Downward surface shortwave radiation over the subtropical Asia–Pacific region simulated by CMIP5 models

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ABSTRACT

The downward surface shortwave radiation (DSSR) over the subtropical Asia–Pacific region simulated by the historical experiments of 15 CMIP5 models is evaluated in this study. The simulated DSSR is compared against two satellite observational datasets, and the possible causes for the DSSR bias of the models are further investigated by dividing the subtropical Asia–Pacific region into five areas. Most of the CMIP5 models underestimate DSSR over the oceans, but overestimate DSSR over land. Aside from the Mediterranean–West Asia (MWA) and Central Asia (CA) areas, both the biases in annual and seasonal mean DSSR are well explained by the bias in surface shortwave cloud radiative forcing (CRF), with an overestimation of the CRF effect over the subtropical North Pacific but an underestimation over other land regions. The effect of cloud plays a dominant role over the subtropical Asia–Pacific region, with relatively weaker influences over MWA and CA in boreal summer and fall.

1. Introduction

The radiation budget is very important in the global energy balance of the climate system (e.g. Ramanathan 1987), and solar radiation is one of the most important energy sources on Earth. The development of satellites in remote sensing techniques has led to great increases in radiation budget measurements, and the development of climate models has enriched our understanding of radiative budget processes. However, the various parameterizations of sub-grid radiation in climate models introduce remarkable uncertainties in radiation-related processes (e.g. Stephens 2005; Shindell et al. 2013; Wang, Yang, and Wu 2014).

CMIP5 collected a large number of data from state-of-the-art GCMs from modeling centers worldwide (Taylor, Stouffer, and Meehl 2012). Over the past several years, great attention has been paid to the quality of CMIP5 TOA solar radiation, but the quality of surface solar radiation has not been well addressed, especially over the subtropical Asia–Pacific region, with its variety of surface properties and climate types (e.g. Wild et al. 2013, 2015; Zhou et al. 2015). Many studies have deemed the representation of clouds and their radiative effects to be the primary sources of inter-model differences and one of the main sources of radiation budget bias (e.g. Wang and Su 2015). However, the effect of cloud may vary spatially due to the different surface properties and characteristics of the regional climate.

The subtropical Asia–Pacific region is characterized by various surface properties and climate types. It contains several special areas, including the Tibetan Plateau (TP) as well as plains and oceans. It also contains monsoon regions as well as desert regions. Those regions and their surrounding areas also possess complex radiation processes associated

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with clouds, non-uniform surface properties or aerosols (e.g. Norris and Iacobellis 2005; Liou, Lee, and Hall 2007; Wiacek, Peter, and Lohmann 2010; Boucher et al. 2013; Lee, Liou, and Wang 2013; Zhang et al. 2013; Wang, Lü, and He 2015). Therefore, this study, focusing on the subtropical Asia–Pacific region, aims at answering the following question: Does the cloud radiative effect play a dominant role on downward surface shortwave radiation (DSSR) in current CMIP5 models for all regions and all seasons? Section 2 introduces the methods and datasets. Section 3 addresses the DSSR simulated by CMIP5 models over the subtropical Asia–Pacific region. Section 4 summarizes the study’s findings.

2. Data and methods

2.1. CMIP5 simulations

In this study, the DSSR outputs of the ‘Historical’ experiments from CMIP5 are evaluated under both all-sky and clear-sky conditions. We adopt 15 available models, covering most of the model development organizations worldwide. The models are listed in Table 1, and more detailed information on these models can be found at http://pcmdi.llnl.gov/. The first ensemble (r1i1p1) is used in our analysis.

2.2. Satellite datasets

Given the uncertainty of satellite surface radiation datasets (Stephens et al. 2012; Pan, Liu, and Fan 2015), we use two satellite products as the reference data, including SRB/GEWEX products (Cox et al. 2006) and EBAF/CERES surface products (Kato et al. 2013). The SRB/GEWEX datasets (version 3.0) span from July 1983 to December 2007, while the EBAF/CERES (version 2.8) datasets cover March 2003 to June 2015. The monthly mean data are used. The horizontal resolution for both datasets is 1.0° × 1.0°.

2.3. Analysis methods

The outputs for all the models are bilinearly interpolated into the same horizontal resolution (1.0° × 1.0°) for the convenience of intercomparison. As for the comparison between the climate models and SRB/GEWEX (EBAF/CERES), the common period from January 1984 to December 2005 (from March 2000 to February 2005) is extracted. Similar to the definition of the cloud radiative forcing (CRF) at the TOA (Charlock and Ramanathan 1985), the surface shortwave CRF is obtained by subtracting the clear-sky DSSR from the all-sky DSSR in this study. The CRF from the CMIP5 models is also assessed against the two observations. The four seasons are spring (March–April–May; MAM), summer (June–July–August; JJA), autumn (September–October–November; SON), and winter (December–January–February; DJF).

