly regression constants based on R_a. Single-station regression coefficients were distributed without any obvious spatial regularity, which indicates that *a* and *b* had no obvious relationships with latitude, longitude or elevation.

We compared the RMSE, MBE and *R* of observed and calculated solar radiation by the eight methods listed in Table 2 for the 30 preserved validation stations (Table 4). It showed that R_s based on the recommended empirical coefficients in FAO56-PM model had the lowest *R* and the largest RMSE and MBE in comparison with observation. Solar radiation based on R_{so} had lower RMSE and MBE than the corresponding methods based on R_a. Solar radiation based on single-station regression coefficients were not satisfactory, probably because of the error introduced by interpolation methods and sparsely distributed stations. In general, $R_{s,rso}$ and $R_{s,rsom}$ were relatively more accurate compared with the other calculations in China. Moreover, the RMSE of $R_{s,rso}$ and $R_{s,rsom}$ were similar, but the MBE of $R_{s,rso}$ was smaller than that of $R_{s,rsom}$ from February to May and from September to November (Fig. 3). Therefore, solar radiation based on annual regression coefficients and R_{so} was recommended due to the least errors compared with measured R_s and its simplicity.

3.3. Calibration of net longwave radiation

Table 5 presents the annual average estimates of tested empirical models and observed R_{nl} at sites on the Tibetan Plateau. Penman modification calculation had the highest accuracy, while FAO24 and FAO56-PM simulations were much lower than observation. The average R_{nl} of Penman modification, FAO24 modification and FAO56-PM were 1972, 1293 and 1080 MJ m^{-2} yr^{-1}, respectively. Some studies showed that R_{nl} was more than 2500 MJ m^{-2} yr^{-1} in the Tibetan Plateau; and about 1466 MJ m^{-2} yr^{-1} in Hunan, Guangdong and Guangxi provinces, 1676 MJ m^{-2} yr^{-1} in East China, 1600–2000 MJ m^{-2} yr^{-1} in Northeast China (Ji, 1985; Zuo, 1991). Such distribution was similar to that of Penman modification R_{nl}. In general, R_{nl} simulation by FAO56-PM model had relatively lower accuracy, while Penman modification method was more exact for China. The results also reveal that R_{nl} was more sensitive to air humidity (denoted by e_a) than cloud cover (denoted by n/N or R_s/R_{so}), since the difference of R_{nl} between FAO24 and FAO56-PM models was smaller than that of

Table 3 – Monthly empirical coefficients *a* and *b* for solar radiation in China

	Month											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
a of $R_{s,rsom}$	0.18	0.18	0.16	0.19	0.21	0.22	0.25	0.25	0.22	0.21	0.20	0.20
b of $R_{s,rsom}$	0.82	0.84	0.86	0.81	0.77	0.74	0.68	0.68	0.75	0.78	0.79	0.78
a of $R_{s,ram}$	0.13	0.13	0.12	0.14	0.16	0.17	0.19	0.20	0.17	0.16	0.14	0.14
b of $R_{s,ram}$	0.65	0.65	0.67	0.63	0.60	0.57	0.52	0.51	0.57	0.60	0.63	0.62

Table 4 – Comparison of observation and calculated solar radiation of the preserved validation stations

	Methods							
	$R_{s,fao}$	$R_{s,zuo}$	$R_{s,ra}$	$R_{s,rso}$	$R_{s,ram}$	$R_{s,rsom}$	$R_{s,ras}$	$R_{s,rsos}$
R	0.932	0.951	0.945	0.952	0.946	0.952	0.941	0.940
RMSE (MJ m^{-2} d^{-1})	2.370	1.910	1.840	1.729	1.837	1.718	1.909	1.930
MBE (MJ m^{-2} d^{-1})	1.209	0.759	−0.085	0.030	−0.105	0.017	0.153	0.146

R: correlation coefficient, RMSE: root mean-square error, MBE: mean bias error.

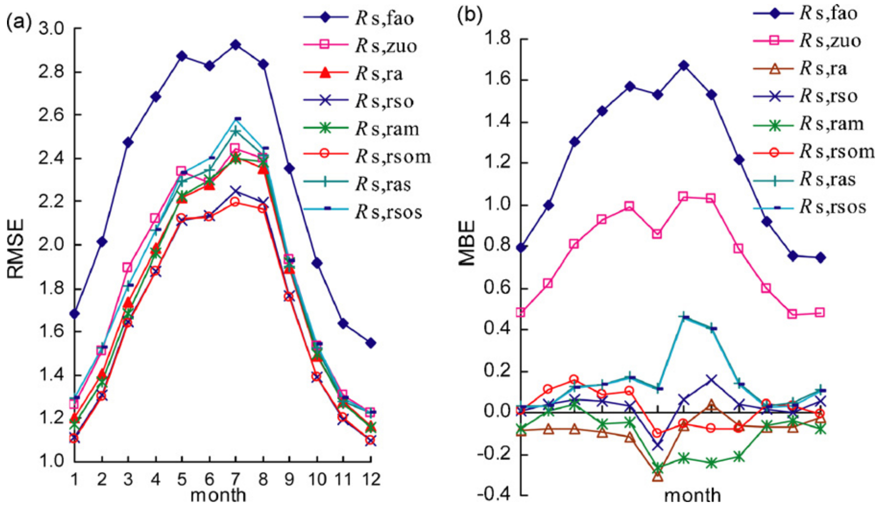

Fig. 3 – Monthly RMSE and MBE of the eight simulation methods compared with observed solar radiation.

