Evaluation of Multiple Forcing Data Sets for Precipitation and Shortwave Radiation over Mainland China

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Abstract. Precipitation and shortwave radiation play important roles in climatic, hydrological and biogeochemical cycles. Several global and regional forcing data sets currently provide historical estimates of these two variables over China, including the Global Land Data Assimilation System (GLDAS), the China Meteorological Administration (CMA) Land Data Assimilation System (CLDAS) and the China Meteorological Forcing Dataset (CMFD). The CN05.1 precipitation data set, a gridded analysis based on CMA gauge observations, also provides high-resolution historical precipitation data for China. In this study, we present an inter-comparison of precipitation and shortwave radiation data from CN05.1, CMFD, CLDAS and GLDAS during 2008–2014. We also validate all four data sets against independent ground station observations. All four forcing data sets capture the spatial distribution of precipitation over mainland China, although CLDAS indicates small annual-mean precipitation amounts than CN05.1, CMFD, or GLDAS. Time series of precipitation anomalies are largely consistent among the data sets, except for a sudden decrease in CMFD after August 2014. All forcing data indicate greater temporal variations relative to the mean in dry regions than in wet regions. Validation against independent precipitation observations provided by the Ministry of Water Resources (MWR) in the middle and lower reaches of the Yangtze River indicates that CLDAS provides the most realistic estimates of spatiotemporal variability in precipitation in this region. CMFD also performs well with respect to annual mean precipitation, while GLDAS fails to accurately capture much of the spatiotemporal variability and CN05.1 contains significant high biases relative to the MWR observations. Estimates of shortwave radiation from CMFD are largely consistent with station observations, while CLDAS and GLDAS greatly overestimate shortwave radiation. All three forcing data sets capture the key features of the spatial distribution, but estimates from CLDAS and GLDAS are systematically higher than those from CMFD over most of mainland China. Based on our evaluation metrics, CLDAS slightly outperforms GLDAS. CLDAS is also closer than GLDAS to CMFD with respect to temporal variations in shortwave radiation anomalies, with substantial differences among the time series. Differences in temporal variations are especially pronounced south of 34°N. Our findings provide valuable guidance for a variety of stakeholders, including land-surface modellers and data providers.

1 Introduction

Precipitation and shortwave radiation are the fundamental sources of water and energy for land surface biological, physical and chemical processes (Zhao and Zhu 2015; Zhang et al. 2010). These fluxes affect moisture and heat exchange between the atmosphere and the land surface (Pan et al. 2014; Tian et al. 2007; Fekete et al. 2004; Gottschalck et al. 2005), and are key meteorological forcing inputs for studies using land process models, including crop simulation, hydrologic modeling, dryland expansion estimation and analysis of dust events (Bart and Lettenmaier 2004; Tang et al. 2008; Huang et al. 2016; Kang et al. 2016). Accurate estimates of precipitation and shortwave radiation are therefore essential for studies of climate change and land surface processes.

