Impacts of different radiation schemes on the prediction of solar radiation and photovoltaic power

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ABSTRACT

The output power of a photovoltaic system largely depends on the amount of solar radiation that can be received by the photovoltaic panel, and the solar radiation energy reaching the ground is affected by the radiation transmission process. However, in engineering practice, numerical simulation prediction schemes tend to adopt a kind of radiation scheme, and the prediction of solar radiation and photovoltaic power cannot always meet the prediction accuracy. In this paper, NCEP–NCAR reanalysis data are used as the initial field, and a variety of radiation parameterization schemes are used to produce simulations for the Xinjiang area. Through analysis of examples, it is found that the simulation results differ greatly depending on the radiation parameterization scheme employed, with the maximum absolute error of the total radiation and the predicted power being 106.67 W m\(^{-2}\) and 3.5 MW, respectively. Meanwhile, the mean absolute percentage error of the total radiation ranges from 8.6% to 17.3%, and that of the predicted power from 11.3% to 20.2%. Having analyzed the simulation results of the different radiation parameterization schemes, we conclude that the RRTM/Dudhia and CAM (Community Atmospheric Model) schemes are the most appropriate when under clear-weather conditions.

1. Introduction

Solar radiation is the most important and ultimate source of energy for the earth system. If, as a kind of clean energy, solar energy can be reasonably and effectively developed, it will contribute to protecting the environment, mitigating against climate change, and providing energy security; thus, it has very important practical significance (Stanhill and Moreshet 1992; Gilgen, Wild, and Ohmura 1998; Yan et al. 2012). In recent years, the world has made solar power a key area in the development and utilization of solar energy resources, and China's photovoltaic industry has developed rapidly against a background of large-scale national projects, promotional programs, and projects involving international cooperation (Qian et al. 2011; Xin 2013).

One of the basic data sources for photovoltaic power generation is solar radiation and, although observationally these data are sparse and somewhat lacking in China, radiation simulation technology can overcome these limitations to provide an objective and quantitative basis for photovoltaic power generation (Wang et al. 2013). With the rapid development in computing technology, numerical models have begun to play an increasingly important role in the simulation of solar radiation (Shimada and Kurokawa 2006; Shen and Hu 2006; Wu, Wang, and Cui 2010). Numerical simulation based on mesoscale meteorological models with high spatial and temporal resolution has been widely used in the assessment of solar energy resources and the forecasting of solar radiation (Ma et al. 2011; Liu and Pan 2012). Wang et al. (2012) used the mesoscale numerical model WRFV3 for a surface shortwave
radiation simulation lasting nearly a month, and the simulation results were highly correlated with the actual observations. The model showed a certain ability and reliability in forecasting surface shortwave radiation, especially for radiation on sunny days. Based on satellite data assimilation of the Local Analysis Prediction System (LAPS) multi-time layer three-dimensional cloud analysis assimilation method, Cheng Xinghong et al. (2014) improved the simulation of total radiation during cloudy and precipitation weather processes. Wang et al. (2005) found that different radiation parameterization schemes had a significant effect on the simulation of short-term weather processes in China, wherein a combination of long- and shortwave radiation parameterization schemes simulated a variety of radiation and cloud cases in reasonable detail, reflecting the weather processes involved.

Along with improvements in radiation simulation requirements, it is also important to identify optimal combinations of schemes based on the existing radiation transmission process (Li et al. 2005; Quan et al. 2009; Peng et al. 2015). Studies have shown that patterns are highly sensitive to radiation parameterization schemes used and, for different radiation parameterization schemes, the differences in climate sensitivity given by different models can reach a factor of three (Kiehl et al. 1985; Cess et al. 1990, 1996).

2. Method

2.1. Study site

Xinjiang is in western China, which is located in central Eurasia and has typical drought climate characteristics. Under the influence of high mountains and its location away from the ocean, Xinjiang is rich in solar energy resources, with characteristics of long sunshine hours, a large temperature difference between day and night, and a long frost-free period. Therefore, we chose to carry out the numerical simulation and sensitivity experiments in Xinjiang as the main simulation area. To analyze the simulation ability of different radiation schemes for clear-sky total radiation, the total solar radiation on 22 July 2015 in Xinjiang was selected, when the weather conditions were as follows: sunny; maximum temperature of 40 °C; minimum temperature of 22 °C; and breezy.

