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# Assessing effect of time scale on the solar radiation sunshine duration relationship


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**Abstract—**Solar radiation is the principal and fundamental energy for many physical, chemical, and biological processes. Estimation of solar radiation from sunshine duration is common employed when no direct observation of solar radiation is available. Particularly, the *Ångström-Prescott* (A-P) model is widely used for its simplicity. This paper investigates the effect of time scale on the A-P parameters and the estimation accuracy using the data of 13 sites in Northeastern China. The results show that the A-P model can not be applied at annual, but less than seasonal time scale. Time scale effects the spatial variation of *a* and *b* parameters of the calibration curve, it has greater effect on parameter *a* than on *b*; while greater effect on temporal variation of *b* than that of *a*, and the differences of the parameters caused by time scales are generally large, however, the large differences of parameters do not result in significant difference of the estimation accuracy. Therefore, parameters at different time scales are interchangeable, the parameters calibrated at larger time scales can be applied to smaller time scales, and vice versa.



*Key-words*: solar radiation, estimation, *Ångström-Prescott* model, parameter, time scales


## 1. Introduction

Solar radiation is the principal and fundamental energy for many physical, chemical, and biological processes, and it is also an essential and important variable to many simulation models, such as agriculture, environment, hydrology, and ecology. However, in many cases, it is not readily available due to the cost and difficulty of maintenance and calibration of the measurement equipment (*Hunt et al.*, 1998). Only a few meteorological stations measure solar radiation. For example, in USA, less than 1% of meteorological stations are recording solar radiation (*NCDC*, 1995; *Thorton* and *Running*, 1999). In China, more than 2000 stations have records of meteorological data, only 122 stations are recording solar radiation. The ratio of stations recording solar radiation to those recording temperature is about 1:500 around the world (*Thorton* and *Running,* 1999). Therefore, developing method to estimate solar radiation has been the focus of many studies.

Major methods including satellite-derived (*Frulla et al*., 1988; *Pinker et al*., 1995; *Olseth* and *Skartveit*, 2001; *Şenkal*, 2010), stochastic algorithm (*Richardson*, 1981; *Wilks* and *Wilby*, 1999; *Hansen*, 1999), empirical relationships (*Ångström*, 1924; *Prescott*, 1940; *Hargreaves*, 1981; *Bristow* and *Campbell*, 1984; *Hargreaves et al*., 1985), interpolation (*Hay* and *Suckling*, 1979; *Rivington et al*., 2006), and learning machine method (*Tymvios et al*., 2005; *Cao et al*., 2006; *Lam et al*., 2008; *Jiang*, 2009; *Chen et al*., 2011) have been developed for the purpose. Among them, the empirical relationship using other commonly measured meteorological data, such as sunshine duration, maximum and minimum temperatures, is attractive for its simplicity, efficiency, and lower data requirement. It is generally recognized that the sunshine-based methods outperform other meteorological variables models (*Iziomon* and *Mayer*, 2002; *Podestá et al*., 2004; *Trnka et al*., 2005), particularly the well-known *Ångström-Prescott* (A-P) model, proposed by *Ångström* (1924) and further modified by *Prescott* (1940), was widely used in different locations of the world (*Ångström*, 1924; *Prescott*, 1940; *Almorox* and *Hontoria*, 2004; *Liu et al*., 2009). Several modifications to the A-P model have been proposed since it was developed (*Newland*, 1988; *Akinoglu* and *Ecevit*, 1990; *Ertekin* and *Yaldiz*, 2000). However, various comparative studies demonstrated that the modifications could not give significant improvement (*Iziomon* and *Mayer*, 2002; *Yorukoglu* and *Celik*, 2006; *Liu et al*., 2009). As the result, the simple A-P model was preferred due to its greater simplicity and wider application.

A number of literatures focused on the studies of A-P model at monthly time scale (*Iziomon* and *Mayer*, 2002; *Almorox* and *Hontoria*, 2004; *Zhou et al*., 2005), because the A-P model was initially developed using the monthly data; moreover, the author emphasized that the A-P model should be calibrated using the monthly data rather than the daily data (*Ångström*, 1956). Some literatures reported the studies at daily time scale (*Yorukoglu* and *Celik*, 2006), even at annual time scale (*Chen et al*., 2006; *Liu et al*., 2009), and showed that the parameters can be quite different in different places. Some of them noticed that the parameters changed with time scales (*Benson et al*., 1984; *Ögelman et al*., 1984), but they did not conclude the effect of the time scale. *Gueymard et al*. (1995) illustrated that the averaging time (time scale) is a critical factor in empirical and statistical models, stressed the importance of studying its effect, and believed that the optimum averaging period for smoothing the data without significant loss of information remains unanswered. The effect of the time scale on relationship between solar radiation and sunshine duration remains unknown. Therefore, more investigation is necessary and important to clarify the effect of time scale on relationship between solar radiation and sunshine duration. The objectives of the current study are Eq.(1) to determine the A-P parameters at five time scales, namely, daily, half-monthly, monthly, seasonal and annual time scales (hereafter referred to as TS1, TS2, TS3, TS4, and TS5, respectively) in Northeastern China; Eq.(2) to investigate the effect of time scale on A-P parameters and estimation accuracy.

## *2. Materials and method*

### *2.1. A-P model and calibration*

The A-P model was proposed by *Ångström* (1924) and further modified by *Prescott* (1940). The original form of this model is:

$$\frac{Rs}{Ra} = a\frac{H}{Ho} + b \quad (1)$$

where $Rs$ is daily actual global radiation [MJ m$^{-2}$ d$^{-1}$], $Ra$ is daily extra-terrestrial solar radiation [MJ m$^{-2}$ d$^{-1}$], $H$ is daily actual sunshine duration [h], $Ho$ is daily potential sunshine duration [h], $a$ and $b$ are empirical parameters which are calibrated from regression analysis between $H/Ho$ and $Rs/Ra$ using the calibration data. The extra-terrestrial solar radiation and potential sunshine duration are calculated using the equations detailed by *Allen et al*. (1998).

$$Ra = 37.6d(\omega \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega), \quad (2)$$

$$d = 1 + 0.033\cos\left(\frac{2\pi}{365}n\right), \quad (3)$$

$$\delta = 0.4093\sin\left(\frac{2\pi}{365}n - 1.39\right), \quad (4)$$

$$\omega = \arccos(-\tan\varphi \tan\delta), \quad (5)$$

$$Ho = 24\omega / \pi , \quad (6)$$

where $d$ is the correction of incoming solar radiation due to the changing distance between the Sun and the Earth, $\omega$ is the sunset hour angle [rad], $\varphi$ is the latitude [rad], $\delta$ is the solar declination angle [rad], $n$ is the number of the day of year starting from the first day of January.

*2.2. Study area and site description*

The current study focuses on Northeastern China (*Fig.1*), consisting of the three provinces of Liaoning, Jilin, and Heilongjiang and the four eastern prefectures of Inner Mongolia: Hulunbeier, Xinan, Tongliao, and Chifeng. The climate of the region has extreme seasonal contrasts, ranging from humid, almost tropical heat in the summer to windy, dry, and cold winter. The heartland of the region is the Northeast China Plain. It lies between the Greater and Lesser Khinggan and Changbai mountains, covering an area of 350 000 $km^2$. It is the main area of maize, millet and soybeans production in China, and hence the eco-environmental models and crop growth simulation are widely studied. However, only 13 meteorological stations provide solar radiation record. Moreover, no literature reported study on the solar radiation estimation for this region, and the information on the A-P model is limited.