Unless otherwise stated, the ‘bias’ refers to the difference between the CMIP5 model and satellite observations. The statistical methods used in this work follow previous studies (e.g. Kim and Liang 2010; Yang et al. 2010). Four statistics are adopted to evaluate the model bias, including the mean error (ME), mean absolute error (MAE), correlation coefficient (R), and root-mean-square deviation (RMSD), which are computed as follows:

\[
ME = \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{J} (m_{ij} - o_{ij}),
\]

\[
MAE = \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{J} |m_{ij} - o_{ij}|,
\]

\[
R = \frac{\sum_{i=1}^{I} \sum_{j=1}^{J} (m_{ij} - \bar{m})(o_{ij} - \bar{o})}{\sqrt{\sum_{i=1}^{I} \sum_{j=1}^{J} (m_{ij} - \bar{m})^2} \sqrt{\sum_{i=1}^{I} \sum_{j=1}^{J} (o_{ij} - \bar{o})^2}},
\]

\[
RMSD = \sqrt{\frac{\sum_{i=1}^{I} \sum_{j=1}^{J} (m_{ij} - o_{ij})^2}{N}},
\]

Table 1. Brief information about the 15 CMIP5 models.

| Model          | Research institute           | Resolution (lon. × lat.) |
|----------------|------------------------------|--------------------------|
| ACCESS1.0      | CSIRO and BoM, Australia     | 1.875° × 1.25°           |
| ACCESS1.3      | CSIRO and BoM, Australia     | 1.875° × 1.25°           |
| BNU-ESM        | College of Global Change and Earth System Sciences, Beijing Normal University, China | 2.8125° × ~2.8° |
| CanESM2        | CCCma, Canada                | 2.8125° × ~2.8°          |
| FGOALS-g2      | LASG, IAP, Chinese Academy of Sciences, China | 2.8125° × ~2.8° |
| GFDL CM3       | NOAA GFDL, United States     | 2.5° × 2°                |
| GFDL-ESM2G     | NOAA GFDL, United States     | 2.5° × ~2°               |
| GFDL-ESM2 M    | NOAA GFDL, United States     | 2.5° × ~2°               |
| INM-CM4.0      | Institute for Numerical Mathematics, Russia | 2° × ~1.5° |
| IPSL-CM5A-MR   | IPSL, France                 | 2.5° × ~1.2672°         |
| IPSL-CM5B-LR   | IPSL, France                 | 3.75° × ~1.895°         |
| MIROC5         | Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (University of Tokyo), and National Institute for Environmental Studies, Japan | 1.40625° × ~1.4° |
| MPI-ESM-MR     | MPI (Meteorology), Germany   | 1.875° × ~1.87°         |
| MRI-CGCM3      | Meteorological Research Institute, Japan | 1.125° × ~1.12° |
| NorESM1-M      | Norwegian Climate Centre, Norway | 2.5° × ~1.895° |
where \(i\) and \(j\) denote the longitude and latitude of the grid, respectively; \(I\) and \(J\) indicate the number of grid points along the latitudinal and longitudinal directions, respectively, for the particular region; \(m\) and \(o\) represent CMIP5 model and observation data, respectively; and \(N = I \times J\) stands for the number of grid points of the particular domain. In this paper, the CRF is negative based on its definition, so a negative bias of CRF indicates that the CMIP5 models overestimate the CRF effect.

3. Results

Figure 1 shows the spatial patterns of bias for all-sky DSSR over the subtropical Asia-Pacific region, using SRB/GEWEX observation as a reference in Figure 1(a)–(p) but EBAF/CERES as a reference in Figure 1(q). The biases of the individual models relative to EBAF/CERES are not shown since their results are similar to those compared with SRB/GEWEX. Except for INM-CM4.0 and MRI-CGCM3, the other CMIP5 models consistently overestimate DSSR over land but underestimate DSSR over ocean. Compared with the oceanic regions, the absolute DSSR bias over land is larger and more spatially non-uniform. Given the differentiated temporal range (22 and 5 years) of the two observations, the robustness of the result to the validating period is tested, and the result does not depend on which time period is selected to obtain the temporal average (figure not shown).

But can the bias of CRF explain the bias of DSSR in the CMIP5 models? As shown in Figure 2(a), the CRF bias is spatially stable over most ocean regions, with a slight overestimation of the CRF effect by the CMIP5 models. This overestimation corresponds well with the underestimation of DSSR over ocean (Figure 1(p) and (q)). The CRF bias over land is more non-uniform than that over ocean. The consistency between Figure 2(a) and (b) shows that the spatial distribution of CRF bias is not sensitive to the choice of validation datasets. As seen in Figure 2(a) and (b), the CRF bias mostly conforms to the DSSR bias over ocean, but it does not conform well with the DSSR bias over land, especially over western and central Asia.

