Does the modern-era retrospective analysis for research and applications-2 aerosol reanalysis introduce an improvement in the simulation of surface solar radiation over China?

Fei Feng | Kaicun Wang

Surface incident solar radiation ($R_s$) is a key parameter of energy and water cycles of the Earth. Reanalyses represent important sources of information on $R_s$. However, reanalyses $R_s$ may have important bias due to their imperfect parameterizations and input errors of cloud and aerosol. NASA’s Global Modelling and Assimilation Office has recently released Version 2 of the Modern-Era Retrospective Analysis for Research and Applications (MERRA2), which incorporates a reanalysis of atmospheric optical depth for the first time. In this study, we evaluate $R_s$ from MERRA2 and its predecessor (MERRA) in China from 1980 to 2014. We first compare three possible reference data sources: (a) observed $R_s$ at 122 stations, (b) satellite retrievals of $R_s$ and (c) $R_s$ values derived from sunshine durations measured at 2,400 weather stations. We find sunshine duration derived $R_s$ is a reliable reference and use it to evaluate MERRA and MERRA2. Our results show that both MERRA and MERRA2 have a high mean bias of 38.63 and 43.86 W/m² over China due to their underestimation of cloud fraction, which is greater in southern China. MERRA2 displays improved capability in reproducing monthly and annual variability, and national mean trend of $R_s$. MERRA overestimates the trend of $R_s$ by 3.23 W/m² in eastern China. MERRA2 reduced this trend bias over the North China Plain likely due to its aerosol assimilation. However, MERRA2 show a negative bias in trend of $R_s$ ($-3.44$ W/m²) in the south China likely due to its overestimation of atmospheric aerosols loading and aerosol-cloud interaction. The results provide guidance for future development of reanalysis and its scientific applications for ecological and hydrological models.

**KEYWORDS**
aerosol, cloud, MERRA2, surface incident solar radiation

**1 | INTRODUCTION**

Surface incident solar radiation ($R_s$) is an essential variable in determining the exchanges of energy and mass within Earth’s climate system (Sellers et al., 1990; Wang et al., 2010; Wild et al., 2013; Wild, 2016; Du et al., 2017, 2018). Data describing $R_s$ at global, national and regional scales represent extremely valuable information for many applications, such as climate model simulations and solar energy generation (Tjernström et al., 2012; Jerez et al., 2015). $R_s$ data sets from reanalyses have been widely used such as the inputs of calculation of evapotranspiration (Feng et al., 2017), impacts of surface temperatures (Du et al., 2017, 2018).

The spatial distribution and the temporal variability in $R_s$ depends heavily on atmospheric parameters, such as cloud
cover and aerosol loading (Wang et al., 2012a; Sanchez Romero et al., 2014). For example, aerosol loading has been considered to be the main factor that affects long-term variations in $R_s$ over Europe (Streets et al., 2006; Ruckstuhl et al., 2008; Folini and Wild, 2011; Nabat et al., 2013, 2015; Wild, 2016), and cloud cover is the factor that has the strongest influence on long-term variations in $R_s$ over the United States (Liepert, 2002; Long et al., 2009; Augustine and Dutton, 2013). Recent studies have argued that atmospheric aerosols are an important factor impacting the long-term $R_s$ variation over China (Zhang et al., 2004; Che et al., 2005; Liang and Xia, 2005; Xia, 2010; Wang and Yang, 2014; Qian et al., 2015).

However, the effects of aerosols are not fully taken into account in most reanalyses, especially the first generation of reanalyses, such as Environmental Prediction and National Center for Atmospheric Research Reanalysis (NCEP1) and National Centers for Environmental Prediction Department of Energy reanalysis (NCEP2) (Kalnay et al., 1996; Kama mitsu et al., 2002; Fujiiwara et al., 2017). The forecast models used to produce NCEP1 and NCEP2 have no aerosol component, whereas most current reanalyses, such as the Modern-Era Retrospective Analysis for Research and Applications (MERRA), Climate Forecast System Reanalysis (CFSR), the European Centre for Medium-Range Weather Forecasts (ERAI) and the Japanese 55-year Reanalysis (JRA55), use climatological mean values, which cannot produce accurate long-term variation of aerosols (Saha et al., 2010; Dee et al., 2011; Rienecker et al., 2011).

Version 2 of the MERRA reanalysis (MERRA2) has recently been released by NASA’s Global Modelling and Assimilation Office (GMAO) (Gelaro et al., 2017). Compared to its predecessor (MERRA), MERRA2 includes many significant improvements. For example, it incorporates online aerosol fields and considers the direct and semi-direct effects of aerosols (Buchard et al., 2017; Randles et al., 2017). These features imply that the $R_s$ estimates in MERRA2 may be improved by this added information on aerosols such as satellite-derived aerosol optical depth (AOD) data from Moderate Resolution Imaging Spectroradiometer (MODIS), the Advanced Very High Resolution Radiometer (AVHRR), The multi-angle imaging spectroradiometer (MISR) instruments and ground-based measured AOD data from Aerosol Robotic Network (AERONET) (Table 1).