A total of 13 stations with long-term available records of solar radiation are used in the present study (*Fig.1*). The mapping of stations roughly range from $38^o$ to $52^o$ latitude North, from $116^o$ to $130^o$ longitude East, and from 49 to 610 m altitude. *Table 1* shows the temporal period and the geographical information of the meteorological stations.

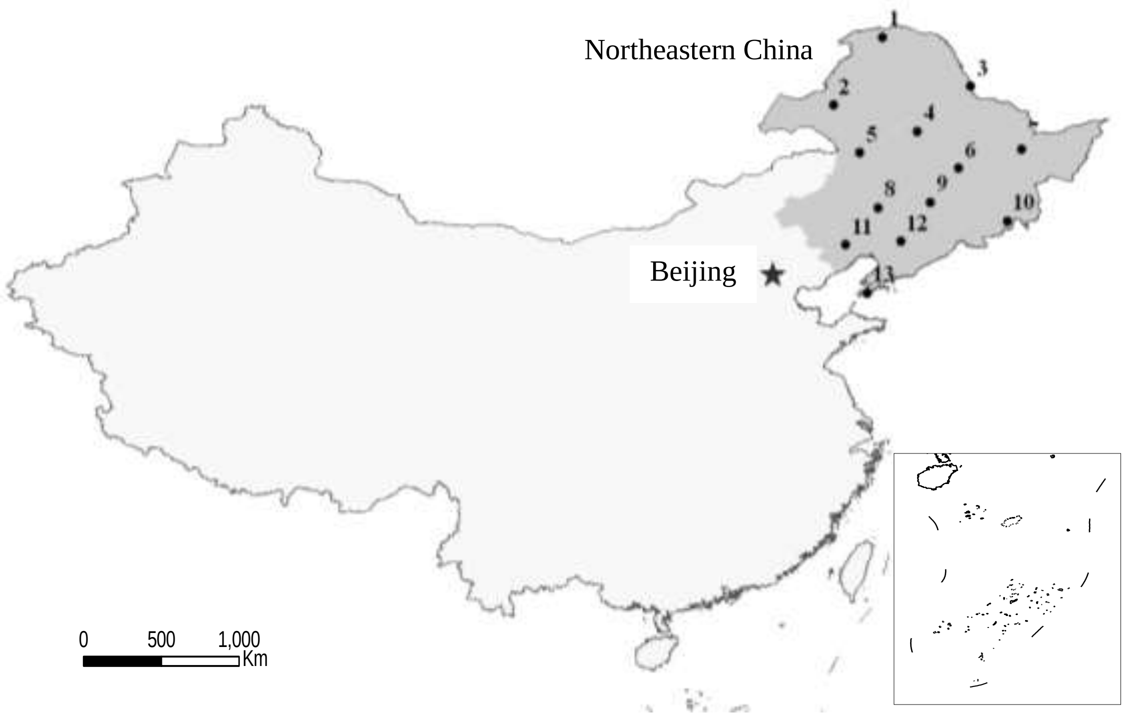


*Fig.1*. Location of the studied meteorological stations in Northeastern China (stations are numbered in compliance with *Table 1*).

*2.3. Data collection and check*

Daily actual global radiation and sunshine duration data of the study sites are used in the present study. The data were obtained from the National Meteorological Information Center (NMIC), China Meteorological Administration (CMA). The period of records ranges from 13 to 40 years covering the period between 1970 and 2009 (*Table 1*). Preliminary quality control tests were conducted by the suppliers. We further check the data according to the following criteria:

(a) For the daily data, records with missing data which were replaced by 32766, daily actual global radiation larger than the daily extra-terrestrial solar radiation, and actual sunshine duration larger than daily potential sunshine duration were removed from the data set.

(b) For half-month, we define days 1–15 as the first half month and day 16 through the end of the month as the latter half month. The half-monthly data is the average value of each day in the whole half-month. A half-month with more than 3 days of missing or faulty data in the same half-month was discarded.

(c) The monthly data is the average value of each day in the whole month. A month with more than 5 days of missing or faulty data in the same month was discarded.

(d) For season, we define March to May as spring, June to August as summer, September to November as autumn, December to February in the next year as winter. A season with more than 15 days of missing or faulty data in the same season, or 8 days of those in the same month was discarded.

(e) A year with more than 30 days of missing or faulty data, or 15 days of those in the same month, or 2 months with more than 10 days of missing or faulty data in the same month was discarded.

Two data sets are created for each time scale. About 75% of the total records are used for calibrating the parameters of A-P model, and the remainder for evaluating the model (*Table 1*). The investigation is operated at five time scales or averaging period, namely, daily (TS1), half-monthly (TS2), monthly (TS3), seasonal (TS4), and annual (TS5) time scales.

*Table 1*. Detailed information of the studied 13 stations in Northeastern China

| **Station ID** | **Station name** | **Latitude (N)** | **Longitude (E)** | **Altitude (m)** | **Calibration period** | **Validation period** |
|---|---|---|---|---|---|---|
| 1 | Mohe | 52.97 | 122.52 | 433.00 | 1997–2006 | 2007–2009 |
| 2 | Hailaer | 49.22 | 119.75 | 610.20 | 1972–1977<br>1982–2000 | 2001–2009 |
| 3 | Heihe | 50.25 | 127.45 | 166.40 | 1970–1999 | 2000–2009 |
| 4 | Fuyu | 47.80 | 124.48 | 162.70 | 1993–2004 | 2005–2009 |
| 5 | Suolun | 46.60 | 121.22 | 499.70 | 1992–2004 | 2005–2009 |
| 6 | Haerbing | 45.75 | 126.77 | 142.30 | 1970–1999 | 2000–2009 |
| 7 | Jiamushi | 46.82 | 130.28 | 81.20 | 1970–1978<br>1983–2000 | 2001–2009 |
| 8 | Tongliao | 43.60 | 122.27 | 178.70 | 1970–1999 | 2000–2009 |
| 9 | ChangChun | 43.90 | 125.22 | 236.80 | 1970–1981<br>1983–1999 | 2000–2009 |
| 10 | Yanji | 42.87 | 129.50 | 257.30 | 1970–1999 | 2000–2009 |
| 11 | Chaoyang | 41.55 | 120.45 | 169.90 | 1970–1999 | 2000–2009 |
| 12 | Shengyang | 41.73 | 123.52 | 49.00 | 1970–1999 | 2000–2009 |
| 13 | Dalian | 38.90 | 121.63 | 91.50 | 1970–1999 | 2000–2009 |

### *2.4. Data description*

*Fig. 2* shows the distribution of the averaged daily solar radiation (*Fig. 2*(a)) and sunshine duration (*Fig. 2*(b)) of the 13 sites in Northeastern China. Solar radiation and sunshine duration range from 4.53 to 21.73 MJ $m^{-2}$ (averaged 13.26 MJ $m^{-2}$ ) and from 4.36 to 9.38 h (averaged 7.15 h), respectively. They generally have a similar tendency, with the maximum in July, and minimum in December. Pearson coefficient between solar radiation and sunshine duration is 0.92 ($p < 0.01$). Larger deviations of solar radiation and sunshine duration occur in April-September, which may be attributed to the large day-to-day fluctuation of the weather variables. Solar radiation shows larger variation than sunshine duration, with the *CV* of 40.68% and 16.87% for them, respectively, where *CV* is the ratio of standard deviation to arithmetic mean.