Although conventional station-based measurements can obtain the values of a measured variable with high accuracy and precision, these measurements can only represent information at local scales (Maurer 2002, Bogh et al. 2004), and are unable to adequately depict spatial variations given the limited number and locations of stations (Duan et al 2012). In the late 1980s, data assimilation techniques were proposed as a means of reconstructing historical forcing data at high resolution (Xie et al. 2011, Zhao et al. 2010). This innovation brought unprecedented opportunities for researchers. The resulting forcing data sets, which typically include precipitation, shortwave radiation, temperature, specific humidity, wind speed, surface pressure, and other meteorological data, are derived by assimilating numerical weather forecast information, ground observation data and remote sensing data into an analysis product (Xie et al. 2011, Zhao et al. 2010, Pan et al. 2010). Many forcing data sets are now available, including the National Centers for Environmental Prediction and the National Center for Atmospheric Research reanalysis (NCEP/NCAR; Kalnay et al. 1996), the Global Land Data Assimilation System (GLDAS; Rodell et al. 2004), the European Center for Medium-range Weather Forecasts (ECMWF) Interim Reanalysis (ERA-Interim; Dee et al. 2011), and the Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015), among many others. In recent years, Chinese researchers have made great progress in developing forcing data sets. Through these efforts, two forcing data sets covering China have been produced, namely the China Meteorological Forcing Dataset (CMFD, released by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences, He and Yang, 2011) and the China Meteorological Administration (CMA) Land Data Assimilation System (CLDAS, Shi et al. 2014). Separate efforts have produced new gridded analyses of station-based measurements, including the CN05.1 interpolation of CMA rain gauge data released by the National Climate Center (Wu and Gao 2013). These forcing data sets are widely used because they have high spatial resolution, cover a large area over a long period, and are convenient to obtain and process. For example, CMFD forcing data have been used to simulate permafrost and seasonally-frozen ground conditions on the Tibetan Plateau (Guo and Wang, 2013), to analyse the impacts of precipitation on springtime vegetation phenology (Shen et al. 2015), to model the land-surface water and energy cycles in a mesoscale watershed (Xue et al. 2013), and to assess climatic and human impacts on surface water resources in the middle reaches of the Yellow River (Hu et al. 2015). The CMFD and GLDAS forcing data sets have also been used to improve land-surface temperature modelling for arid regions in China (Chen et al. 2011), while GLDAS has been applied to analyze long-term variations in terrestrial water storage in the Yangtze River basin (Huang et al. 2013) and the recently-released CLDAS

has been adopted in a recent drought monitoring study (Han, 2015). The CN05.1 data set also has been used in many fields, such as simulating climate change over China (Gao et al. 2013) and studying shifts in the western Pacific subtropical high (Huang et al. 2015).

However, forcing data have considerable uncertainties, regardless of whether these data are generated by interpolating ground observations or derived from reanalysis products (Qian et al. 2006). Biases associated with a forcing data set can propagate into model results (Wang et al, 2016), which may in turn be unrealistic if the forcing data are unreliable (Cosgrove et al. 2003). For example, errors in precipitation and shortwave radiation can have profound impacts on simulations of soil moisture, runoff and heat fluxes (Luo et al. 2003). It is therefore necessary to evaluate the accuracy of forcing data sets so that the relevant biases are fully recognized when they are applied in studies of land surface processes (Pan et al. 2014).

Several previous studies have evaluated the forcing data sets examined in this work. Wang et al. (2016) evaluated the performance of CMFD daily precipitation estimates over the Qinghai–Tibetan Plateau from 2009 to 2012 and found systematic overestimates through much of the year (more than 255 days). Wang et al. (2014, 2016) assessed the reliability of GLDAS monthly precipitation data in China from 1979 to 2012 by visual comparison with direct observations, and found that both GLDAS-1 and GLDAS-2 precipitation match the direct observations well. Wang et al. (2011) validated GLDAS-1 daily and monthly precipitation data for a mesoscale basin in northeast China during March 2003 to March 2006, and concluded that both daily and monthly precipitation estimates from GLDAS were of high quality. Wang and Zeng (2012) evaluated six reanalysis products (MERRA, NCEP–NCAR, CFSR, ERA-40, ERA-Interim, and GLDAS-1) against in situ measurements from 63 weather stations on the Tibetan Plateau, and found that GLDAS provided the best overall performance with respect to both daily and monthly precipitation.

Although the quality of GLDAS data has been validated and confirmed by previous studies, these data are not bias-free. In particular, the credibility of GLDAS over continental China in recent years has yet to be assessed. The CN05.1, CMFD and CLDAS data sets have been developed and maintained by Chinese scientists and are supposed to be accurate and reliable because they are more strictly constrained by surface observations. However, no comprehensive evaluation of these forcing data sets has yet been conducted over mainland China. In this study, we present an inter-comparison of precipitation and shortwave radiation products from CN05.1, CMFD, CLDAS and GLDAS, along with an evaluation against available in situ observations. The results of this inter-comparison will assist researchers in selecting and understanding meteorological forcing data, and will also help to guide further innovations and improvements in these data sets.

