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Differences between observed and calculated solar radiations and their impact on simulated crop yields

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ABSTRACT

Global solar radiation, a key input variable for crop growth models, is often estimated from sunshine duration with the Ångström–Prescott model due to limited observational data. Few studies have explored the possible difference between the calculated and observed solar radiation data, and how this difference transfers to differences in simulated crop yield. This paper compared observed global solar radiation and calculated values using the Ångström–Prescott (AP) model and the Johnson–Woodward (JW) model at different time scales. We further used the farming systems model APSIM to investigate the difference in simulated wheat and maize yields caused by the use of observed and calculated solar radiations at eight sites in the North China Plain (NCP). The results revealed significant differences between the observed and calculated solar radiations, which also varied among sites. Overall, the calculated daily global solar radiations with the AP model and the JW model could explain 87–92% of the variations in the observed ones. The AP model performed slightly better (RMSE of 2.06–2.80 MJ m^{-2} day^{-1}, RRMSE of 14.49–21.50%) than the JW model (RMSE of 2.29–2.97 MJ m^{-2} day^{-1}, RRMSE of 16.35–22.82%). Using different coefficients (a and b) in the AP model between seasons and sites did not improve the estimated global solar radiation compared to using fixed coefficients across the study sites. In general, the calculated solar radiation in the maize growing seasons better correlated with the observed solar radiation than those in the wheat seasons at most of the sites. As a consequence, the simulated potential yields of maize using the two sources of solar radiation data were much more closely correlated than those of wheat. While both the calculated and observed solar radiations showed the same directions of change with years, the rate of change per year differed significantly at some locations. Similar results were also found in the trend of change in simulated wheat and maize potential yields using the two sources of solar radiations, i.e., similar change direction, but different rates of change. These results indicate that further research is needed in order to construct more reliable solar radiation data for use in the crop modeling. This will include stricter quality control of observed data and use of improved calculation method for global solar radiation.

1. Introduction

Solar radiation is a key input variable for crop growth models. Unfortunately, it is often not available at many locations, and has to be estimated from more frequently measured sunshine hours or air temperature (Ångström, 1924; Prescott, 1940; Bristow and Campbell, 1984; Hoogenboom, 2000; Rivington et al., 2005). Inaccuracy in the estimation of global solar radiation could impact significantly on the simulated crop yields (Rivington et al., 2006). Nowadays, crop models have been increasingly used for estimation of crop potential yield, for determining crop yield gap, refining management strategies and quantifying the impacts of climate change on crop production (Lobell et al., 2009; Wang et al., 2012, 2014). In spite of the wide use of solar radiation data estimated using different methods as input for crop modeling, the potential inaccuracy of the estimations and the subsequent impact on simulated crop yield has been rarely investigated.

Several studies showed that sunshine duration-based estimation models perform better than air temperature-based estimation models (Chen et al., 2004; Podesta et al., 2004; Rivington et al., 2005). The Ångström–Prescott (AP) model has been widely used

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to calculate daily global solar radiation from sunshine duration (Doorenbos and Pruitt, 1977; Allen et al., 1998; Almorox and Hontoria, 2004), and the calculated solar radiation values are subsequently used in crop models. A large number of studies compared the difference between observed global solar radiation and those calculated with the Ångström–Prescott model (Boisvert et al., 1990; Iziomon and Mayer, 2002; Liu et al., 2009a,b). A general conclusion was that the Ångström–Prescott model could effectively estimate daily global solar radiation, but its coefficients *a* and *b* depend on sites and seasons (Podesta et al., 2004; Tymvios et al., 2005), though a single set of coefficient was often used in simulation studies to analysis crop potential yield and yield gaps in a given region (Liu et al., 2010, 2012). Another method to convert sunshine duration to solar radiation is the Johnson–Woodward (JW) model. It contains only one empirical constant (Johnson et al., 1995; Woodward et al., 2001; Rivington et al., 2005). It has been used effectively in tropical rainforest, New Zealand and UK, but has not been evaluated in other climate regions.

One study (Pohlert, 2004) compared simulated maize yield under the potential and water-limited production conditions using observed daily global solar radiation and daily global solar radiation estimated with three empirical solar radiation models (Ångström, Bristow and Campbell, the Allen global solar radiation models) at two locations in temperate region (Wageningen in the Netherlands and Córdoba in Argentina) and one location in the tropics (Los Baños in the Philippines). The results showed that all the three models could be applied to close incomplete global solar radiation series for maize growth simulation with the WOFOST model at temperate locations. However, the Bristow and Campbell, and the Allen global solar radiation models may not be used to generate daily data for a full season at tropical locations, as the simulated yield distributions differ significantly due to poor prediction skill of the solar radiation models. This implies that the accuracy of solar radiation estimation changes with the methods used and also across regions, potentially leading to changed spatiotemporal distribution of simulated crop yield.