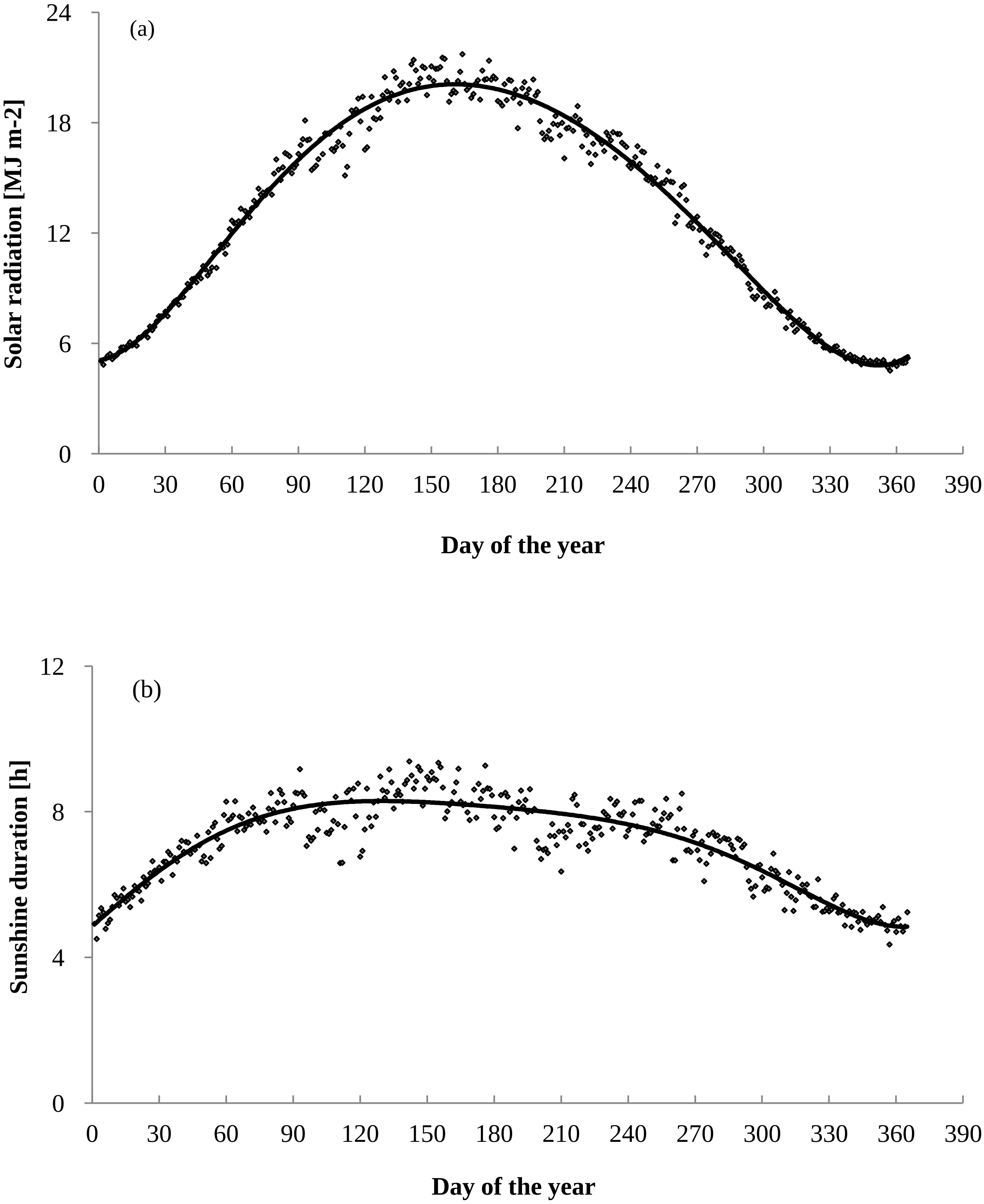


*Fig.2.* Distribution of the averaged daily solar radiation (a) and sunshine duration (b) of the 13 sites in Northeastern China.

## *2.5. Performance criteria*

To assess the performance of the model, root mean square error (*RMSE*), relative root mean square error (*RRMSE*) [%] and coefficient of determination ($R^2$) are determined. $R^2$ is commonly calculated based on the calibration dataset while *RMSE*, and *RRMSE* are based on the validation dataset. The metric $R^2$ varying from 0 to 1 is adopted to measure the fit of the model on calibration data, where the higher the value, better the fit. The *RMSE* provides information on the short term performance of the correlations by allowing a term by term comparison of the actual deviation between the estimated and measured values. The smaller the value, the better the model's performance. *RRMSE* is a dimensionless index allowing comparisons among a range of different model responses regardless of units. The value of *RRMSE* ranges from 0 to infinity. The smaller the *RRMSE*, the better is the model's performance. *RMSE* and *RRMSE* are calculated by the following equations:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}}, \tag{7}$$

$$RRMSE = \frac{100}{\bar{y}}\sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}}, \tag{8}$$

where $n$, $y$, $\hat{y}$, and $\bar{y}$ represent the number of testing data, the observed value, estimated value, and average value of the observation, respectively.

The metric *CV* calculated as ratio of standard deviation to arithmetic mean is adopted to measure the variation of the parameter. The higher the value, the larger the parameter's variation.

## 3. Results and discussion

### *3.1. Variations of A-P model parameters at five time scales*

#### *3.1.1. A-P model parameters calibrated at TS1*

The calibrated parameters *a* and *b* at five time scales are summarized in *Table 2*. Using daily data (TS1), parameter *a* varies from 0.499 in Chaoyang to 0.606 in Heihe (averaged 0.545), *b* from 0.146 in Tongliao to 0.277 in Fuyu (averaged 0.196), and the sum of *a* and *b* (*a*+*b*) from 0.669 in Tongliao to 0.787 in Fuyu (averaged 0.741). Evidently, *a*+*b* are most stable with the *CV* of 4.89% followed by parameter a (*CV*=5.74%), while parameter *b* shows a larger variation with the *CV* of 21.44%.