2 Data

2.1 Forcing data sets

2.1.1 CN05.1

CN05.1 provides precipitation along with daily mean, minimum and maximum temperatures (Wu and Gao 2013). In this paper, we use 0.25°×0.25° gridded monthly precipitation data over mainland China. These data have been interpolated from more than 2000 gauge stations over mainland China. An "anomaly approach" (New et al. 2000) was applied during the interpolation step. As meteorological stations are mainly located in eastern China where the terrain is flatter and the economy is more developed, CN05.1 may have large uncertainties in western China.

2.1.2 CMFD

The CMFD forcing data set was developed by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (He and Yang, 2011). This product covers the region 70°E–140°E and 15°N–55°N, and includes precipitation, downward shortwave radiation, downward longwave radiation, 2-meter air temperature, specific humidity, wind speed and surface pressure. The Tropical Rainfall Measuring Mission (TRMM) 3B42 precipitation product is used as the background field for the precipitation analysis; however, this product provides relative few data north of 40°N and no data north of 50°N. GLDAS precipitation estimates are used as the background state in these regions. Gauge observation data from 740 stations in the CMA network are used to correct systematic departures in the background data. Global Energy and Water cycle Experiment–Surface Radiation Budget (GEWEX–SRB) radiation data are used as the background state for the CMFD shortwave radiation analysis. As with precipitation, GLDAS is used to replace GEWEX–SRB when the latter is unavailable. CMA stations measurements of shortwave radiation (see section 2.2.2) are used to adjust this background state. Additional basic information for these data is listed in table 1

2.1.3 CLDAS

We evaluate version 2.0 of the CLDAS data set. This data set was developed by CMA (Shi et al. 2014) and provides hourly spatial coverage within 60°E–160°E and 0°N–65°N on a 0.0625°×0.0625° grid. The CLDAS dataset includes a variety of land surface forcing data, including precipitation, shortwave radiation, temperature, specific humidity, wind speed and surface pressure, as well as soil status variables. It is a relatively new product, with temporal coverage from 2008 to 2017. Precipitation is combined and interpolated from two products, the Climate Prediction Center Morphing Technique (CMORPH) analysis and an hourly merged precipitation analysis (V1.0) produced by CMA. The latter merges observations made at automatic weather stations in China together with CMORPH analyses using a probability density function (PDF) and optimal interpolation (OI) algorithm (Shen et al. 2014). Shortwave radiation is retrieved from the FY-2C/E series of geostationary meteorological satellites. The Discrete Ordinates Radiative Transfer Program for a Multi-Layered Plane-Parallel Medium (DISORT) method is used for radiation transfer calculations in conducting the retrievals (Shi et al. 2011).

2.2.4 GLDAS

The 0.25°×0.25° monthly GLDAS-1 forcing data (shortened to GLDAS in this paper) is provided by the US National Aeronautics and Space Administration (NASA). Precipitation estimates in this version are based on the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center Merged Analysis of Precipitation (CMAP), which combines satellite data (IR and microwave) with gauge measurements. CMAP estimates are downscaled to higher spatial and temporal resolutions using simulated precipitation fields from the Global Data Assimilation System (GDAS). Cloud and snow products from the Air Force Weather Agency (AFWA) Agricultural Meteorology modeling system (AGRMET) are used to calculate downward shortwave and longwave radiation fluxes via an AFWA-supplied procedure (Rui and Beaudoing, 2017; Rodell et al. 2004).

2.2 Validation data set

2.2.1 MWR precipitation data

We use precipitation observations from a rain gauge network maintained by the Hydrology Bureau in the Ministry of Water Resources (MWR) of China (Xu et al. 2016) as reference data for validating the forcing data sets. In this study, we use precipitation measurements collected from rain gauges located in Hubei, Hunan and Jiangxi provinces during 2014. These MWR-provided precipitation data are independent of the forcing data sets, which use data from surface stations operated by CMA. Data from 5490 stations are suitable for inclusion in this study after quality control procedures. The locations of these stations are shown in figure 1.