In the North China Plain, one of the most important agricultural production regions in China, the solar radiation environment has been changing since the 1980s due to increasing atmospheric aerosol caused by industrial development. There has been no investigation on the accuracy of solar radiation data estimated using different methods and their impact on simulated crop yield, although many modeling studies have been conducted using the solar radiation data estimated with the AP model (Chen et al., 2010b,c; Wang et al., 2012, 2014). It is unknown whether the trend of change in simulated crop yields remains consistent if estimated versus measured solar radiation data are used in the modeling. This is particularly important for climate change impact studies, where accurate quantification of the trends of change in both climatic variables and simulated crop yield are essential.

Table 1
Periods of available observed solar radiation data and the data used in this study, and the ratio of missing to total number of observed data for the used records at the eight study sites in the North China Plain.

Sites	Available records	Used records	Ratio of missing data to total number of used records
Beijing	1957–2011	1961–2011	0.04%
Leting	1992–2011	1993–2011	0.4%
Tianjin	1959–2011	1961–2011	0.8%
Jinan	1961–2011	1961–2011	0.2%
Juxian	1990–2011	1990–2011	0.6%
Zhengzhou	1961–2011	1961–2011	0.7%
Nanyang	1990–2011	1992–2010	0.4%
Gushi	1961–2011	1961–2011	0.07%

The objectives of this study are to investigate: (1) the performance of the Ångström–Prescott model and the Johnson–Woodward model to estimate global solar radiation at different time scales in the North China Plain, (2) if the performance of the Ångström–Prescott model can be improved by using different coefficients between seasons and sites, (3) the difference between the change trends in observed and calculated global solar radiation at the eight sites in the North China Plain, and (4) whether the simulated yield time series with estimated solar radiation data can be used for trend analysis in climate change impact studies.

2. Materials and methods

2.1. Study sites and climate data

Eight sites were selected in this study, i.e., Beijing (39.8° N, 116.47° E, 31 m), Leting (39.43° N, 118.88° E, 11 m), Tianjin (39.08° N, 117.07° E, 3 m), Jinan (36.68° N, 116.98 °E, 52 m), Juxian (35.58 °N, 118.08 °E, 107 m), Zhengzhou (34.72 °N, 113.65 °E, 110 m), Nanyang (33.03 °N, 112.58 °E, 129 m) and Gushi (32.02 °N, 115.07 °E, 57 m). These sites are selected because observed solar radiation data are available on site. They are roughly uniformly distributed across North China Plain (Fig. 1). Annual average air temperatures at Beijing, Leting, Tianjin, Jinan, Juxian, Zhengzhou, Nanyang and Gushi were 12.7, 12.1, 13.2, 15, 13.4, 15, 16 and 16.1 °C, while annual precipitation totals were 553, 546, 536, 702, 803, 644, 801 and 1067 mm, respectively.

Table 1 shows the periods of available observed records of solar radiation, data used in this study and the ratio of missing data to total number of observed data using at the eight study sites. The

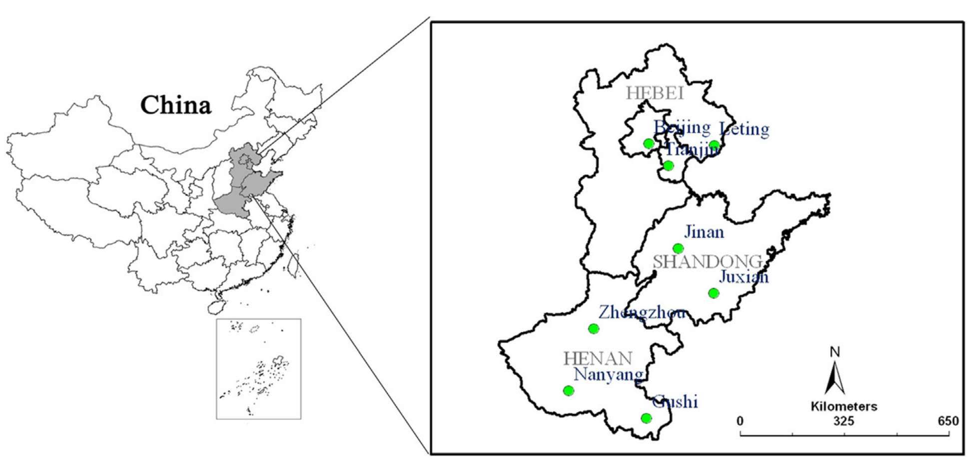

Fig. 1. The North China Plain (NCP) and the locations of the eight study sites.