*Table 2.* The parameters of A-P model calibrated at five time scales in the study area

| **Station** | **TS1** | | | | **TS2** | | | | **TS3** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***a*** | ***b*** | ***a+b*** | $R^2$ | ***a*** | ***b*** | ***a+b*** | $R^2$ | ***a*** | ***b*** | ***a+b*** | $R^2$ |
| Mohe | 0.538 | 0.241 | 0.779 | 0.757 | 0.600 | 0.206 | 0.806 | 0.567 | 0.627 | 0.190 | 0.817 | 0.483 |
| Hailaer | 0.518 | 0.252 | 0.770 | 0.725 | 0.518 | 0.252 | 0.770 | 0.522 | 0.517 | 0.253 | 0.769 | 0.445 |
| Heihe | 0.606 | 0.163 | 0.769 | 0.780 | 0.665 | 0.126 | 0.791 | 0.692 | 0.701 | 0.104 | 0.805 | 0.649 |
| Fuyu | 0.509 | 0.277 | 0.787 | 0.813 | 0.484 | 0.292 | 0.776 | 0.656 | 0.481 | 0.294 | 0.775 | 0.615 |
| Suolun | 0.551 | 0.232 | 0.783 | 0.743 | 0.483 | 0.276 | 0.759 | 0.473 | 0.463 | 0.288 | 0.752 | 0.404 |
| Haerbing | 0.532 | 0.192 | 0.724 | 0.721 | 0.484 | 0.220 | 0.705 | 0.524 | 0.439 | 0.247 | 0.686 | 0.403 |
| Jiamushi | 0.548 | 0.182 | 0.730 | 0.754 | 0.602 | 0.153 | 0.755 | 0.582 | 0.628 | 0.138 | 0.766 | 0.491 |
| Tongliao | 0.523 | 0.146 | 0.669 | 0.676 | 0.506 | 0.158 | 0.663 | 0.466 | 0.495 | 0.165 | 0.660 | 0.401 |
| ChangChun | 0.597 | 0.163 | 0.760 | 0.806 | 0.610 | 0.155 | 0.765 | 0.670 | 0.626 | 0.145 | 0.771 | 0.613 |
| Yanji | 0.550 | 0.183 | 0.733 | 0.788 | 0.473 | 0.223 | 0.697 | 0.540 | 0.447 | 0.237 | 0.684 | 0.455 |
| Chaoyang | 0.499 | 0.202 | 0.701 | 0.790 | 0.423 | 0.251 | 0.674 | 0.566 | 0.402 | 0.264 | 0.667 | 0.503 |
| Shengyang | 0.563 | 0.164 | 0.727 | 0.809 | 0.516 | 0.191 | 0.707 | 0.590 | 0.504 | 0.197 | 0.702 | 0.496 |
| Dalian | 0.556 | 0.152 | 0.708 | 0.720 | 0.499 | 0.188 | 0.687 | 0.555 | 0.503 | 0.186 | 0.690 | 0.480 |
| Average | 0.545 | 0.196 | 0.741 | 0.760 | 0.528 | 0.207 | 0.735 | 0.569 | 0.526 | 0.209 | 0.734 | 0.495 |
| *CV* [%] | 5.74 | 21.44 | 4.89 | — | 13.11 | 24.84 | 6.48 | — | 17.20 | 28.98 | 7.39 | — |

*Table 2.* (continued)

| **Station** | **TS4** | | | | **TS5** | | | |
|---|---|---|---|---|---|---|---|---|
| | ***a*** | ***b*** | ***a+b*** | $R^2$ | ***a*** | ***b*** | ***a+b*** | $R^2$ |
| Mohe | 0.572 | 0.218 | 0.791 | 0.363 | 0.507 | 0.249 | 0.756 | 0.086 |
| Hailaer | 0.543 | 0.234 | 0.777 | 0.344 | 0.422 | 0.301 | 0.723 | 0.275 |
| Heihe | 0.725 | 0.088 | 0.813 | 0.587 | 0.973 | -0.071 | 0.902 | 0.373 |
| Fuyu | 0.514 | 0.275 | 0.789 | 0.564 | 0.371 | 0.346 | 0.717 | 0.222 |
| Suolun | 0.452 | 0.296 | 0.748 | 0.355 | 0.028 | 0.554 | 0.582 | 0.001 |
| Haerbing | 0.370 | 0.286 | 0.656 | 0.364 | 0.040 | 0.475 | 0.515 | 0.001 |
| Jiamushi | 0.672 | 0.113 | 0.785 | 0.372 | 0.577 | 0.157 | 0.734 | 0.142 |
| Tongliao | 0.502 | 0.158 | 0.660 | 0.347 | 0.801 | -0.050 | 0.751 | 0.187 |
| ChangChun | 0.654 | 0.127 | 0.781 | 0.533 | 0.284 | 0.340 | 0.624 | 0.055 |
| Yanji | 0.431 | 0.246 | 0.677 | 0.405 | 0.335 | 0.291 | 0.625 | 0.040 |
| Chaoyang | 0.371 | 0.284 | 0.655 | 0.443 | -0.200 | 0.639 | 0.439 | 0.063 |
| Shengyang | 0.481 | 0.209 | 0.691 | 0.396 | 0.099 | 0.421 | 0.521 | 0.009 |
| Dalian | 0.436 | 0.228 | 0.664 | 0.393 | 0.294 | 0.317 | 0.611 | 0.027 |
| Average | 0.517 | 0.213 | 0.730 | 0.420 | 0.349 | 0.305 | 0.654 | 0.114 |
| *CV* [%] | 21.82 | 33.04 | 8.57 | — | 92.45 | 67.64 | 19.18 | — |

The values of $R^2$ vary from 0.676 to 0.813 (averaged 0.760). Although these values indicate that the simple linear equation gives goodness of fit on the calibration data set, other researchers have proposed several modifications by changing the order of *H/Ho*, such as, quadratic (*Akinoglu* and *Ecevit*, 1990), cubic (*Ertekin* and *Yaldiz*, 2000), and logarithmic models (*Ampratwum* and *Dorvlo*, 1999). In our work, we have used these functions to model the relation between *Rs/Ra* and *H/Ho*, however, they return quite similar values of $R^2$ to those of the simple linear A-P model within the same station. Several comparative studies also demonstrated that they returned almost identical values of $R^2$ and gave very similar accuracy (*Iziomon* and *Mayer*, 2002; *Almorox* and *Hontoria*, 2004; *Yorukoglu* and *Celik*, 2006). Therefore, there is no reason to choose a complex function to gain probably negligible accuracy at the cost of losing the simplicity and convenience of the simple A-P model. The goodness of fit also questions the restriction of A-P model calibration to monthly mean daily data (TS3) made by *Ångström* (1956).

*3.1.2. A-P model parameters calibrated at TS2*

There are many satellite imagine products data that scientists are using to study global change. Many products have been developed with Moderate Resolution Imaging Speetroradiometer (MODIS) data, these include 16-day composite images, such as the widely used MODIS Vegetation Index product. Together with these data, the 16-daily mean solar radiation is usually needed to parameterize or validate ecosystem process models and eco-environment simulation models. However, no literature has reported the study of A-P model at this time scales. In the present work, we calibrate the parameters and evaluate the performances of A-P model at half-monthly time scale (TS2), which differs little from the 16-day time scale, but does not result in significantly differences to the results. At this time scale, parameter *a* varies from 0.423 in Chaoyang to 0.665 in Heihe (averaged 0.528), *b* from 0.126 in Heihe to 0.292 in Fuyu (averaged 0.207), and *a+b* from 0.663 in Tongliao to 0.806 in Mohe (averaged 0.735) (*Table 2*). The stability of the parameters is in order: *a+b* (*CV*=6.48%) > *a* (*CV*=13.11%) > b (*CV*=24.84). $R^2$ varies from 0.466 to 0.692 (averaged 0.569). The values of $R^2$ indicate that A-P model gives goodness of fit, it therefore could be used to estimate solar radiation at this time scale.