2.2.2 Shortwave radiation station data

We use two station-based shortwave radiation data sets to validate the forcing data. The first is an estimated data based on the station data provided by CMA. This data set has some mutual dependence with CMFD, as it estimates radiation fluxes using a hybrid model that is not fully independent of the background data used for CMFD. The second station-based data set is independent of all four forcing data sets. Figure 2 shows the distribution of stations in these two networks, with basic information for these data listed in table 2

1) Station-based shortwave radiation fluxes from CMA

Daily estimates of surface solar radiation through 2010 are provided by the Data Assimilation and Modeling Center for Tibetan Multi-spheres (http://dam.CMFD.ac.cn/). This data set is produced using data from two sources. The first source is a hybrid model (Yang et al. 2001, 2006) based on air temperature, air pressure, relative humidity, and sunshine duration at 716 CMA stations. The other is an ANN-based (Artificial Neural Network) model at 96 radiation stations. Owing to the high accuracy of the ANN-based model, these estimates are used to dynamically correct the hybrid model estimates at monthly time scales. The ANN-based model has been trained using recent observations to estimate historical variations in shortwave

radiation at the 96 radiation stations (Tang et al. 2013). For this validation, we select 625 stations with full data coverage during 2008–2010.

2) Independent station-based shortwave radiation fluxes

① CERN shortwave radiation stations

The Chinese Ecosystem Research Network (CERN) was established in 1988 by the Chinese Academy of Sciences (Su et al. 2005). We use observations of shortwave radiation provided by 35 CERN field stations covering a variety of ecosystems during 2008–2014, including farmlands, forests, grasslands, lakes and coastal regions. As shown in figure 2, these stations are distributed relatively evenly across mainland China and cover a range of climate regimes. The CERN stations are independent of the CMA stations used in CMFD and CLDAS, and therefore provide an ideal reference for validating the estimates of shortwave radiation provided in these three forcing data sets despite their relatively sparse spatial density.

② HiWATER shortwave radiation stations

Observations of shortwave radiation have been collected at eight stations in the Heihe River for the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) campaign (Li et al. 2013). These data have been widely used for land-surface process studies (Liu et al. 2016; Cheng et al. 2014). Among the eight stations, 2–3 sites are distributed in each of the upper, middle and lower reaches of the Heihe River basin.

③ TPE shortwave radiation stations

Daily records of shortwave radiation from the meteorological data sets of the Ngari Desert Observation and Research Station and the Muztagh Ata Station for Westerly Environment Observation and Research are obtained from the Third Pole Environment (TPE) Database (http://www.tpedatabase.cn). These stations along the western border of China, as shown in figure 2, and are used to evaluate the performance of the three forcing data sets over the western Tibetan Plateau where very few CMA ground stations are located.

3 Methodology

We validate estimates of precipitation and shortwave radiation on a variety of spatial and temporal scales. Three metrics are computed from each data set for mainland China: the area-weighted average (Mean), the standard deviation (SD) and the coefficient of variation (CV). The latter two metrics reflect the amplitude of internal variance within the data set. Monthly anomalies are derived by subtracting the seven-year monthly climatology. We then use temporal coefficient of variation (TCV) to compare temporal fluctuations across the forcing data sets. A larger value of TCV indicates greater temporal variability. For further comparisons, CMFD and CLDAS are resampled to match the 0.25°×0.25° grid intrinsic to the CN05.1 and GLDAS data sets using bilinear interpolation. Validation against gauge- and station-based observations is conducted by using a pixel-point method (Chen et al. 2013) to pair station data with the appropriate gridded forcing data. Evaluation metrics used in this pixel-point comparison include the root-mean-square error (RMSE) and bias. Bias reflects the degree to which the forcing data set over- or underestimates the reference data. Taylor diagrams (Taylor 2001) are used

to further describe the correspondence between forcing data and reference data. These diagrams show the ratio of standardized deviations, the correlation coefficient and the unbiased RMSE between the forcing data and the reference observations. These statistics can quantify how well the forcing data resembles the observation. These metrics are formulated as follows:

$$\text{SD} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{1}$$

$$\text{CV} = \frac{SD}{\bar{x}} \tag{2}$$

$$\text{Correlation coefficient} = \frac{\sum_{i=1}^{N}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i-\bar{x})^2 \sum_{i=1}^{N}(y_i-\bar{y})^2}} \tag{3}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(x_i-y_i)^2}{N}} \tag{4}$$