Figure 1. The annual mean bias of all-sky DSSR (downward surface shortwave radiation) in the CMIP5 models, calculated as the difference between the model and satellite observation (units: W m\(^{-2}\)): (a–o) bias for the individual models relative to SRB/GEWEX data; (p) bias of the MME (multi-model ensemble) relative to SRB/GEWEX data; (q) bias of the MME relative to EBAF/CERES data.
Figure 2. The spatial patterns of CRF (cloud radiative forcing) biases in the MME (multi-model ensemble) relative to (a) SRB/GEWEX and (b) EBAF/CERES (units: W m⁻²), and the (c) ME (mean error), (d) MAE (mean absolute error), and (e) RMSD (root-mean-square difference) of DSSR (downward surface shortwave radiation) for five areas within the Asia–Pacific region.

Notes: In (c–e), the MME is denoted as the bullet and the inter-model spread is denoted as the bar; the all-sky DSSR bias relative to SRB/GEWEX under all-sky (clear-sky) is in blue (red); and the DSSR bias relative to EBAF/CERES under all-sky (clear-sky) is in black (green). The five areas lined up along the x-axis are MWA (Mediterranean–West Asia), CA (central Asia), the TP (Tibetan Plateau), ECWP (eastern China–western Pacific), and NP (subtropical North Pacific).

Given the spatial non-uniformity of the biases in DSSR and CRF, the research region is divided into several areas. The TP (26°–40°N, 75°–105°E) has widely been considered as a representative region to study complex radiative transfer processes and the quality of radiation data (e.g. Wu et al. 2005; Liou, Lee, and Hall 2007; Yang et al. 2010; Zhou et al. 2015). However, following the regional division approach over the subtropical Asia–Pacific region in Wang, Lü, and He (2015), we select five areas located in the same latitudes (26°–40°N) but with different regional climatic features: (1) Mediterranean–West Asia (MWA; 15°–45°E); (2) central Asia (CA; 45°–75°E); (3) the TP (75°–105°E); (4) eastern China–western Pacific (ECWP; 105°–135°E); and (5) subtropical North Pacific (NP; 150°–180°E). These five regions are marked in Figure 2(b). The cloud fraction is very limited over MWA and CA (Boucher et al. 2013). The TP is covered by complex three-dimensional clouds associated with a notable CRF effect (Wei and Zhong 1997; Wang, He, and Chen 2010). Over ECWP, thick stratus clouds resulting from the blocking effects of the TP prevail (e.g. Yu, Wang, and Zhou 2004; Zhang et al. 2013). Meanwhile, low cloud is prevalent over NP (Boucher et al. 2013).
But how does the existence of cloud influence the DSSR quality in the CMIP5 models over the different regions? The model biases of DSSR under all-sky and clear-sky conditions are further evaluated in terms of ME (Figure 2(c)), MAE (Figure 2(d)), and RMSD (Figure 2(e)). Aside from CA, the mean biases show few differences relative to either SRB/GEWEX or EBAF/CERES. The three biases show that the clear-sky DSSR is much better simulated by CMIP5 models than all-sky DSSR over the TP, ECWP, and NP. The biases for the clear-sky DSSR are nearly zero over NP. However, the DSSR biases under clear-sky conditions are as large as those under all-sky conditions over MWA and CA. The particular behavior of the CMIP5 models over MWA and CA indicates the DSSR biases are affected more by some other factor than that over other regions located in the same latitudes.

By showing the biases for the individual models as a scatter diagram (Figure 3), the inter-model relationship between DSSR bias and CRF bias is investigated. The regional variation of the correlation between two MEs (Figure 3(a) and (b)) is similar to that of the correlation between DSSR bias and CRF bias (Figure 3). The inter-model relationship between two MAEs (Figure 3(c) and (d)), as well as two RMSDs (Figure 3(e) and (f)). Over the TP, ECWP, and NP, the correlation coefficients are statistically significant at the 95% confidence level. The correlation coefficients between the two MEs are even higher than 0.86 (Figure 3(a) and (b)).
The CRF biases generally provide a strong constraint on the DSSR bias. However, over MWA and CA, the CRF biases show a relatively weaker relationship with the DSSR biases.

Based on previous studies (e.g. Wang, Yang, and Wu 2014; Wang and Su 2015), the TOA radiation biases are closely associated with the TOA cloud radiative effects. Similarly, the bias of DSSR can be largely explained by the CRF bias over most regions of the subtropical Asia–Pacific region, as seen from the above analyses. The underestimation of DSSR over ocean is principally associated with the overestimation of the CRF effect, while the overestimation of DSSR over land is associated with the underestimation of the CRF effect, with the exception of MWA and CA.