*3.1.3. A-P model parameters calibrated at TS3*

Using the monthly mean daily data, parameter *a* varies from 0.402 in Chaoyang to 0.701 in Heihe (averaged 0.526), *b* from 0.104 in Heihe to 0.294 in Fuyu (averaged 0.209), and *a+b* from 0.660 in Tongliao to 0.817 in Mohe (averaged 0.734), while $R^2$ varies from 0.401 to 0.649 (averaged 0.495). The A-P model was initially developed using the monthly mean daily data. More than 30 years later, the author stressed that the parameters of the model should be calibrated from the monthly mean daily data rather than the daily data (*Ångström*, 1956). Consequently, a large amount of literatures reported the researches of the A-P model at TS3 (*Iziomon* and *Mayer*, 2002; *Almorox* and *Hontoria*, 2004; *Zhou et al.*, 2005). Another reason may be in that monthly mean daily data are more easily available than daily data. However, in the present work, better fits between *Rs/Ra* and $H/H_0$ are obtained at TS1 and TS2, as can be seen from *Table 2*, where the A-P model shows a 20.10% – 83.80% (averaged 53.47%), and 6.54% –29.94% (averaged 14.97%) higher $R^2$ than those at TS3, respectively. Similar result was reported by *Tymvios et al.* (2005) who obtained higher $R^2$ of the A-P models established by using the daily data than that by monthly data of Athalassa. *Liu et al* (2009) also obtained a better fit between $H/H_0$ and *Rs/Ra* using daily data (TS1) than monthly mean daily data (TS3) of 29 stations in the Yellow River basin. These results again confirm our question of the restriction and suggest that it is unnecessary to restrict the A-P model calibration only to the monthly mean daily data.

### *3.1.4. A-P model parameters calibrated at TS4 and TS5*

There is no any literature reported the study of A-P model using the seasonal mean daily (TS4) data. In the present work, the values of $R^2$ vary from 0.344 to 0.587(averaged 0.420), indicating that the A-P model retains goodness of fit and can be used at seasonal time scale. Parameter *a* vary from 0.370 in Haerbing to 0.725 in Heihe (averaged 0.517), *b* from 0.088 in Heihe to 0.296 in Suolun (averaged 0.213), and *a+b* from 0.655 in Chaoyang to 0.813 in Heihe (averaged 0.730). Evidently, *a+b* are much more stable (*CV*=8.57%) than parameter *a* (*CV*=21.82%) and *b* (*CV*=23.04%) individually.

The values of $R^2$ are very low at annual time scale (TS5), varying from 0.001 to 0.374 (averaged 0.114) is greater than 0.3only in Heihe (0.374), implying that the A-P model hardly explain the variation in solar radiation at TS5. The poor fit was also reported by *Chen et al*. (2006) who found that the fit was not improved by adding precipitation and air temperature data to the A-P equation. *Liu et al*. (2009) calibrated the A-P model using the hardly mean data from 13 sites in Yellow River basin. The returned $R^2$ varied from 0.02 to 0.61, it was greater than 0.5 at only two sites. Therefore, according to the analysis, the relation between solar radiation and sunshine duration can not be modeled by the A-P equation at hardly time scale, and the following discussion would be limited to the results fromTS1-TS4.

## *3.2. Analyses of effect of time scale on A-P model parameters*

The spatial stability of parameters are dependent on time scale, as it can be seen from *Table 2*, where parameters at TS1 are the most stable with the *CV* of 5.74%, 21.44%, and 4.89% for *a*, *b*, and *a+b*, respectively, followed by those at TS2 and TS3; while they show the largest spatial variations at TS4 with the *CV* of 21.82%, 33.04%, and 8.57%, respectively. Parameter *a* shows the largest differences of *CV* amongst different time scales, ranging from 4.09% between TS2 and TS3 to 16.08% between TS1 and TS4 (averaged 8.72%); while *a+b* shows small differences ranging from 0.91% between TS2 and TS3 to 3.68% between TS1 and TS4 (averaged 1.99%). These values indicate that time scale has greater effect on spatial variation of *a* than that of *b* and *a+b*.

There are significant correlations between the same parameters amongst different time scales, with the correlation coefficient $r > 0.6$ and averaged *r* of 0.851 (*Table 3*). The most significant correlations are found between parameters at TS2 and TS3, with the *r* of 0.991 ($p < 0.01$), 0.981 ($p < 0.01$), and 0.991 ($p < 0.01$) for *a*, *b*, and *a+b*, respectively. The correlations differ greatly among the parameters, *a+b* correlates most significantly amongst different time scales, with the $r > 0.8$ ($p < 0.01$) and averaged *r* of 0.917. These significant correlations indicate that the parameters at one time scale could be obtained from those at another time scale, and thus, the increase the availability of parameters without the need for calibration at all time scales.

Parameter *a* tends to decrease and *b* increase at larger time scales compared with those at smaller scale , as it can be seen in *Table 2*, where more than 61% of the stations have lower values of *a*, while higher *b* at larger time scales. The differences of the parameters caused by time scale are generally large, with 41% of the differences for *a* and 60% for *b* are greater than 10%. At some stations, this difference could be very large (e.g., Dalian, Chaoyang, Jamushi, Haerbing). Evidently, time scale has greater effect on temporal variation of *b* than that of *a*, with the differences ranging from 0.01% to 43.77% (averaged 9.99%) for *a* and from 0.09% to 61.74% (averaged 15.86%) for *b*. However, the differences of parameters *a* and *b* are always opposite as shown in *Fig. 3*, further confirming the stability of *a+b* with less variation at all spaces and time scales.

*Table 3.* Correlation efficient ($r$) between the parameters amongst different time scales

| Time scale | Parameter | TS1 | | | TS2 | | | TS3 | | | TS4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ***a*** | ***b*** | ***a+b*** | ***a*** | ***b*** | ***a+b*** | ***a*** | ***b*** | ***a+b*** | ***a*** | ***b*** | ***a+b*** |
| | *a* | 1 | | | | | | | | | | | |
| TS1 | *b* | –0.544 | 1 | | | | | | | | | | |
| | *a+b* | 0.234 | 0.689** | 1 | | | | | | | | | |
| | *a* | 0.729** | –0.225 | 0.369 | 1 | | | | | | | | |
| TS2 | *b* | –0.682* | 0.807** | 0.346 | –0.726** | 1 | | | | | | | |
| | *a+b* | 0.323 | 0.544 | 0.910** | 0.670* | 0.024 | 1 | | | | | | |
| | *a* | 0.688** | –0.189 | 0.376 | 0.991** | –0.701** | 0.684** | 1 | | | | | |
| TS3 | *b* | –0.702** | 0.702** | 0.207 | –0.821** | 0.981** | –0.134 | –0.813** | 1 | | | | |
| | *a+b* | 0.365 | 0.468 | 0.857** | 0.737** | –0.076 | 0.991** | 0.761** | –0.241 | 1 | | | |
| | *a* | 0.612* | –0.107 | 0.405 | 0.934** | –0.618* | 0.692** | 0.949** | –0.736** | 0.762** | 1 | | |
| TS4 | *b* | –0.663* | 0.601* | 0.076 | –0.850** | 0.904** | –0.260 | –0.849** | 0.947** | –0.360 | –0.868** | 1 | |
| | *a+b* | 0.360 | 0.436 | 0.816** | 0.732** | –0.100 | 0.957** | 0.760** | –0.264 | 0.972** | 0.830** | –0.444 | 1 |

* Significant at 0.05 significance level.
** Significant at 0.01 significance level.