The variability in $R_s$ over China has drawn much attention recently, due to the increase in aerosol emissions that has accompanied the urbanization and economic growth of China. Thus, China represents an ideal place to evaluate the performance of MERRA2 relative to MERRA. There are large uncertainties in the aerosol simulation in current climate models. MERRA2 take the first step forward to assimilate aerosol observation. Previous studies have reported that MERRA have large biases in China (Wang et al., 2015). Evaluating the performance of MERRA2 over China are rarely been found in previous study (Feng and Wang, 2018).

| Name | MERRA2 | MERRA |
|------|--------|-------|
| Model | GEOS 5.12.4 | GEOS 5.0.2 |
| Spatial resolution | $0.5^\circ \times 0.625^\circ$ | $0.5^\circ \times 0.667^\circ$ |
| Analysis period | 1980–present | 1979–2016 |
| Shortwave parameterization | Chou and Suarez (1999) | Chou and Suarez (1999) |
| Cloud overlap scheme | Maximum-random | Maximum-random |
| Cloud parameterization | Moorthi and Suarez (1992) and Bacmeister et al. (2006) | Moorthi and Suarez (1992) and Bacmeister et al. (2006) |
| Aerosols | Analysed aerosols derived using the GOCART model; the GEOS-5 model is used to assimilate the surface and satellite data | Climatological aerosols derived using the GOCART model with GEOS-4 MERRA AGCM |
| Reference | Molod et al. (2015) | Rienecker et al. (2011) |

In this study, we first compare three possible reference data sources: (a) observed $R_s$ at 122 stations, (b) satellite retrievals of $R_s$ and (c) $R_s$ values derived from sunshine durations measured at 2,400 weather stations. This study use the sunshine duration-derived $R_s$ which can provide a good spatial temporal pattern of $R_s$ over China. We find sunshine duration-derived $R_s$ is the reliable reference data set over China and use it to evaluate MERRA and MERRA2. The climatology, spatial pattern, variability and trend in $R_s$ from MERRA and MERRA2 are evaluated. Trends in this study are calculated using the traditional linear trend method, that is, the linear regression method. Further analyses of the cloud fraction and the AOD and their relationships with $R_s$ uncover the reasons of the assessment results.

The assessment results in this study offers a reference for future development of reanalysis data, that is, interannual variabilty of atmospheric aerosol and radiation-aerosols interactions process (Randles et al., 2017). Aerosols impacts cloud cover and precipitation through radiation-aerosols interactions process (Archernicholls et al., 2016). The accurate simulation of radiation-aerosols interactions will help to improve the clouds scheme and precipitation simulation in reanalyses. Moreover the output of this assessment provide a guide for researchers when selecting reanalysis data as initial conditions for ecological and hydrological models (Domo, 1920; Roderick and Farquhar, 2002; Wang et al., 2017).

2 | DATA

2.1 | Modern-era retrospective analysis for research and applications

The MERRA reanalysis is a global reanalysis developed by NASA-GMAO and was released in 2009 (Rienecker et al., 2011). The primary goal of MERRA is to use massive data
from the satellite constellations that make up NASA’s Earth Observing System (EOS) to improve the ability of the reanalysis to simulate the water and energy cycles. MERRA covers the full satellite era from 1979 to 2016 with a horizontal resolution of 1/2° latitude by 2/3° longitude and 72 vertical layers. The MERRA products are generated using version 5.2.0 of the Goddard Earth Observing System (GEOS) atmospheric model. The data assimilation system used to produce MERRA is a three-dimensional variational data assimilation system (3DVAR) that gradually adjusts the forecast results towards observations during its corrector segment.

The Community Radiative Transfer Model (CRTM) is used to directly assimilate the satellite radiance data. Specifically, the shortwave radiation parameterization method follows the maximum-random cloud overlap scheme (Chou and Suarez, 1999). The climatological mean aerosol distribution data are generated by the Goddard Chemistry, Aerosol, Radiation and Transport (GOCART) model (Colarco et al., 2010).

### 2.2 Modern-era retrospective analysis for research and applications-2

The follow-on product, MERRA2, was released in 2015 by NASA-GMAO (Gelaro et al., 2017). MERRA2 has a horizontal resolution of 0.5° latitude by 0.625° longitude and 72 vertical layers and covers the period from 1980 to the present. MERRA2 represents an upgraded version of the MERRA reanalysis, and many improvements have been made to the forecast model, the data assimilation system and the observational data used. MERRA2 applies a new atmospheric model (GEOS 5.12.4) (Molod et al., 2015).

Although the shortwave radiation parameterization of MERRA2 is the same as that used in MERRA (Table 1), MERRA2 has an improvement of conservation of mass as well as many alterations to the related physics parameterizations, such as a reduction of anvil fractions by one half, increased re-evaporation of precipitation, new critical relative humidity that depends on resolution, and limiting the cloud base to be at or above the boundary layer depth. All of these changes affect the amount of water vapour and clouds, which in return affect the $R_s$.

MERRA2 includes a significant improvement in that it incorporates an aerosol component and assimilates aerosol observations (Buchard et al., 2017; Randles et al., 2017). The aerosol information used in MERRA contains climatological aerosol values generated by the GOCART model. The aerosol values in MERRA2 are directly generated by the GOCART model based on GEOS-5 in real time, and the MODIS “dark target” algorithm derived data are assimilated into the MERRA2 and AOD data from Multi-angle Imaging SpectroRadiometer (MISR) over bright land surfaces only (Randles et al., 2017). The satellite-derived AOD values include those derived from AVHRR over the ocean (1980–2002), MODIS Terra (2000–present) and MODIS Terra/Aqua (2002–present) over land and MISR (2000–2014) over bright surfaces, such as desert areas (Randles et al., 2017).