In order to elucidate the distinct CRF effect on DSSR over MWA or CA, we next examine the results for each season. The simulated DSSR for the four seasons are evaluated in terms of MAE (Figure 4(a)–(d)) under both all-sky and clear-sky conditions. The figures for ME and RMSD are excluded since the results are similar to those of MAE. In MAM (Figure 4(a)) and DJF (Figure 4(d)), the biases for clear-sky DSSR are slightly smaller than those for all-sky DSSR. However, the DSSR biases under clear-sky

Figure 4. (a–d) The DSSR (downward surface shortwave radiation) MAE (mean absolute error) under both all-sky and clear-sky conditions in different seasons: (a) MAM (March–May); (b) JJA (June–August); (c) SON (September–November); and (d) DJF (December–February). The (e) ME (mean error) and (f) MAE (mean absolute error) of total cloud fraction relative to SRB/GEWEX in terms of both annual and seasonal means.

Notes: The MME (multi-model ensemble) is denoted as the bullet and the inter-model spread is denoted as the bar; in (a–d), the all-sky DSSR bias relative to SRB/GEWEX under all-sky (clear-sky) conditions is colored in blue (red), and the DSSR bias relative to EBAF/CERES under all-sky (clear-sky) conditions is colored in black (green); in (e, f), the mean biases of cloud fraction are shown for the whole year (cyan), MAM (blue), JJA (red), SON (black), and DJF (green).
The mean bias of total cloud fraction shows no distinct difference among the five regions. The CMIP5 models mostly underestimate total cloud fraction in terms of both the annual and seasonal mean. Although the CRF effect on DSSR biases is relatively weaker over MWA and CA, the mean bias of total cloud fraction shows no distinct difference among the five regions. Over MWA and CA, the bias of total cloud fraction also shows no distinct difference among the four seasons. Therefore, over MWA and CA, the effect of cloud cannot fully explain the large DSSR bias under clear-sky conditions and the seasonal variation of the difference between the all-sky and clear-sky DSSR bias.

The above analyses indicate the importance of other factors on DSSR bias over MWA and CA, especially in JJA and SON. The improper treatments in radiative transfer processes regarding land type, surface albedo, or diffusion radiation over deserts may be possible causes for DSSR simulation biases (Sun et al. 2016). Many parts of MWA and CA have a hot desert climate, with dust and dust storms occurring frequently (e.g. Middleton 1986; Hussain, Mir, and Afzal 2005; Orlovsky, Orlovsky, and Durdyev 2005). In general, dust storms are extremely active during May through September, with the highest frequencies in June and July (Middleton 1986; Goudie and Middleton 2000; Indoitu, Orlovsky, and Orlovsky 2012). This is consistent with when the difference of the DSSR bias between all-sky and clear-sky conditions is the smallest (Figure 4(b) and (c)).

Most climate models require the direct and diffuse solar radiation as separate input variables. Circumsolar radiation due to aerosol and cloud particles contributes to direct solar irradiance to some degree (WMO 2010). However, the treatment of circumsolar radiation has not been well considered in most radiation schemes used in climate models. As shown from the analyses of Sun et al. (2016) for the Saharan desert, the inappropriate treatment of circumsolar radiation under dust aerosol conditions leads to large errors in direct solar irradiance, and the error is at least one order of magnitude. Therefore, over MWA and CA, the large DSSR bias, even under clear-sky conditions, may possibly be attributable to the improper determination of direct solar irradiance involving the circumsolar contribution in climate models.

**4. Summary**

In this study, the performance of 15 CMIP5 models in simulating surface radiative flux over the subtropical Asia-Pacific region is evaluated against SRB/GEWEX and EBAF/CERES satellite observations. Attention is paid to the mean state and the difference among the four seasons.

Most of the CMIP5 models overestimate DSSR over land, but underestimate DSSR over ocean. The overestimation (underestimation) of DSSR over the TP and ECWP (NP) mainly originates from the underestimated (overestimated) of the CRF effect. The simulated DSSR over land shows stronger bias, and its bias is characterized by stronger spatial non-uniformity. The complex land–atmosphere interaction may explain the distinct performance of CMIP5 models between land and ocean areas.

However, over MWA and CA, the DSSR bias is not well explained by CRF, especially in JJA and SON. Since dust storms occur frequently during these seasons, the improper determination of circumsolar radiation under dust aerosol conditions may also contribute to the bias in DSSR over these two regions. In order to improve the model performance in these regions, special attention from modeling groups is required.

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