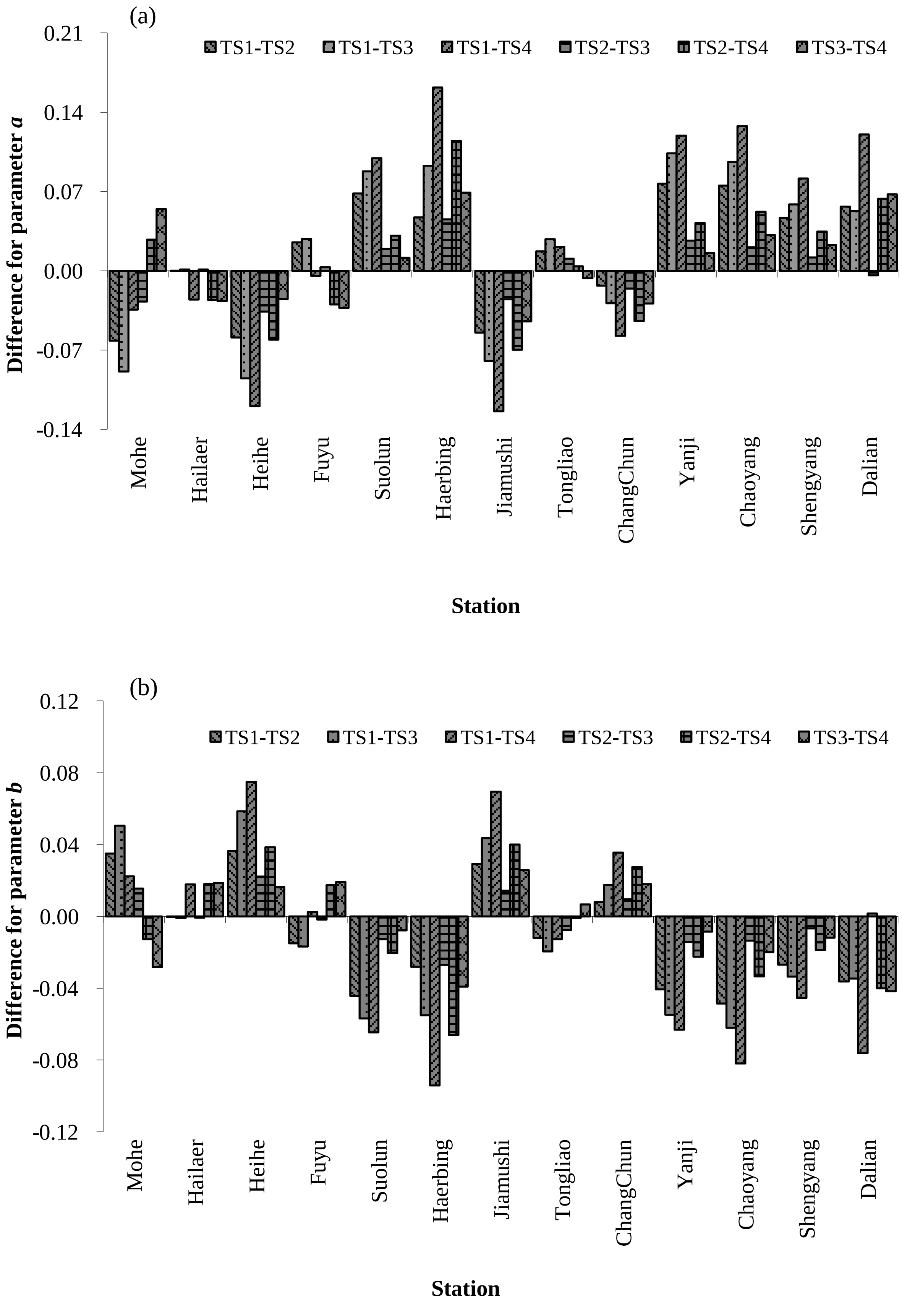


*Fig.3.* Difference of the parameter *a* (a) and *b* (b) among daily (TS1), half-monthly (TS2), monthly (TS3), and seasonal (TS4) time scales in the study area.

### 3.3. Comparison of the solar radiation estimation using parameters from different time scales

Conceptually, the calibrated parameters should only be used at the same time scale, namely, parameters calibrated from daily data should only be used to estimate daily solar radiation, while those calibrated at TS2, TS3, and TS4 should only be used at the corresponding time scales. It was also stated that the comparison in solar radiation at different scales can only be made possible when the estimation is in the same time scale. However, in many cases, no observation of meteorological data is available at some time scales, making the calibration difficult. To solve this problem, two possible alternatives may be considered, one is to use the values recommended by other authors who conducted the similar work. For example, *Ångström* suggested values of 0.2 and 0.5, and *Prescott* suggested 0.22 and 0.54 for the parameters *a* and *b* (*Prescott*, 1940), respectively; *Page* (1961) gave the corresponding values of 0.23 and 0.48, which was believed to be applicable anywhere in the world. However, lots of literatures reported the parameters for different places and showed that they varied from location to location, namely, they are site-dependent.

Another alternative is to directly use parameters calibrated at other time scales, for example, using the parameters at TS3 to estimate solar radiation at TS1, TS2, and TS4. This has never been done before but actually is of potential importance for practical applications, since monthly data are widely available. Therefore, in our work, an attempt is made to estimate solar radiation using the parameters calibrated at other different time scales, and the performances are summarized in *Tables 4–7*.

#### 3.3.1. Estimating daily solar radiation using the parameters calibrated at all time scales

The A-P model gives good performances when using the parameters calibrated at TS1–TS4 to estimate the daily solar radiation, with the $RMSE < 2.7$ MJ m$^{-2}$ (averaged 2.002 MJ m$^{-2}$) and $RRMSE < 20\%$ (averaged 15.01%) (*Table 4*). The estimation using parameters at TS1 is overall the best, with the lowest averaged *RMSE* of 1.949 MJ m$^{-2}$ and *RRMSE* of 14.61%. However, it is noted that it is only slightly better than those using the parameters at TS2–TS4, with nearly identical averaged *RMSE* and *RMSE* of those at TS2–TS4 (*RMSE* of 1.978, 2.01, 2.068 MJ m$^{-2}$; *RRMSE* of 14.83%, 15.07%, 15.52%, respectively).

These values again prove that the A-P model can be used to estimate daily solar radiation with a good performance; furthermore, it implies that the parameters calibrated at TS2, TS3, and TS4 can replace those at TS1 in daily solar radiation estimation, suggesting that the parameters calibrated at larger time scale can be applied to smaller time scale.