Table 5 – Comparison of observation and calculated net longwave radiation (unit: MJ m^{-2} yr^{-1})

Methods	Penman modification	FAO24 modification	FAO56-PM	Observation
Nagqu	2733	1716	1523	2789
Lhasa	3018	1915	1732	3112
Garze	2519	1608	1402	2504

Penman modification and the other two simulations. As a result, Penman simulation method combined with the minimum and maximum temperatures was recommended to calculate R_{nl} for China.

Based on the above analysis, the radiation part of FAO56-PM model in China was calibrated as:

$$R_n = 0.77 \times \left(0.2 + 0.79\left(\frac{n}{N}\right)\right)R_{so} - \sigma\left(\frac{(T_{x,k}^4 + T_{n,k}^4)}{2}\right) \times (0.56 - 0.25\sqrt{e_a})\left(0.1 + 0.9\left(\frac{n}{N}\right)\right) \quad (12)$$

3.4. *Reference crop evapotranspiration in China*

The average ET_o calculated by FAO56-PM model was 979 mm yr^{-1} and the regional difference was from 543 to 1751 mm yr^{-1}; while the average ET_o of the recommended calibration model was 769 mm yr^{-1} and the regional difference was from 404 to 1520 mm yr^{-1} averaged during 1971–2000 in China. In general, ET_o was overestimated by 27% if no local calibration was performed on FAO56-PM model. Moreover, no obvious difference was detected between the spatial distribution pattern of ET_o before and after calibration. Lower ET_o was distributed in Northeast China, Tianshan Mountains, and eastern region of the Tibetan Plateau; higher values was in areas from the Tarim Basin to the Qaidam Basin, western part of Inner Mongolia and Gansu regions, eastern part of Xinjiang region, dry valleys of Hengduan Mountains and southeast coastal areas (Fig. 4).

The range of ET_o is different from that reported by previous researchers, such as 500–1200 mm yr^{-1} (Gao et al., 1978) or 700–1300 mm yr^{-1} (Sun, 1984). In these studies, no significant

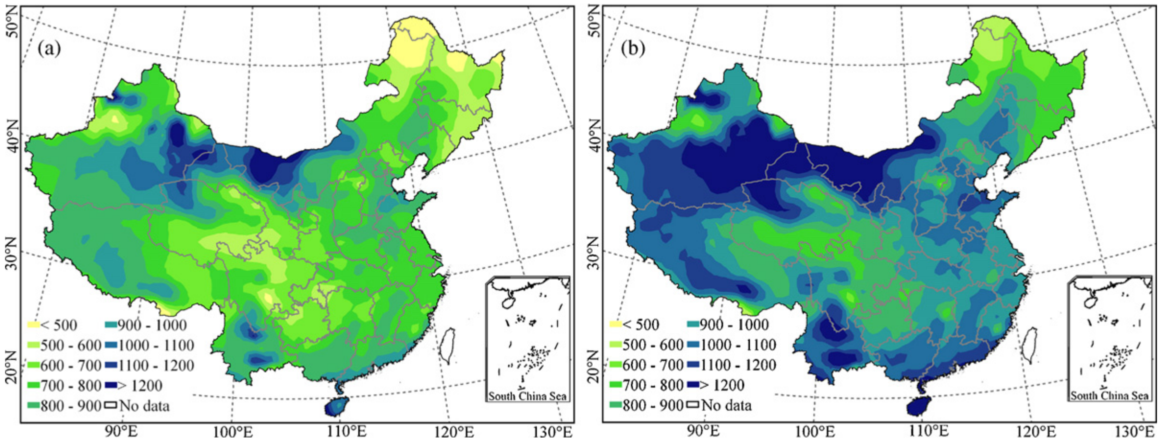

Fig. 4 – Spatial distribution of reference crop evapotranspiration in 1971–2000 over China. (a) Calibration model, (b) FAO56-PM model.

difference was detected in East China; however, there were obvious differences in West China and the Tibetan Plateau probably because of the sparsely distributed meteorological stations and various ET_o models.

4. Conclusions

Net radiation has great effect on reference crop evapotranspiration and is often calculated by empirical model, the accuracy of which is determined by site-specific empirical coefficients. In case of applying FAO56-PM model to study ET_o in China, the empirical radiation model needs to be calibrated according to local climatic conditions.

In the present study, the Ångström model based on simple annual linear regression coefficients of 0.20 and 0.79 yielded the least error compared with measured R_s of the validation stations, and was thus recommended for estimating solar radiation in China. The simulated net longwave radiation of FAO56-PM model was lower than R_{nl} measurements in China and especially the Tibetan Plateau. The optimal calibration of net longwave radiation was based on Penman estimation combined with the minimum and maximum temperatures, which was more close to the actual radiation distribution in China. Inadequate calibration of the empirical coefficients of radiation part in the FAO56-PM model would cause a significant effect on reference crop evapotranspiration. ET_o was overestimated of 27% if no local calibration of empirical radiation coefficients was performed in China. Using the recommended calibration, ET_o was about 769 mm yr^{-1} averaged in China during the last three decades in the 20th century.

The study provides a meaningful and more accurate application of the universally used FAO56-PM reference crop evapotranspiration model in planning and efficient use of agricultural water resources. Local calibration of its radiation formula is strongly recommended in China. Further research is required to evaluate the radiation-based calibration of the FAO56-PM model proposed in this study, especially the more sensitive net longwave radiation. It must be declared that the meteorological stations are sparse and insufficient in western China; therefore, more measurements are needed to validate the calibration.

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