$$\text{Bias} = \sum_{i=1}^{N} x_i - \sum_{i=1}^{N} y_i \tag{5}$$

$$\text{Relative bias} = \frac{\sum_{i=1}^{N} x_i}{\sum_{i=1}^{N} y_i} - 1 \tag{6}$$

$$\text{TCV} = \frac{\sqrt{\frac{1}{m}\sum_{j=1}^{m}(t_j-\bar{t})^2}}{\bar{t}} \tag{7}$$

where x_i is an element of the evaluated data set and $\bar{x}$ is the average value for the evaluated data set; y_i is an element of the reference data set and $\bar{y}$ is the average for the reference data set; N is the number of data points included in the comparison; m is the number of months during 2008 to 2014 with valid data in both data sets; t_j is a gridded monthly value of precipitation or shortwave radiation and $\bar{t}$ is the average of t_j.

4 Evaluation of precipitation data

4.1 Spatial distribution of precipitation

Figure 3 shows the spatial distributions of precipitation based on the four forcing data sets. All four data sets capture the increase in annual mean precipitation from northwest China to southeast China. The distributions of precipitation based on CMFD and CN05.1 are generally similar, although these two data sets still have some mutual discrepancies in western China (e.g. over the Tibetan Plateau). The area for which annual mean precipitation exceeds 1500 mm is smaller in CLDAS and GLDAS than in CN05.1 and CMFD, and precipitation over northern China is considerably smaller in CLDAS than in the other three data sets. As shown in table 3, mean precipitation over China is significantly lower in CLDAS, while CMFD has the largest mean value. The spatial SD and CV are more similar among the four data sets.

4.2 Temporal variations in precipitation

Figure 4 shows time series of monthly mean precipitation anomalies averaged over mainland China based on the four forcing data sets. The four data sets match each other well through most of the evaluation period, indicating that these forcing data sets generally reproduce inter-annual and decadal variability in mean precipitation averaged over mainland China. Notably,
5   mean precipitation anomalies based on CMFD are lower than those based on the other data sets after August 2014. Figure 5 shows the spatial distribution of the TCV, which represents the temporal standard deviation normalized by the mean value in each grid cell during the seven-year analysis period. The spatial distribution of TCV in southeast China is similar among the four data sets, with small values through most of this region. The four data sets also show similar distributions of normalized variance in northern China, where inter-annual variability is much stronger. Values of TCV are generally similar between
10 CMFD and CN05.1, while CLDAS and GLDAS indicate greater variance in most areas of northern China, especially in dry regions (Xinjiang, Gansu and Inner Mongolia) where TCV values may exceed 1.5. The area in which TCV exceeds 1.0 is larger in CLDAS than in the other three forcing data sets. Likewise, the mean value of TCV averaged over mainland China is largest in CLDAS.

4.3 Comparison with MWR station data

15 Comparison of the spatial distributions of precipitation based on the four forcing data sets reveals evident differences among these data sets in the middle and lower reaches of the Yangtze River (red polygon in figure 3). We therefore use independent MWR gauge-based observation data to further evaluate the forcing data sets in this region. As shown in figure 6, annual mean estimates of precipitation based on CMFD and CLDAS are more consistent with the MWR observations according to the RMSE and bias metrics. Comparison of MWR data with GLDAS and CN05.1 precipitation estimates shows values of
20 RMSE that are about twice as large as that for CLDAS. For GLDAS, the large RMSE appears to result primarily from a poor representation of the spatial variability in this region, as indicated by greater dispersion in the scatter plot. For CN05.1, the large RMSE results instead from a systematic high bias in annual mean precipitation throughout Hubei, Hunan and Jiangxi provinces. Monthly variations in bias and RMSE for these four data sets during 2014 are listed in table 4. Based on these metrics, CLDAS provided the most accurate estimates of precipitation in this region during most months of 2014. A Taylor
25 diagram based on these data (figure 7) confirms that CLDAS performed well during this year, as the orange points representing CLDAS are concentrated together in a region with correlation coefficients between 0.6 and 0.9 and normalized variance close to 1, indicating low values of unbiased RMSE. These results indicate that monthly precipitation based on CLDAS is stable and reliable in this region. The performance of the other three data sets varies greatly from month to month, with particularly wide spreads for CMFD and CN05.1.