### 2.3 Ground observations

$R_s$ measurement in China begins at 1957. In the beginning of the measurements, there are two types of solar radiation instruments including Yanishevsky thermoelectric pyrheliometers and pyranometers imported from former Soviet Union.
(Wang et al., 2015). The stations in this time period are divided into two classes. The first-class stations measure direct solar radiation by a pyrheliometer and diffuse solar radiation by a pyranometer, and $R_s$ is calculated from these measurements. The second-class stations only use pyranometers to measure $R_s$. However, after 1960s, with the aging of the imported instruments, most stations in China used imitations of the former Soviet Union radiometers. During the period of 1990–1993, China replaces its instruments by new automated instruments to solve the instruments aging problem. After that, most $R_s$ are directly measured by a pyranometer.

The map of the 122 stations provided $R_s$ measurements can be found at Figure 1. The time series of annual mean of monthly anomaly $R_s$ averaged from 122 stations over China show that observed $R_s$ have spurious stronger decreasing trend from 1981 to 1989 and abrupt increase from 1990 to 1993 over China (Figure 2). This unrealistic trend of $R_s$ is also revealed by observation of diurnal temperature range (Wang et al., 2010a; Wang and Dickinson, 2013). The degradation of instrument sensitivity from 1980 to 1989 and instrument replacement from 1990 to 1993 has been identified as the main reason for this issue (Wang, 2014; Ma et al., 2015). Therefore, directly using the $R_s$ observations to validate long-term trend of $R_s$ might not be a good choice. Moreover the spatial representativeness of 122 weather stations is limited when analyzing the spatial pattern of $R_s$.

We use monthly mean $R_s$ values derived from sunshine durations measured at 2,400 weather stations of the Climate Data Center of the Chinese Meteorological Administration (CDC/CMA) from 1980 to 2014 (Figure 1). sunshine durations are measured at weather station most by the Jordan sunshine recorders over China (Wang et al., 2015). The Jordan sunshine recorders consist of one opaque metal cylinder with two small holes in its sides (Xu et al., 2011). Sunlight entering the small holes and falls on light-sensitive paper and leaves a mark on the light-sensitive paper when the direct solar radiation longer than 120 W/m², which is a measure of sunshine durations (Che et al., 2005; Zhao et al., 2010; Wang et al., 2015). The light-sensitive paper is replaced every day and avoids a sensitivity drift problem. Compared with field observations used to estimate $R_s$, sunshine duration data are relatively widely available and cover a lengthy period of time that extends from the late 19th century to the present (Martin et al., 2009; Sanchezlorenzo et al., 2009).

The sunshine duration-derived $R_s$ values are calculated following the methods of (Yang et al., 2006; Wang, 2014). This method can be summarized as follows:

$$R_s = a_0 + a_1 \times \frac{n}{N} + a_2 \times \frac{(n^2)}{N}$$

$$R_s = \int I \times \frac{\tau}{C_1} \sin(h) \cdot dt + \int I \times \frac{\tau}{C_1} \sin(h) \cdot dt$$

where $n$ is the measured sunshine duration, $N$ is the theoretical value of sunshine duration. $a_0$, $a_1$ and $a_2$ are determined

| TABLE 2 | Statistical summary of the linear trends of monthly anomaly surface solar ($R_s$) radiation in the regional mean over China in MERRA and MERRA2 |
|---------|-------------------------------------------------|
| Sites numbers | 1980–2014 | 2000–2014 |
| SunDu | 122 | −0.66 (0.03) | −0.23 (0.82) |
| Obs | 122 | 1.83 (0.00) | 2.29 (0.02) |
| CERES | 122 | − | −0.61 (0.57) |
| MERRA | 122 | 1.09 (0.00) | 4.06 (0.00) |
| MERRA2 | 122 | −1.36 (0.00) | −2.09 (0.00) |
| SunDu | 2,400 | −0.90 (0.01) | −1.29 (0.28) |
| MERRA | 2,400 | 1.42 (0.00) | 4.80 (0.00) |
| MERRA2 | 2,400 | −1.42 (0.00) | −2.26 (0.01) |

There are 2,400 stations provided sunshine duration-derived $R_s$ (SunDu), including 122 stations provided both observed (Obs) $R_s$ and SunDu data. CERES represents the CERES EBAF surface data. $p$ Values, which indicate significance are shown in the brackets.
followed the method of Wang (2014). $R_c$ is the daily surface total solar radiation under clear-sky conditions. $I$ is solar irradiance at the top of the atmosphere. $\tau_b$ and $\tau_d$ are atmospheric transmittance for direct solar radiation and diffuse solar radiation. $h$ is the solar elevation.

The $R^2$ between the monthly observed $R_s$ and Sunshine duration (SunDu)-derived $R_s$ is 0.93 and $SD$ is 17.06 W/m². Using satellite $R_s$ retrievals (see Section 2.4 also) as reference, the sunshine duration-derived $R_s$ show more consistent results with that of satellite $R_s$ retrievals with an $R^2$ of 0.94 and a $SD$ of 16 W/m² (Figure 3). The time series of the sunshine duration-derived $R_s$ are also in agreement with that of satellite retrievals (Figure 2), the results from monthly anomaly $R_s$ trend calculated by the sunshine duration-derived $R_s$ are more close to that of satellite retrievals (Table 2).

Existing studies have also confirmed that sunshine duration data can be used to evaluate the impact of change of aerosols and clouds on $R_s$ at time scales ranging from daily to decadal (Tang et al., 2011; Wang et al., 2012b; Sanchezlorenzo et al., 2013; Sanchezromero et al., 2014; Manara et al., 2015; Wild, 2016). Our results further suggest that sunshine duration data can be used as validation data.