2.2. Model setting

The mesoscale WRF model (v3.5) was used for the simulation, with a horizontal resolution of 9 km, horizontal grid points of 262 (east and west) × 229 (south and north), the vertical direction divided into 45 layers, and a simulation area as shown in Figure 1. The center of the simulation area was (41°N, 86°E) and the top of the model was 50 hPa. The experiment used a one-way nested grid, and the main physical processes included: WSM 6-class micro-physics scheme; the Yonsei University scheme; the MMS Monin–Bukhov near-surface layer scheme; the Noah-SLUCM (Single-layer Urban Canopy Model) coupled modeling system; and the Kain–Fritsch cumulus convection parameterization scheme. The initial field and boundary conditions required for the model integration were taken from the FNL reanalysis data of NCEP, with a horizontal resolution of 1° × 1° and a temporal resolution of four times per day.

To simulate and analyze the effects of different radiation parameterization schemes on clear-sky solar radiation, six combinations are shown in Table 1. The simulation time was from 0800 Beijing Time (BJT) 21 July 2015 to 0200 BJT 23 July 2015, where the combination of long- and shortwave schemes in case1 was RRTM/Dudhia, and the other five combinations were the same schemes for long- and shortwave radiation in the WRF mode, which were the Community Atmospheric Model (CAM) scheme, Rapid Radiative Transfer Model for Global Circulation Models (RRTMG) scheme, Goddard scheme, Fu-Liou-Gu (University of California at Los Angeles) scheme, and Geophysical Fluid Dynamics Laboratory (Eta) scheme.

3. Results

In this paper, the analysis of the simulated effects of solar radiation and photovoltaic power is carried out in the case of a 30 MW photovoltaic power plant in Xinjiang on 22 July 2015. The observation instrument is in a photovoltaic power plant (42.86°N, 93.24°E) in Xinjiang, which has a total of 204856 PV modules with model STP245-28wd, polysilicon and 40 degrees bracket angle. The meteorological variables monitored are mainly radiation-related (total radiation, direct radiation, scattered radiation), with a resolution of 1.0 W m⁻², as well as ambient temperature (°C), wind speed (m s⁻¹), air pressure (hPa), humidity (%), and sunshine duration (h), with a resolution of 0.1.

3.1. Results of the different radiation schemes

The time series of simulated radiation values for the six radiation schemes, along with the observed values, are shown in Figure 2. It can be seen from the figure that the simulated value of the climbing stage is in good agreement with the observed value in the morning. The simulation value and the observed value of the noon radiation reach their maximum values and, because of the numerical simulation system error, it can be seen that the simulation value is greater than the observed value. In the afternoon, there is a time difference between the simulated radiation value and the observed value when they begin to reduce.
Since the magnitude of the reduction is close, the simulation value is always greater than the observed value.

The difference between the simulated total radiation and the observed value, and the difference between the predicted power and the measured power, are shown in Figure 3. It can be seen from the figure that the simulated total radiation and the predicted power of the different radiation schemes are different from their measured counterparts. The simulated total radiation results of the Case1 scheme are generally lower than the observed values from 0700 to 1600 BJT and the maximum error is $-49.05\, \text{W}\, \text{m}^{-2}$, but the simulated values are generally higher than the observed values from 1600 to 2100 BJT and the maximum error is $50.93\, \text{W}\, \text{m}^{-2}$. The Case2–Case6 radiation scheme simulation results are generally higher than the observed value, where Case6 has a simulated value of $106.67\, \text{W}\, \text{m}^{-2}$ greater than the observed, and the simulation results of the six radiation schemes are all higher than the observed from 1600 to 2100 BJT. In addition to the Case5 scheme, the predicted power of the remaining five schemes is generally less than the measured value from 0900 to 1400 BJT and the maximum error is about $-1.8\, \text{MW}$ for Case1, but the predicted power is higher than the measured value from 1400 to 2100 BJT and the maximum error is about $3.5\, \text{MW}$ for Case6. Also, the predicted power of the Case1 scheme is the highest with measured deviation before 1400 BJT compared with the other five schemes, and the closest to the measured value after 1400 BJT.

From the above analysis the difference between the total radiation and the predicted power of the different radiation schemes is positive and negative, with the maximum absolute error of the total radiation being $106.67\, \text{W}\, \text{m}^{-2}$ and the maximum absolute error of the predicted power being $3.5\, \text{MW}$.

