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Comparison of deterministic and data-driven models for solar radiation estimation in China

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ABSTRACT

Solar radiation is an indispensable input for many applications, contributing to different fields, including energy, meteorology, ecology, agriculture and industry. A lot of parameterization schemes have been developed for estimating solar radiation in sites around the world. This paper presented a comparative study on the performances of four shortwave solar radiation (SSR) models in different climates, including Yang's hybrid model (YHM), an efficient physically based model (EPP), an hourly solar radiation model (HSRM) and a neural network model (ANNM). Daily meteorological variables observed at 837 stations in China were used as model inputs for YHM and ANNM. MODIS atmospheric and land products (MOD08_D3, MYD08_D3, MOD08_M3, MYD08M3, MOD09CMG, and MYD09CMG) were used to derive the required parameters for EPP and HSRM. Cloud fraction and solar zenith angle were found to be the major parameters influencing the model accuracies. The results indicated that YHM performed superior to EPP, ANNM and HSRM with daily mean *RMSE* of 2.414, 2.535, 2.855 and 3.645 $MJm^{-2}day^{-1}$, respectively. The monthly mean *RMSE* for all models were generally higher in July (3.37 $MJm^{-2}day^{-1}$) and lower in January (1.997 $MJm^{-2}day^{-1}$). It was observed that the monthly mean *RMSE* was 2.95 MJm^{-2} day^{-1} in humid areas, while it is 2.773 $MJm^{-2}day^{-1}$ in semi-arid areas. Monthly and annual mean SSR (ASSR) during 2002–2015 were calculated to reveal the spatial and temporal variations of SSR across China using daily meteorological data, MOD08_M3 and MOD08_M3 products based on YHM and EPP models. The result showed that there was not obvious variation trends for ASSR in China, the largest value (14.521 $MJm^{-2}day^{-1}$) was observed in 2003, while the smallest ASSR (14.182 $MJm^{-2}day^{-1}$) was in 2014; the ASSR values were generally higher in Qinghai-Tibet and lower in northeastern China.

1. Introduction

Solar energy is a clean, renewable and sustainable energy for solar energy applications around the world [1,2]. Accurate estimation of solar radiation at given locations are required for radiation conversion device and photovoltaic cells [3,4]. Moreover, solar radiation is closely related to global environmental changes, such as snowline depression, glacier retreat and permafrost thawing [5]. Solar radiation is a major factor controlling the sources and sink of energy between the land and atmosphere [6]. Solar radiation is also an essential term in hydrological processes like snowmelt, sublimation, evapotranspiration and soil thaw [7]. The utilization of solar energy is a promising outlook for energy crisis and climate change. Many engineers, energy experts, policy-makers and climate advocates have paid great attentions to the utilization of solar energy [8], which has been applied to our lives, such as the design for agriculture, water resources and passive heating of buildings. Efforts had been made for the production of solar electricity and the conversion of solar radiation into heat around the

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Nomenclature

β	Angstrom turbidity coefficient
C	Adjusting function of total cloud data
E_R	Correction factor for the earth-sun distance (m)
I_b	Direct solar radiation in clear sky (MJ $m^{-2}day^{-1}$)
I_g	Global solar radiation in clear sky on a horizontal surface (MJ $m^{-2}day^{-1}$)
I_s	Diffuse solar radiation in clear sky on a horizontal surface (MJ $m^{-2}day^{-1}$)
I_b'	Clear sky beam irradiance on an actual surface
I_s'	Clear sky diffuse irradiance on an actual surface
I_{SC}	Solar constant (1366.1 W/m^2)
K	Coefficient associated with cloud effect to solar radiation
m	Relative air mass
m'	Pressure-corrected air mass
r_g	Ground albedo
r_s	Sky albedo
T_a	Transmittance of aerosol absorptance and scattering
T_c	Transmittance of cloud scattering and absorption
T_o	Transmittance of aerosol absorptance and scattering
T_r	Transmittance of Rayleigh scattering
T_u	Transmittance of aerosol absorptance and scattering
TCP	Cloud fraction
θ	Solar zenith angle (degrees)
ψ	Hillside slope (degrees)
T_w	Transmittance of water vapor absorption
Q_b	beam radiation fluxes under real weather conditions on actual surfaces (MJ $m^{-2}day^{-1}$)
Q_s	Diffuse radiation fluxes under real weather conditions on actual surfaces (MJ $m^{-2}day^{-1}$)
Q_g	Global radiation fluxes under real weather conditions on actual surfaces (MJ $m^{-2}day^{-1}$)
τ_b^{clr}	Beam transmittance for clear sky
τ_d^{clr}	Diffuse transmittance for clear sky
τ_b^{cld}	Beam transmittance for cloudy sky
τ_d^{cld}	Diffuse transmittance for cloudy sky
$\rho_{a,clr}$	Atmospheric spherical albedo for clear sky
$\rho_{a,cld}$	Atmospheric spherical albedo for cloudy sky
$\rho_{a,all}$	Atmospheric spherical albedo for all sky
ρ_g	Ground surface albedo
R_0	Solar radiation on a horizontal surface at the extraterrestrial level
R_{clr}'	Surface solar radiation without considering the multiple scattering between the atmosphere and ground surface (MJ $m^{-2}day^{-1}$)
R_{cld}'	Surface solar radiation for cloudy sky without considering the multiple scattering between the atmosphere and ground surface (MJ $m^{-2}day^{-1}$)
R_{clr}	Surface solar radiation for clear sky (MJ $m^{-2}day^{-1}$)
R_{cld}	Surface solar radiation for cloudy sky (MJ $m^{-2}day^{-1}$)
R_{all}	Surface solar radiation for all sky (MJ $m^{-2}day^{-1}$)