5 Evaluation of shortwave radiation data

5.1 Comparison against ground measurements

We compare the forcing data sets against station observations to evaluate their ability to reproduce the ground observations (figure 8). The CMFD data set compares well with station observations from CMA (figure 8a), while CLDAS (figure 8d)

5   and GLDAS (figure 8g) are biased high relative to the station observations at about 96% of the validation points. This conclusion is supported by a Taylor diagram based on these data (figure 9), which shows that CMFD is highly correlated with a similar variance and an extremely small unbiased RMSE relative to the CMA stations. Based on the same metrics, CLDAS performs slightly better than GLDAS in reproducing observed shortwave radiation fluxes. Although these results strongly suggest that estimates of shortwave radiation from CMFD are more realistic than those from CLDAS or GLDAS,

10   their significance is called into question by the cross-dependence between these site observations and the CMFD shortwave radiation product (section 2.2.2). To account for this problem, we also use station observations from CERN that are completely independent of all three forcing data sets. The results of this comparison are similar to those of the previous comparison. Shortwave radiation products from CMFD (figure 8b) coincide well with the observations, while most shortwave radiation products from CLDAS (figure 8e) and GLDAS (figure 8h) generally overestimate the observed fluxes.

15   Figure 9 likewise indicates that CMFD outperforms CLDAS and GLDAS with respect to spatiotemporal variability in these areas, while CLDAS outperforms GLDAS.

As the CMA and CERN observation stations are relatively sparsely distributed in western China, we also validate the forcing data sets against observations of shortwave radiation at eight observation stations in the Heihe River basin and two observation stations in western Tibetan Plateau. CMFD (figure 8c) again provides the closest match with the in situ

20   observations, while CLDAS (figure 8f) and GLDAS (figure 8i) again overestimate the observed fluxes. The Taylor diagram (figure 9) indicates that the three forcing data sets reproduce the spatiotemporal variability at these locations comparably well, although CLDAS produces a slightly smaller unbiased RMSE than the other two data sets and GLDAS shows the worst agreement with the observed values in all three metrics (correlation, normalized variance, and unbiased RMSE). The RMSE and relative bias in the mean values at the station locations are substantially larger for CLDAS and GLDAS than for CMFD,

25   but GLDAS produces the largest linear correlation coefficient between mean values at the station locations. These results are consistent with those of previous studies. Wang et al. (2011) showed that GLDAS estimates of shortwave radiation at the Changchun, Shenyang and Yanji stations in China were consistently too large during 2000–2006, while Qi et al. (2015) reported that GLDAS systematically overestimated surface shortwave radiation fluxes in the Biliu Basin (in the coastal region of northern China) from March 2000 to December 2007.

5.2 Spatial distribution of shortwave radiation

As discussed in the previous section, the shortwave radiation fluxes provided by CMFD correspond well with station-based observations. We therefore use CMFD as a reference data set to evaluate the broader performance of CLDAS and GLDAS within mainland China.

As shown in figure 10, the spatial distributions of shortwave radiation fluxes based on the three forcing data sets have several common characteristics. Surface shortwave radiation is consistently larger in western China is higher than in eastern China, with the largest shortwave radiation fluxes located over the Tibetan Plateau and relatively small shortwave radiation fluxes in northeastern China. Based on CMFD (figure 10a), the regions where surface shortwave radiation exceeds 200 W m^{-2} are limited to seven provinces: Xinjiang, Inner Mongolia, Qinghai, Tibet, Sichuan and Yunnan. Except for Tibet and Qinghai, these areas are relatively small. By contrast, both CLDAS and GLDAS indicate that the areas where shortwave radiation exceeds 200 W m^{-2} extend into northern China, and particularly Hebei and Shandong provinces. In GLDAS, fluxes exceeding 200 W m^{-2} even appear in southeastern China. Area-mean fluxes based on CLDAS and GLDAS are likewise larger than those based on CMFD, although the latter contains more spatial heterogeneity as indicated by larger values of SD and CV (table 5).