Manual observations of total cloud cover amount from the 2,400 weather stations are also used in this study. The ground based measurements of cloud amounts are through human eyes assessment for each weather stations. Manual measurements of cloud cover were halt in 2013 in China and changes to the automatic meteorological observation stations. However, national baseline climate stations still conduct manual measurements of cloud cover after 2013. Observed cloud amount in 10th are linearly converted to the percentage scale to enable the comparison with reanalysis-derived cloud fraction values.

### 2.4 Satellite data

Monthly mean satellite $R_s$ retrievals from the newly released CERES EBAF-surface data (version 4.0) are also used in this study. The CERES EBAF-surface product provides
more reliable $R_s$ data by regulating the input data. Specifically, the MODIS cloud property retrievals are adjusted by cloud profiling radar and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations detectors (CALIPSO), and the temperature and humidity profiles from the atmospheric infrared sounder (AIRS) are constrained by the Atmospheric Infrared Sounder. The newly released version 4.0 product uses a consistent of temperature and humidity data throughout the time series data and improves the continuity in the time series of clear sky surface solar radiation anomalies over land by using the entire record of MODIS collection 5 data to derive AOD over land (Loeb et al., 2018). Previous studies have demonstrated the reliability of MODIS aerosol products (Sayer et al., 2013).

We use the MODIS Collection 6 (C6.1) monthly AOD Deep Blue products (MOD08) as AOD reference data for comparison with the MERRA2 AOD products (Levy et al., 2013). The MOD08 products used in this study extend from 2000 to 2014 and have a spatial resolution of 1°. Existing studies have demonstrated the reliability of MODIS aerosol products (Sayer et al., 2013).

3 | RESULTS

Section 2 has shown the reliability of SunDu-derived $R_s$ and it has a high temporal coverage than satellite retrievals of $R_s$. Therefore, in this section, $R_s$ values from MERRA and MERRA2 are assessed by comparing with SunDu-derived $R_s$ from 1980 to 2014. For the comparisons, the sunshine duration-derived $R_s$ observations are interpolated to 1° × 1° grids (Du et al., 2017). Similarly, the MERRA2 and MERRA data are interpolated to the same 1° pixels. Regional characteristic of $R_s$ are also analysed along with the cloud fraction and the AOD over four subregions (Figure 1). These four subregions are the Loess Plateau, eastern Inner Mongolia, southern China and the North China Plain.
3.1 | Multiyear averages of $R_s$

Figure 4 shows the multiyear means of the SunDu-derived monthly mean $R_s$, the cloud fraction from 1980 to 2014 and the biases of MERRA and MERRA2. $R_s$ shows low values (approximately 140–180 W/m$^2$) in southeastern and northeastern China, whereas high values (approximately 180–240 W/m$^2$) occur in Inner Mongolia, Tibet and most of western China. Both MERRA and MERRA2 significantly overestimate $R_s$ by 38.63 and 43.86 W/m$^2$, respectively, which is more obviously in the Sichuan Basin.

This is likely due to their underestimation of cloud fraction (Figures 4–5). The observed cloud fraction shows high values in southern China and in northern China approximately 0.3–0.6. However, MERRA and MERRA2 tend to underestimate the cloud fraction, especially in the Sichuan Basin, which is a wake region of the westerlies. The underestimation of the cloud fraction by the meteorological and climate models has also been reported by previous studies (Zhao et al., 2013; Naud et al., 2014; Zhang et al., 2016). For instance, Zhao et al. (2013) suggested that the cloud parameterization used in MERRA may underestimate cloud amounts, thus leading to underestimates in the atmospheric absorption of shortwave radiation. We further compare the different vertical heights of multiyear mean cloud fraction from CERES SYN1deg data, MERRA and MERRA2. Even though the definitions of heights of low, middle and high clouds among CERES SYN1deg data, MERRA and MERRA2 are different, the comparisons results can roughly show that MERRA and MERRA2 both produce negative bias of low clouds (Figure 6).

3.2 | Monthly and annual variability in $R_s$

Figure 7 and Table 3 show that MERRA2 provides an improved representation of the monthly and annual variability in $R_s$ compared with MERRA. Table 3 shows that the $R^2$ of the monthly anomaly mean $R_s$ from MERRA2 improve by approximately 22.50%. The $SD$ of the monthly anomaly means decrease by 6.64% to 12.36 W/m$^2$ in MERRA2. These results indicate that MERRA2 improves the temporal
variability in $R_s$ by assimilating atmospheric aerosol optical depth.

The variability of $R_s$ is impacted by both clouds and aerosols. However, MERRA does not include inter-annual variability of atmospheric aerosols. Observations show that at monthly scale, observed $R_s$ and cloud fraction has a strong negative correlation coefficient in almost every grid in China (Figure 7). However, the correlation coefficients become weaker and insignificant in the north China. $R_s$ is negatively and weakly correlated with cloud fraction in south China at annual scale. MERRA substantially overestimate the absolute correlation coefficient between $R_s$ and cloud fraction at annual scale due to that it does not include inter-annual variability of atmospheric aerosol. The

|           | Stat | $R_s$ Stat | MERRA | MERRA2 | CF Stat | MERRA | MERRA2 | AOD Stat | MERRA2 |
|-----------|------|------------|-------|--------|---------|-------|--------|----------|--------|
| Monthly original | $R^2$ | 0.84 | 0.87 | 0.51 | 0.48 | 0.35 |
|            | Bias | 38.63 | 43.86 | -0.10 | -0.13 | 0.03 |
|            | SD   | 19.59 | 17.77 | 0.11 | 0.11 | 0.03 |
| Monthly anomaly mean | $R^2$ | 0.40 | 0.49 | 0.46 | 0.49 | 0.29 |
|            | SD   | 13.24 | 12.36 | 0.07 | 0.07 | 0.14 |
| Annual anomaly | $R^2$ | 0.18 | 0.28 | 0.25 | 0.30 | 0.38 |
|            | Bias | 38.63 | 43.87 | -0.10 | -0.13 | 0.02 |
|            | SD   | 6.78 | 6.23 | 0.04 | 0.03 | 0.05 |