world [9]. It is the most abundant form of renewable energy and can be harnessed for power generation using large solar array farms. In Germany, solar photovoltaic energy was promoted in early 1970s [10]; In Japan, a lot of technology-push policies were promulgated for solar energy utilization sine 1950s [11]. Comparing with developed countries, the photovoltaic energy industry started relatively late in China, but it experienced an explosive increase since 2000s [12]. Owning to the high cost of construction and maintenance of observation platform, in-situ measurements of solar radiation were relatively sparse, particularly in remote and mountainous regions. Baseline Surface Radiation Network (BSRN) provides high-quality and high temporal resolution measurements of SSR [13], however sites were relatively sparse distributed around the world. The world radiation data center (WRDC) also provided solar radiation data during 1953–2013 over 1677 sites around the world [14]. Similarly, The Global Energy Balance Archive (GEBA) compiled monthly SSR data from more than 2500 worldwide stations [15]. However, the temporal resolution of WRDC and GEBA were relatively poor. The Global Energy and Water Exchanges-Surface Radiation Budget project (GEWEX-SRB) and the International Satellite Cloud Climatology Project–flux data (ISCCP-FD) were two widely used SSR products with high spatial-temporal resolution, but the accuracy of these two products need to be further improved [16]. Moreover, equipment errors and operation-related problems were other limitations to the accuracy of solar radiation. Therefore, various models have been developed and applied to estimate solar radiation, especially in remote regions without direct SSR measurements.

Numerous attempts have been made to retrieve SSR from routine meteorological measurements and satellite signals. These models could be roughly divided into two types, the deterministic models and data-driven models [17]. The deterministic models assumed that the attenuation of solar radiation was an inevitable consequence of some factors including humidity, air temperature, sunshine duration and altitude [18,19]. The deterministic models could be further divided into empirical parameterization models and physical models according to the mathematical forms. The former revealed internal relations between SSR and routine meteorological variables including sunshine duration, temperature, and cloud fraction. Ertekin et al. [20] estimated daily SSR using eighteen sunshine-based empirical models in Turkey, the result showed that a linear model developed by Gopinathan [21] and a hybrid model developed by Jin et al. [22] produced the lowest errors. Using the ratio of sunshine duration to daylight duration, Li et al. [23] reconstructed the spatial-temporal variations of SSR in Tibet during the past 40 years. Based on the relationship between SSR and air temperature, Bristow et al. [24] developed a simple model to estimate SSR. The Bristow-Campbell model was proved to have better performance than Allen model in Chile [25]. However, above empirical models did not consider the physical process and the effects of terrains and climate features. Thus, it is inflexible to incorporate the changing calibrated parameters and limited for generalization in remote regions. Physical models provide an effective way to estimate SSR with high accuracy, Leckner [26] developed a clear-sky model, taking into account all physical transferring processes; Bird [3] presented a spectral model for estimating SSR in cloudless sky; Maxwell [27] modified Bird's algorithm and developed a cloudy-sky SSR model; Gueymard [28] proposed a two-band model in clear sky, which was generally in good agreement with observed SSR. Besides surface meteorological measurements, remote sensing provided an alternative way to get continuous information of SSR at regional and global scales. Both geostationary satellites and polar orbiting satellites could provide observations with different spatial and temporal resolution. Zhang et al. [29] developed an all-sky shortwave and longwave fluxes product by exploiting GISS (NASA Goddard Institute for Space Studies) radiative transfer model and improved the ISSCP data sets. These products were validated to have better accuracies than Earth Radiation Budget Experiment (ERBE) and Clouds and the Earth's Radiation Energy System (CERES). RoupIoz et al. [30] proposed a method to estimate SSR over Tibet using MODIS products considering the terrain effects, the result showed that this method could effectively retrieve SSR at square kilometer level. Huang [31] developed an advanced algorithm to retrieve SSR in China by combing two simplified radiative transfer model using MODIS products. Compared with polar-orbiting