Spatial distributions of the differences among the forcing data sets are shown in figure 11. Surface shortwave radiation fluxes based on CLDAS and GLDAS are much larger than those based on CMFD over most parts of China. Positive differences between CLDAS and CMFD cover more than 95% of the area of mainland China, with particularly pronounced estimates in some areas of Xinjiang province and the area bounded by 24°N–44°N and 105°E–120°E. Estimates of surface shortwave radiation from GLDAS are also significantly higher than those from CMFD except for over the Tibetan Plateau. The statistical metrics listed in table 5 show similar absolute values for the average difference, RMSE and relative bias, although the differences between CLDAS and CMFD are slightly less than those between GLDAS and CMFD for all three metrics. Correlation coefficients between the three forcing data sets are consistently around 0.9. Overall, CLDAS and GLDAS are similar, with overestimates relative to CMFD in most regions of mainland China.

5.3 Temporal variations in shortwave radiation

Figure 12 shows time series of shortwave radiation anomalies averaged over mainland China. CMFD and CLDAS generally match each other well, particularly during the middle part of the record, but with different amplitudes of month-to-month variations. GLDAS indicates the largest fluctuations relative to the mean annual cycle among these three data sets. The absolute difference between GLDAS and CMFD exceeds that between CLDAS and CMFD in 52 of 84 months. CLDAS consistently shows positive anomalies after year 2013 and primarily shows negative anomalies before January 2011. These changes suggest a potential drift relative to the climatological annual cycle during the analysis period. No such drift is evident in CMFD. Mean shortwave radiation from GLDAS was also consistently larger than its climatological annual cycle through most of 2012–2014. Table 6 summarizes the temporal variations in shortwave radiation based on CLDAS and

GLDAS relative to CMFD. The two data sets perform comparably with respect to CMFD based on these summary statistics, with CLDAS showing slightly smaller values of RMSE and bias and GLDAS showing a slightly higher correlation relative to CMFD.

The spatial pattern of TCV for shortwave radiation of the three forcing data sets have some common characteristics, the highest TCV appears in northwest and northeast China while the smallest TCV can be found in southwest China. For the south of 34°N, the TCV of CLDAS is lower than 0.25 while CMFD is higher than 0.25 in the southeast. In addition, the estimation of TCV in CMFD and GLDAS has an obviously higher value in the vicinity of Sichuan province and Chongqing province than the surrounding areas. The TCV of the three data sets are similar to each other north of 34°N and the difference mainly lies in the south of China. The characteristics mentioned above are shown in figure 13.

6 Discussion

Although these forcing data sets have many characteristics in common and can accurately reflect the broad features of precipitation and shortwave radiation over mainland China, our analysis identifies many important differences. These differences arise from multiple factors, including different resolutions, different underlying data and different algorithms for combining those data.

We have compared the spatial distributions of precipitation in the forcing data sets and evaluated their quality in the middle and lower reaches of the Yangtze River. CLDAS performs better at both annual and monthly time scales because it merges observations from more than 30 000 stations, which has substantial benefits for the quality of the analysis. CMFD is able to reproduce annual mean values, but is less realistic at monthly scales. The sharp decrease in the CMFD precipitation analysis after August 2014 is particularly surprising. Relative to CN05.1 and CLDAS, CMFD used fewer precipitation observations from a smaller selection of stations, which may influence the quality of its analysis in 2014. GLDAS is a global data set. The accuracy of this data set in mainland China may thus be limited by a dearth of assimilated observations in China. Although both CMFD and GLDAS use remote sensing data as the initial background state, they differ considerably due to differences in both the satellite data and the station data they use. CN05.1 was constructed solely from station data based on a mathematical interpolation. It is therefore reasonable that CN05.1 does not perform as well as the other forcing data sets in regions where stations are sparse.