The AOD from MERRA2 are evaluated using MODIS AOD as reference, 2000–2014.
overestimation is reduced in MERRA2. However, the correlation coefficient of MERRA2 $R_s$ and cloud fraction, which is much weaker than that of observed data in south China, due to MERRA2 substantially overestimate AOD (Figures 5, 7). Observation show that $R_s$ and cloud fraction is not correlated at annual scale in north China, however, they are strongly correlated in MERRA2. This is probably due to MERRA2 low capability in reproducing annual variability of natural source aerosol, that is, dust, in this area. Based on the observations, the $R_s$-cloud correlations in North China is weaker due to the impacts of aerosols such as dust. On the other hand, reanalyses have imperfect simulation of aerosols and produce a stronger $R_s$-cloud correlations in North China, which represents a unrealistic relationship $R_s$-cloud correlations in North China (Figure 7).

### 3.3 Long-term trends in $R_s$

Figure 8 shows the spatial patterns of the trends in the SunDu-derived $R_s$ values and the cloud fraction from 1980 to 2014 and the corresponding biases of MERRA2 and MERRA. Generally, the SunDu-derived $R_s$ values contain a significant decreasing trend of about $-4$ to $-5$ W m$^{-2}$ decade$^{-1}$ over the North China Plain (Figure 8).

The biases in the trend in the cloud fraction seen in the reanalyses compared to the observations display the opposite spatial pattern compared with that of $R_s$ (Figure 8). MERRA substantially overestimate the trend of $R_s$ in eastern China, due to its underestimation of trend of cloud fraction (Figure 8). MERRA2 overestimates the $R_s$ trend only in southeastern Inner Mongolia and the North China Plain. Unlike MERRA, MERRA2 slightly underestimates the $R_s$ trend in southern China.

Observation based on SunDu-derived $R_s$ shows a national mean trend $-0.90$ W m$^{-2}$ decade$^{-1}$ in $R_s$ from 1980 to 2014, while MERRA has a national mean trend $4.80$ W m$^{-2}$ decade$^{-1}$ and it is $-2.26$ W m$^{-2}$ decade$^{-1}$ for MERRA2 (Table 2). MERRA overestimates the national mean trend of $R_s$ by 6.09 W/m$^2$. Figure 9 shows that MERRA2 has a substantial increase in AOD (0.08 per decade) after assimilation atmospheric aerosols, which results in a decreasing trend of $-2.14$ W m$^{-2}$ decade$^{-1}$ in
clear sky $R_s$. This explains why national mean trend of $R_s$ of MERRA2 is more consistent with that of sunshine-derived surface solar radiation. However, AOD in MERRA does not have temporal variability and its clear sky $R_s$ has a near zero trend (0.7 W m$^{-2}$ decade$^{-1}$). This is another reason that MERRA substantially overestimate the national mean trend of $R_s$.

3.4 Annual variability in $R_s$ and related factors over the subregions of China

Four regions within China are selected to analyse the regional long-term variations in $R_s$, the cloud fraction and the AOD (Figure 1). The annual mean values of the monthly anomaly of $R_s$, the cloud fraction and the AOD in eastern Inner Mongolia, the Loess Plateau, southern China and the North China Plain are shown in Figure 10. In the Loess Plateau, the amplitude variations in the AOD in MERRA2 are small, which is inconsistent with field observations in this region (Bi et al., 2011). The patterns of temporal variation in $R_s$ are very similar in MERRA and MERRA2. However, both MERRA and MERRA2 fail to capture the observed pattern of variation in $R_s$, especially during 1980–1990. In eastern Inner Mongolia, the SunDu-derived $R_s$ values reflect a decreasing trend that accompany with an increasing trend in the observed cloud fraction. Moreover, the AOD shows an increasing trend in this area. Compared with the observed variations in $R_s$, MERRA and MERRA2 both show large biases during 1980–1990 and 2000–2010. However, MERRA2 nearly captures the pattern of variation in $R_s$ in approximately 2005.

In Southern China, the AOD increases dramatically. MERRA2 shows large discrepancies in the period between 2000 and 2010 when compared with the SunDu-derived $R_s$. These discrepancies may be due to the inaccurate simulation of wet deposition in MERRA2. In the North China Plain, the AOD shows an increasing trend (Qian et al., 2007), and MERRA2 displays good performance in that it captures the pattern of a decreasing trend in $R_s$ (Li et al., 2007, 2016). This results also confirm a previous study (Zhang et al., 2015) that revealed the aerosol play an important role of long-term variation of $R_s$ in this region (Wang et al., 2012a).
Compared with observations, MERRA2 performance has obvious difference for different regions. Even though MERRA does not assimilate aerosols observation, MERRA performed slightly better than MERRA2 in south China. This is might attribute to the overestimation aerosols of MERRA2 in south China, and an enhanced aerosols-cloud-radiation interaction effect, together produce unrealistic $R_s$ variation in MERRA2. In north China such as East inner Mongolia, there are large differences between observations and MERRA2 and this discrepancy might be the imperfect simulation of dust in MERRA2 (Qin et al., 2018). Moreover, MERRA2 AOD is not fully constrained by the assimilation before 2000, which lead to inhomogeneous issues. Based on the results of the figure 10, the biases of MERRA2 AOD over China, which might related with simulation of dust in North China and wet deposition process in South China.