### 3.2. Error statistics

To compare the effects of the different radiation schemes on the total radiation and predicted power, the mean absolute percentage error (MAPE) and point ratio of error not exceeding 5% (pre5) results are analyzed (Table 2). MAPE is calculated as

$$
\text{MAPE} = \frac{1}{n} \sum_{i=1}^{n} \frac{|x_{pi} - x_{ai}|}{x_{ai}} \times 100\%,
$$

where $x_{pi}$ is the predicted value of the $i$th data, $x_{ai}$ is the real value of the $i$th data, and $n$ is the number of data. This indicator reflects the error of the absolute value of the predicted result, which can reflect the error to a certain extent. It can be seen from the table that the total radiation MAPE of Case1 and Case2 is in both instances less than 9%, and the minimum error is 8.6% for Case2. Meanwhile, the total radiation MAPE of Case3–Case6 is more than 10% and the maximum error is 17.3% for Case6. The MAPE for the predicted power of Case1 and Case2 is less than 15%, and for Case3–Case5 it is between 15.7% and 17.2% while the maximum error is 20.2% for Case6. The pre5 is calculated as

$$
\text{pre5} = \frac{n_{5}}{n} \times 100\%,
$$

where $n_{5}$ is the number of data with the error not exceeding 5%, and $n$ is the number of data. This indicator reflects the probability that the deviation between the predicted and actual values is within an acceptable range. It can be seen from the table that the largest pre5 of the total radiation simulation is 75.5% for Case3, and the smallest is 49% for Case5. For the remaining four radiation schemes, the ratio is between 65.3% and 75.5. The largest pre5 of the predicted power is 73.5% for Case6 and the smallest is 63.3% for Case3. For the remaining four radiation schemes, the ratio is between 65.3% and 71.4%.

From the above analysis, it can be seen that the MAPE of the simulated total radiation for the Case4, Case5 and Case6 schemes is greater than 11%, and the MAPE of the predicted power is greater than 16%. Because the error is too large for Case4, Case5, and Case6, they are not suitable...
for the simulation of radiation on clear-sky days, among the six schemes. The MAPE of the simulated total radiation for Case3 is 10.3%, but the MAPE of the predicted power is greater than 15%, and so it is not recommended as the best option. The MAPE of the simulated total radiation for Case1 and Case2 is less than 10%, the MAPE of the predicted power is less than 13%, and the pre5 is more than 65%. The errors for Case1 and Case2 are relatively small among the six schemes.

Overall, the Case1 and Case2 schemes are relatively good, so this combination of long- and shortwave schemes, corresponding to the RRTM/Dudhia and CAM schemes, respectively, can be considered as the best choice for simulation under clear-sky conditions.
Table 2. Error statistics, based on a power plant at Xinjiang (30 MW).

|                   | Case1 | Case2 | Case3 | Case4 | Case5 | Case6 |
|-------------------|-------|-------|-------|-------|-------|-------|
| Total MAPE (%)    | 8.9   | 8.6   | 10.3  | 11.9  | 11.5  | 17.3  |
| pre5 (%)          | 67.3  | 67.3  | 75.5  | 73.5  | 49.0  | 65.3  |
| Predicted power   | 11.3  | 13.0  | 15.7  | 17.2  | 16.2  | 20.2  |
| MAPE (%)          | 65.3  | 71.4  | 63.3  | 67.3  | 67.3  | 73.5  |

4. Conclusion

In this study, the influence of different radiation schemes on the solar radiation and predicted power was simulated using the mesoscale WRF model (v3.5), and the simulation results from different combinations of schemes were analyzed based on comparison with the measured data from a power station. The main conclusions are as follows:

1. The effect of the different radiation schemes on solar radiation and predicted power was obvious. The maximum absolute error of the total radiation was 106.67 W m\(^{-2}\), and the maximum absolute error of the predicted power was 3.5 MW.

2. The minimum MAPE of the simulated total radiation was 8.6% for the CAM scheme and the maximum was 17.3% for the GFDL (Eta) scheme. The largest pre5 was 75.5% for the RRTMG scheme and the smallest was 49% for the FLG (UCLA) scheme.

3. The minimum MAPE of the predicted power was 11.3% for the RRTM/Dudhia scheme and the maximum was 20.2% for the GFDL (Eta) scheme. The largest pre5 was 73.5% for the GFDL (Eta) scheme and the smallest was 63.3% for the RRTMG scheme.

4. The RRTM/Dudhia and CAM schemes are appropriate when simulating under clear-sky conditions.

Disclosure statement

No potential conflict of interest was reported by the authors.

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