*Table 4*. Root mean square error (*RMSE*) and relative root mean square error (*RRMSE*) of estimation daily solar radiation by A-P model using the parameters calibrated at all time scales.

| Station | RMSE [MJ m$^{-2}$] | | | | RRMSE [%] | | | |
|---|---|---|---|---|---|---|---|---|
| | TS1 | TS2 | TS3 | TS4 | TS1 | TS2 | TS3 | TS4 |
| Mohe | 1.712 | 1.654 | 1.674 | 1.644 | 14.09 | 13.62 | 13.78 | 13.53 |
| Hailaer | 2.303 | 2.303 | 2.302 | 2.326 | 17.37 | 17.37 | 17.37 | 17.55 |
| Heihe | 1.636 | 1.809 | 1.969 | 2.019 | 12.70 | 14.04 | 15.29 | 15.67 |
| Fuyu | 1.871 | 1.917 | 1.923 | 1.867 | 13.30 | 13.62 | 13.67 | 13.27 |
| Suolun | 1.795 | 1.890 | 1.918 | 1.931 | 12.30 | 12.95 | 13.15 | 13.23 |
| Haerbing | 1.728 | 1.691 | 1.756 | 2.014 | 13.70 | 13.41 | 13.92 | 15.97 |
| Jiamushi | 1.489 | 1.575 | 1.592 | 1.671 | 11.85 | 12.53 | 12.66 | 13.29 |
| Tongliao | 2.615 | 2.591 | 2.579 | 2.611 | 18.41 | 18.24 | 18.16 | 18.39 |
| ChangChun | 1.906 | 1.920 | 1.946 | 2.020 | 14.26 | 14.37 | 14.56 | 15.11 |
| Yanji | 1.663 | 1.782 | 1.852 | 1.862 | 12.91 | 13.83 | 14.38 | 14.46 |
| Chaoyang | 2.516 | 2.549 | 2.591 | 2.678 | 18.43 | 18.67 | 18.98 | 19.62 |
| Shengyang | 2.240 | 2.176 | 2.174 | 2.195 | 16.80 | 16.32 | 16.30 | 16.46 |
| Dalian | 1.860 | 1.865 | 1.857 | 2.051 | 13.75 | 13.79 | 13.73 | 15.17 |
| Average | 1.949 | 1.978 | 2.010 | 2.068 | 14.61 | 14.83 | 15.07 | 15.52 |

### *3.1.2. Estimating half-monthly and monthly mean solar radiation using the parameters calibrated at all time scales*

When estimating half-monthly and monthly mean solar radiation using the parameters calibrated at TS1–TS4, the A-P model also performs well, with the $RMSE < 2.1$ MJ m$^{-2}$ (averaged 1.073 MJ m$^{-2}$) and $RRMSE < 15\%$ (averaged 8.01%) (*Table 5*), as well as $RMSE < 2$ MJ m$^{-2}$ (averaged 0.990 J m$^{-2}$) and $RRMSE < 14\%$ (averaged 7.38%) (*Table 6*), respectively. The estimation of half-monthly solar radiation using parameters at TS2 is slightly better than that using parameters at TS1, TS3, and TS4, as it can been see from *Table 5*, where the differences for *RMSE* are less than 1%, and only in Jiamushi is greater than 0.1 MJ m$^{-2}$. Similar result is also found in the estimation of monthly solar radiation (*Table 6*), with the differences for *RMSE* and *RRMSE* less than 0.1 MJ m$^{-2}$ and 1%, respectively.

These results indicate that the parameters calibrated at TS1, TS3, and TS4 can replace those at TS2 in half-monthly solar radiation estimation, and parameters calibrated at TS1, TS2, and TS4 can replace those at TS3 in monthly solar radiation estimation, not only suggesting that the parameters calibrated at a smaller time scale can be applied to larger time scales, but also again confirming that the parameters calibrated at a larger time scale can be applied to smaller time scales. Namely, the parameters at different time scales are interchangeable.

*Table 5*. Root mean square error (*RMSE*) and relative root mean square error (*RRMSE*) of estimation of half-monthly mean solar radiation by A-P model using the parameters calibrated at all time scales.

| Station | RMSE [MJ $m^{-2}$] | | | | RRMSE [%] | | | |
|---|---|---|---|---|---|---|---|---|
| | **TS1** | **TS2** | **TS3** | **TS4** | **TS1** | **TS2** | **TS3** | **TS4** |
| Mohe | 0.822 | 0.751 | 0.737 | 0.736 | 6.77 | 6.18 | 6.07 | 6.06 |
| Hailaer | 1.577 | 1.577 | 1.576 | 1.606 | 11.90 | 11.90 | 11.89 | 12.12 |
| Heihe | 0.758 | 0.793 | 0.838 | 0.879 | 5.88 | 6.16 | 6.51 | 6.82 |
| Fuyu | 1.018 | 1.018 | 1.018 | 1.021 | 7.23 | 7.24 | 7.24 | 7.25 |
| Suolun | 0.881 | 0.946 | 0.978 | 1.004 | 6.04 | 6.49 | 6.71 | 6.88 |
| Haerbing | 0.799 | 0.748 | 0.740 | 0.804 | 6.34 | 5.93 | 5.87 | 6.38 |
| Jiamushi | 0.658 | 0.682 | 0.714 | 0.797 | 5.23 | 5.42 | 5.68 | 6.34 |
| Tongliao | 2.044 | 2.016 | 1.999 | 2.042 | 14.40 | 14.20 | 14.08 | 14.38 |
| ChangChun | 0.842 | 0.857 | 0.879 | 0.929 | 6.30 | 6.41 | 6.58 | 6.95 |
| Yanji | 0.702 | 0.698 | 0.726 | 0.748 | 5.45 | 5.42 | 5.64 | 5.81 |
| Chaoyang | 1.786 | 1.727 | 1.721 | 1.719 | 13.08 | 12.65 | 12.60 | 12.59 |
| Shengyang | 1.259 | 1.163 | 1.144 | 1.131 | 9.44 | 8.72 | 8.58 | 8.48 |
| Dalian | 0.813 | 0.783 | 0.778 | 0.831 | 6.01 | 5.80 | 5.75 | 6.15 |
| Average | 1.074 | 1.058 | 1.065 | 1.096 | 8.01 | 7.89 | 7.94 | 8.17 |

*Table 6*. Root mean square error (*RMSE*) and relative root mean square error (*RRMSE*) of estimation of monthly mean solar radiation by A-P model using the parameters calibrated at all time scales.