4 | DISCUSSION AND CONCLUSIONS

The spatiotemporal patterns of $R_s$ are affected by clouds and aerosols. However, most reanalyses use imperfect cloud parameterizations and climatological mean aerosol values, and these practice may introduce large biases in simulated values of $R_s$ (Fujiwara et al., 2017). The recently released MERRA2 updates GEOS model and incorporates analysed aerosol data and improve cloud parameterizations. In this study, we compare the climatology, variability, trends and
regional variations of $R_s$ and its relationship with the cloud fraction and the AOD from MERRA and MERRA2.

Our results show that MERRA and MERRA2 both overestimate the multiyear mean $R_s$ and underestimate the multiyear mean cloud fraction from 1980 to 2014. In particular, both MERRA and MERRA2 display large biases over the Sichuan Basin. The regional $R_s$ estimation results over the Loess Plateau also indicate that the bias in $R_s$ in MERRA and MERRA2 might result from that of clouds. The improved estimation of $R_s$ in MERRA2 is seen mainly in regions such as the North China Plain, where aerosol loadings are high.

MERRA generally overestimates the $R_s$ trend in eastern China. MERRA2 improves the estimated trend in $R_s$, especially over the North China Plain. However, MERRA2 underestimates the trend in $R_s$ in the south China. The results from clear sky $R_s$ trend validation also suggest that MERRA2 might have the overloading of aerosols in south China.

MERRA2 shows improvements in the $R_s$ monthly variations, the monthly anomaly $R_s$ variations and the annual $R_s$ variations. These results indicate that updated GEOS model and incorporating analysed aerosol data improves the estimation of $R_s$ variability. However, MERRA2 still has biases, which would cause adverse consequences for atmospheric and ecological applications. For example, positive bias of $R_s$ will produce excess of net radiation at the surface and impact the hydrology cycle (Rotenberg and Yakir, 2010). Collectively, more work need to be done to conduct control experiments to analyse cloud, aerosols impact on $R_s$, especially for cloud-aerosols interaction and validate MERRA2 at different regions with comprehensive approaches.

ACKNOWLEDGEMENTS

This study was funded by the National Key Research and Development Program of China (2017YFA0603601), and the National Natural Science Foundation of China (41525018). We thank Guocan Wu, Runze Li, Qian Ma, and Chunlue Zhou for their insightful comments. The MERRA and MERRA2 data can be downloaded from https://gmao.gsfc.nasa.gov/reanalysis/.

REFERENCES

Archernicholls, S., Lowe, D., Schultz, D.M. and Mcfiggans, G. (2016) Aerosol-radiation-cloud interactions in a regional coupled model: the effects of convective parameterisation and resolution. Atmospheric Chemistry and Physics, 15, 27449–27499.

Augustine, J.A. and Dutton, E.G. (2013) Variability of the surface radiation budget over the United States from 1996 through 2011 from high-quality measurements. Journal of Geophysical Research-Atmospheres, 118, 43–53.

Bacmeister, J.T., Suarez, M.J. and Robertson, F.R. (2006) Rain reevaporation, boundary layer convection interactions, and Pacific rainfall patterns in an AGCM. Journal of the Atmospheric Sciences, 63, 3383–3403.

Bi, J., Huang, J., Fu, Q., Wang, X., Shi, J., Zhang, W., Huang, Z. and Zhang, B. (2011) Toward characterization of the aerosol optical properties over loess plateau of northwestern China. Journal of Quantitative Spectroscopy and Radiative Transfer, 112, 346–360.

Buchard, V., Randles, C. A., Silva, A. M. D., Darmenov, A., Colarco, P. R., Govindaraju, R., Ferrare, R., Hair, J., Beyersdorf, A. J. and Ziemba, L. D. (2017) The MERRA-2 aerosol reanalysis, 1980 – onward, part II: evaluation and case studies. Journal of Climate, 30, 6651–6672.

Che, H.Z., Shi, G. Y., Zhang, X. Y., Arimoto, R., Zhao, J. Q., Xu, L., Wang, B. and Chen, Z. H. (2005) Analysis of 40 years of solar radiation data from China, 1961–2000. Geophysical Research Letters, 32, 2341–2352.

Chou, M.D. and Suarez, M.J. (1999) A solar radiation parameterization for atmospheric studies, NASA TM-104606. NASA Technical Memorandum, 15, 1–51.

Colarco, P., Silva, A.D., Chin, M. and Diehl, T. (2010) Online simulations of global aerosol distributions in the NASA GEOS-4 model and comparisons to satellite and ground-based aerosol optical depth. Journal of Geophysical Research-Atmospheres, 115, 1307–1314.

Dorno, C. (1920) On observations of solar and sky radiations and their importance to climateology and biology and also to geophysics and astronomy. Monthly Weather Review, 48, 18–24.

Du, J., Wang, K.C., Wang, J. and Ma, Q. (2017) Contributions of surface solar radiation and precipitation to the spatiotemporal patterns of surface and air warming in China from 1960 to 2003. Atmospheric Chemistry and Physics, 17, 4931–4944.

Du, J., Wang, K.C., Wang, J., Jiang, S. and Zhou, C. (2018) Diurnal cycle of surface air temperature within China in current reanalyses: evaluation and diagnostics. Journal of Climate, 31, 4585–4603.

Feng, F. and Wang, K.C. (2018) Merging satellite retrievals and reanalyses to produce global long-term and consistent surface incident solar radiative datasets. Remote Sensing, 10, 115.

Feng, F., Li, X., Yao, Y. and Liu, M. (2017) Long-term spatial distributions and trends of the latent heat fluxes over the global cropland ecosystem using multiple satellite-based models. PLoS One, 12, e0183771.

Folini, D. and Wild, M. (2011) Aerosol emissions and dimming/brightening in Europe: sensitivity studies with ECHAM5-HAM. Journal of Geophysical Research-Atmospheres, 116, 21104.

Fujisawa, M., Wright, J. S., Manney, G. L., Gray, L. J., Anstey, J., Birner, T., Davis, S., Gerber, E. P., Harvey, V. L. and Hegglin, M. I. (2017) Introduction to the SPARC Reanalysis Intercomparison Project (S-RIP) and overview of the reanalysis systems. Atmospheric Chemistry and Physics, 17, 1–52.

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G. and Reichle, R. (2017) The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). Journal of Climate, 30, 5419–5454.

Jerez, S., Tobin, L., Vautard, R., Montávez, J. P., López-Romero, J. M., Thais, F., Bartok, B., Christensen, O. B., Colette, A. and Déqué, M. (2015) The impact of climate change on photovoltaic power generation in Europe. Nature Communications, 6, 10014.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G. and Woollen, J. (1996) The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society, 77, 437–451.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J., Fiorino, M. and Potter, G. (2002) Ncep doe amip-ii reanalysis (r-2). Bulletin of the American Meteorological Society, 83, 1631–1643.

Kato, S., Loeb, N. G., Rose, F. G., Doelling, D. R., Rutan, D. A., Caldwell, T. E., Yu, L. and Weller, R. A. (2013) Surface irradiances consistent with CERES-derived top-of-atmosphere shortwave and longwave irradiances. Journal of Climate, 26, 2719–2740.

Levy, R.C., Mattoo, S., Munchak, L.A., Remer, L.A., Sayer, A.M., Patadia, F. and Hsu, N.C. (2013) The collection 6 MODIS aerosol products over land and ocean. Atmospheric Measurement Techniques, 6, 2989–3034.
Li, Z., Xia, X., Cribb, M., Mi, W., Holben, B., Wang, P., Chen, H., Tsay, S. C., Eck, T. F. and Zhao, F. (2007) Aerosol optical properties and their radiative effect: less arid regions in China. *Journal of Geophysical Research-Atmospheres, 112*, 321–341.

Li, Z., Lai, W. K. M., Ramanathan, V., Wu, G., Ding, Y., Manoj, M. G., Liu, J., Qian, Y., Li, J. and Zhou, T. (2016) Aerosol and monsoon climate interactions over Asia. *Reviews of Geophysics, 54*, 886–929.

Liang, F. and Xia, X.A. (2005) Long-term trends in solar radiation and the associated climatic factors over China for 1961-2000. *Annales Geophysicae, 23*, 2425–2432.

Liepert, B.G. (2002) Observed reductions of surface solar radiation at sites in the Mediterranean region from a comparative evaluation and blending of remote sensing and model products. *Journal of Geophysical Research, 107*, 1314.

Macedonio, G., Moorti, S., Suarez, M.J. and Molina, C. (2014) The signal of aerosol-induced changes in sunshine duration: a review of the evidence. *Journal of Geophysical Research-Atmospheres, 119*, 4657–4647.

Sayer, A.M., Hsu, N.C., Bettenhausen, C. and Jeong, M.J. (2013) Validation and uncertainty estimates for MODIS collection 6 “Deep Blue” aerosol data. *Journal of Geophysical Research-Atmospheres, 118*, 7864–7872.

Wang, K.C., Dickinson, R.E., Wild, M. and Liang, S. (2010) Contribution of semi-arid forests to the climate system. *Science, 327*, 451–454.

Ruckstuhl, C., Philion, R., Behrens, K., Coen, M. C., Diirr, B., Heimo, A., Mätzler, C., Nyeki, S., Ohmura, A. and Vuilleumier, L. (2008) Aerosol and cloud effects on solar brightening and the recent rapid warming. *Geophysical Research Letters, 35*, 82–90.

Saha, S., Moorthi, S., Pan, H. L., Wu, X. R., Wang, J. D., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., Liu, H. X., Stokes, D., Grumbine, R., Gayno, G., Wang, J., Hou, Y. T., Chuang, H. Y., Jiang, H. M. H., Sela, J., Iredell, M., Treadon, R., Klein, D., Van Delst, P., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H. L., Yang, R. Q., Lord, S., Van den Dool, H., Kumar, A., Wang, W. Q., Long, C., Chelliah, M., Xue, Y., Huang, B. Y., Schemm, J. K., Ebisuzaki, W., Lin, R., Xie, P. P., Chen, M. Y., Zhou, S. T., Higgins, W., Zou, C. Z., Liu, Q. H., Chen, Y., Han, Y., Cucurull, L., Reynolds, R. W., Rutledge, G. and Goldberg, M. (2010) The NCEP climate forecast system reanalysis. *Bulletin of the American Meteorological Society, 91*, 1015–1057.