| Station | RMSE [MJ $m^{-2}$] | | | | RRMSE [%] | | | |
|---|---|---|---|---|---|---|---|---|
| | **TS1** | **TS2** | **TS3** | **TS4** | **TS1** | **TS2** | **TS3** | **TS4** |
| Mohe | 0.753 | 0.675 | 0.653 | 0.662 | 6.20 | 5.57 | 5.38 | 5.46 |
| Hailaer | 1.526 | 1.526 | 1.525 | 1.557 | 11.52 | 11.52 | 11.51 | 11.76 |
| Heihe | 0.685 | 0.702 | 0.731 | 0.760 | 5.32 | 5.46 | 5.68 | 5.90 |
| Fuyu | 0.960 | 0.960 | 0.960 | 0.962 | 6.82 | 6.83 | 6.82 | 6.84 |
| Suolun | 0.783 | 0.869 | 0.902 | 0.929 | 5.37 | 5.96 | 6.19 | 6.37 |
| Haerbing | 0.717 | 0.668 | 0.654 | 0.693 | 5.69 | 5.30 | 5.19 | 5.50 |
| Jiamushi | 0.593 | 0.614 | 0.641 | 0.711 | 4.72 | 4.89 | 5.11 | 5.66 |
| Tongliao | 1.984 | 1.958 | 1.942 | 1.985 | 13.99 | 13.80 | 13.69 | 13.99 |
| ChangChun | 0.717 | 0.727 | 0.743 | 0.780 | 5.37 | 5.44 | 5.57 | 5.84 |
| Yanji | 0.623 | 0.617 | 0.637 | 0.653 | 4.84 | 4.79 | 4.95 | 5.08 |
| Chaoyang | 1.708 | 1.650 | 1.642 | 1.636 | 12.51 | 12.09 | 12.03 | 11.99 |
| Shengyang | 1.183 | 1.088 | 1.068 | 1.052 | 8.87 | 8.16 | 8.01 | 7.89 |
| Dalian | 0.709 | 0.670 | 0.664 | 0.698 | 5.25 | 4.96 | 4.91 | 5.16 |
| Average | 0.995 | 0.979 | 0.982 | 1.006 | 7.42 | 7.29 | 7.31 | 7.50 |

The *RMSE* and *RRMSE* for estimation of half-monthly and monthly solar radiation are much lower than those for estimation of daily solar radiation, implying that after the data smoothing by half-monthly or monthly averaging process, most of the instrumental random errors and day-to-day fluctuation of the data are removed. Therefore, if each day within the averaging lag takes the same values of the corresponding time scale mean daily solar radiation, it would not match the day-to-day variation of solar radiation. *Liu et al.* (2009) found that the *RMSE* increased greatly if the monthly mean daily solar radiation estimated at TS3 was directly used as the daily solar radiation approximation. *Gueymard et al.* (1995) stressed the importance of studying the effect of the averaging time (time scale), and believed that the optimum averaging period for smoothing the data remain unanswered. According to our analysis, the optimum averaging period should be less than 15 days, so that most of the instrumental random errors are removed without significant loss of information of the data. It would be significant to investigate further to determine the optimum lag, but it is beyond the objective of this study.

*Table 7*. Root mean square error (*RMSE*) and relative root mean square error (*RRMSE*) of estimation of seasonal mean solar radiation by A-P model using the parameters calibrated at all time scales.

| **Station** | **RMSE [MJ m$^{-2}$]** | | | | **RRMSE [%]** | | | |
|---|---|---|---|---|---|---|---|---|
| | **TS1** | **TS2** | **TS3** | **TS4** | **TS1** | **TS2** | **TS3** | **TS4** |
| Mohe | 0.316 | 0.254 | 0.237 | 0.216 | 2.47 | 1.99 | 1.85 | 1.69 |
| Hailaer | 1.389 | 1.389 | 1.388 | 1.413 | 10.37 | 10.37 | 10.36 | 10.55 |
| Heihe | 0.550 | 0.556 | 0.568 | 0.581 | 4.23 | 4.27 | 4.37 | 4.47 |
| Fuyu | 0.788 | 0.801 | 0.801 | 0.788 | 5.48 | 5.57 | 5.57 | 5.48 |
| Suolun | 0.644 | 0.753 | 0.786 | 0.812 | 4.32 | 5.06 | 5.28 | 5.45 |
| Haerbing | 0.600 | 0.551 | 0.529 | 0.547 | 4.71 | 4.32 | 4.15 | 4.29 |
| Jiamushi | 0.486 | 0.498 | 0.516 | 0.562 | 3.83 | 3.92 | 4.06 | 4.43 |
| Tongliao | 1.861 | 1.836 | 1.820 | 1.863 | 13.01 | 12.83 | 12.72 | 13.02 |
| ChangChun | 0.515 | 0.520 | 0.531 | 0.556 | 3.82 | 3.86 | 3.94 | 4.13 |
| Yanji | 0.516 | 0.463 | 0.457 | 0.457 | 3.97 | 3.56 | 3.52 | 3.52 |
| Chaoyang | 1.605 | 1.557 | 1.551 | 1.545 | 11.67 | 11.32 | 11.28 | 11.23 |
| Shengyang | 1.105 | 1.039 | 1.014 | 0.990 | 7.95 | 7.47 | 7.29 | 7.12 |
| Dalian | 0.566 | 0.512 | 0.505 | 0.544 | 4.02 | 3.63 | 3.58 | 3.86 |
| Average | 0.842 | 0.825 | 0.823 | 0.837 | 6.14 | 6.01 | 6.00 | 6.09 |

### 3.3.3. *Estimating seasonal mean solar radiation using the parameters calibrated at all time scales*

When estimating seasonal mean daily solar radiation using the parameters calibrated at TS1-TS4, the A-P model retains good performances, with the $RMSE < 1.9\ \mathrm{MJ\,m^{-2}}$ (averaged $0.833\ \mathrm{MJ\,m^{-2}}$) and $RRMSE < 13\%$ (averaged 6.07%). The *RMSE* and *RRMSE* are much lower than those at TS1-TS3 due to the data smoothing by seasonal averaging process. Similarly, no significant difference of *RMSE* and *RRMSE* resulted by time scales is found, as it can be seen in *Table 7*, where only the differences for *RMSE* in Shengyang and Suolun are greater than $0.1\ \mathrm{MJ\,m^{-2}}$, and only that for *RRMSE* in Suolun is greater than 1%. These results indicate that the parameters calibrated at TS1, TS2, and TS3 can replace those at TS4 in the estimation of seasonal solar radiation, again proving that the parameters calibrated at a smaller time scale can be applied to larger time scales.

## *4. Conclusion*

Solar radiation is the principal and fundamental energy for many physical, chemical, and biological processes. Estimation of solar radiation from sunshine duration is common employed when no direct observation of solar radiation is available. Particularly, the *Ångström-Prescott* model is widely used for its simplicity. This paper investigates the effect of time scale on the *Ångström-Prescott* parameters and the estimation accuracy in Northeastern China. The relation between solar radiation and sunshine duration can not be modeled by the *Ångström-Prescott* equation at annual time scale, but less than seasonal time scales. Time scale effects the spatial variation of parameters, it has greater effect on parameter *a* than on *b*, and larger spatial variation are presented at larger time scales. Parameter *a* tends to decrease and *b* increase at larger time scales, and the differences of the parameters caused by time scale are generally large, with 41% of the differences for *a* and 60% for *b* are greater than 10%. Evidently, time scale has greater effect on temporal variation of *b* than that of *a*. However, the large differences of parameters caused by time scale do not result in significant difference of the estimation accuracy, estimation using the parameters from other time scales give the most identical performances with that using the parameters from itself time scale, therefore, parameters at different time scales are interchangeable, the parameters calibrated at larger time scales can be applied to smaller time scales, and vice versa.

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