Sanchez-Lorenzo, A., Calbó, J., Brunetti, M. and Deser, C. (2009) Dimming/brightening over the Iberian Peninsula: trends in sunshine duration and cloud cover and their relations with atmospheric circulation. *Journal of Geophysical Research-Atmospheres, 114*, 195–200.

Sanchez-Lorenzo, A., Azorin-Molina, C., Wild, M., Vicenteserrano, S.M., López-Moreno, J.I. and Corellcustardoy, D. (2013) Feasibility of sunshine duration records to detect changes in atmospheric turbidity: A case study in Valencia (Spain). *American Institute of Physics Conference Proceedings, 1531*, 736–739.

Sanchezromero, A., Sanchez-Lorenzo, A., Calbó, J., González, J.A. and Azorin-Molina, C. (2014) The signal of aerosol-induced changes in sunshine duration records: a review of the evidence. *Journal of Geophysical Research-Atmospheres, 119*, 4657–4647.

Wang, K., Ye, H., Chen, F., Xiong, Y. and Wang, C.P. (2010a) Urbanization effect on the diurnal temperature range: different roles under solar dimming and brightening. *Journal of Climate, 25*, 1022–1027.

Wang, K.C., Dickinson, R.E., Wild, M. and Liang, S. (2012a) Two-decadal aerosol trends as a likely explanation of the global dimming/brightening transition. *Geophysical Research Letters, 33*, 292–306.

Tang, W.J., Yang, K., Qin, J., Cheng, C.C.K. and He, J. (2011) Solar radiation trend across China in recent decades: a revisit with quality-controlled data. *Atmospheric Chemistry and Physics, 11*, 393–406.

Wang, Y.W. and Yang, Y.H. (2014) China's dimming and brightening: evidence, causes and hydrological implications. *Annales Geophysicae, 32*, 41–55.

Wang, K.C., Dickinson, R.E., Wild, M. and Liang, S. (2010) Evidence for decadal variation in global terrestrial evapotranspiration between 1982 and 2002: 2. Results. *Journal of Geophysical Research Atmospheres, 115*, D20113.

Wang, K., Ye, H., Chen, F., Xiong, Y. and Wang, C.P. (2010a) Urbanization effect on the diurnal temperature range: different roles under solar dimming and brightening. *Journal of Climate, 25*, 1022–1027.

Wang, K.C., Dickinson, R.E., Wild, M. and Liang, S. (2012a) Atmospheric impacts on climatic variability of surface incident solar radiation. *Atmospheric Chemistry and Physics, 12*, 9581–9592.

Wang, Y., Yang, Y., Zhao, N., Liu, C. and Wang, Q. (2012b) The magnitude of the effect of air pollution on sunshine hours in China. *Journal of Geophysical Research Atmospheres, 117*, 116–116.
Wang, K.C., Ma, Q., Li, Z. and Wang, J. (2015) Decadal variability of surface incident solar radiation over China: observations, satellite retrievals, and reanalyses. *Journal of Geophysical Research-Atmospheres*, 120, 6500–6514.

Wang, J., Dong, J., Wang, S., Zhang, L., He, H., Yi, Y., Lu, G., Oyler, J., Smith, W. K. and Zhao, M. (2017) Decreasing net primary production due to drought and slight decreases in solar radiation in China from 2000 to 2012. *Journal of Geophysical Research*, 122, 261–278.

Wild, M. (2016) Decadal changes in radiative fluxes at land and ocean surfaces and their relevance for global warming. *Wiley Interdisciplinary Reviews: Climate Change*, 7, 91–107.

Wild, M., Folini, D., Schär, C., Loeb, N., Dutton, E.G. and König-Langlo, G. (2013) The global energy balance from a surface perspective. *Climate Dynamics*, 40, 3107–3134.

Xia, X. (2010) Spatiotemporal changes in sunshine duration and cloud amount as well as their relationship in China during 1954–2005. *Journal of Geophysical Research Atmospheres*, 115(86), D00K06.

Xu, J., Masuda, K., Ishigooka, Y., Kuwagata, T., Haginoya, S., Hayasaka, T. and Yasunari, T. (2011) Estimation and verification of daily surface shortwave flux over China. *Journal of the Meteorological Society of Japan*, 89A, 225–238.

Yang, K., Koike, T. and Ye, B. (2006) Improving estimation of hourly, daily, and monthly solar radiation by importing global data sets. *Agricultural and Forest Meteorology*, 137, 43–55.

Zhang, Y.L., Qin, B.Q. and Chen, W.M. (2004) Analysis of 40 year records of solar radiation data in Shanghai, Nanjing and Hangzhou in eastern China. *Theoretical and Applied Climatology*, 78, 217–227.

Zhang, X., Xia, X. and Xuan, C. (2015) On the drivers of variability and trend of surface solar radiation in Beijing metropolitan area. *International Journal of Climatology*, 35, 452–461.

Zhao, D., Luo, Y., Gao, G., Changhan, Z. and Yanbo, S. (2010) Long-term changes and essential climatic characteristics of sunshine duration over China during 1961-2007. *Resources Science*, 32, 701–711.

Zhao, L., Lee, X. and Liu, S. (2013) Correcting surface solar radiation of two data assimilation systems against FLUXNET observations in North America. *Journal of Geophysical Research-Atmospheres*, 118, 9552–9564.

---

**How to cite this article:** Feng F, Wang K. Does the modern-era retrospective analysis for research and applications-2 aerosol reanalysis introduce an improvement in the simulation of surface solar radiation over China? *Int J Climatol*. 2019;39:1305–1318. https://doi.org/10.1002/joc.5881