With respect to shortwave radiation, we find that CMFD significantly outperforms CLDAS and GLDAS. Only about 100 sparsely distributed radiation stations have been deployed in China since 1961, and the radiation observations reported by these stations are often unusable due to erroneous values or missing data (Shi et al. 2008). The observations of surface solar radiation available for merging into CLDAS and GLDAS are therefore limited. By contrast, CMFD assimilated a 50-year reconstruction of daily surface solar radiation at 716 CMA stations (section 2.1.2). Although these data are based on model outputs, they have been widely validated and show good performance throughout China. The shortwave radiation products provided by CMFD are therefore in better agreement with direct observations.

7 Conclusions

In recent years, an increasing number of forcing data sets have been developed to support climatological, agricultural and hydrological research. In this study, we have presented an inter-comparison and evaluation of precipitation and shortwave radiation products from the CN05.1, CMFD, CLDAS and GLDAS forcing data sets over mainland China. The results provide useful guidance to the users and producers of these data sets.

For precipitation, all four forcing data sets show similar spatial distributions, with a positive gradient in precipitation from northwestern China to southeastern China. Precipitation estimates from CLDAS are systematically smaller than those from the other data sets in most areas of mainland China. The temporal variability of monthly-mean precipitation anomalies is generally consistent among the four forcing data sets, except for a sudden decrease in CMFD precipitation after August 2014. The spatial distribution of temporal variability (as represented by TCV) is inversely related to the spatial distribution of precipitation amount, with larger variability in dry regions than in wet regions. Variability is also larger in CLDAS than in the other data sets, as is the area where TCV exceeds 1.0. We have validated the forcing data sets against independent rain gauge observations provided by MWR for the middle and lower reaches of the Yangtze River valley during 2014. Based on this validation, CLDAS provides the best performance at both annual and monthly time scales with the lowest RMSE and highest correlation coefficient among the four forcing data sets. CMFD provides good estimates of annual mean precipitation at the MWR stations, but this agreement is considerably reduced at monthly time scales. CN05.1 greatly overestimates precipitation in this region relative to the MWR observations.

For shortwave radiation, comparisons against ground-based observations show that both CLDAS and GLDAS substantially overestimate shortwave radiation. These data also have much higher RMSEs and biases relative to direct observations, and relatively low correlation coefficients. CLDAS slightly outperforms GLDAS; however, CMFD significantly outperforms both with respect to the validation data. All forcing data sets capture the key features of the spatial distribution of shortwave radiation, with higher values in western China than eastern China and the largest values centred over the Tibetan Plateau. The spatial characteristics of CLDAS and GLDAS are especially similar, with both data sets indicating much larger shortwave fluxes than CMFD in most parts of mainland China. Differences between CLDAS and CMFD are generally smaller than those between GLDAS and CMFD. Time series of anomalies in area-mean shortwave radiation averaged over China show large fluctuations in GLDAS and a gradual drift in CLDAS. Estimates from CMFD are more stable. Temporal variability in the three forcing data sets is more similar north of 34°N, with larger differences in the south. All three data sets indicate that shortwave radiation is more variable over northern China than over southern China.

In summary, none of these data sets clearly outperforms the others with respect to both precipitation and shortwave radiation. CLDAS, which has the highest spatial and temporal resolution, appears to provide the most realistic estimates of precipitation. However, this data set also considerably overestimates shortwave radiation. CMFD is also available at high resolution, and its estimates of shortwave radiation data match well with station-based observations. Its estimates of annual mean precipitation are also reliable, but this reliability at annual time scales masks relatively large errors in monthly

precipitation. GLDAS estimates of both precipitation and shortwave radiation over mainland China have considerable room for improvement, as do CN05.1 estimates of precipitation, particularly in regions where station data are sparse. These products are widely used and continually being developed and improved. Our results will help researchers to make more informed decisions when selecting data, contribute to uncertainty quantification, and provide guidelines that can help data providers to improve these data sets and others like them. Our results also highlight the large uncertainties that remain in currently-available forcing data, especially in western China where the density of ground stations is low. There is a great need to improve the quality of forcing data in this region.

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Table 1. Basic information of the forcing data sets and the MWR precipitation data used to validate them.

Name	Type	Analyzed period	Available period	Variables	Spatial resolution	Number of sites
CN05.1	forcing data set	2008-2014	1961-2014	precipitation	0.25°	
CMFD	forcing data set	2008-2014	1979-2016	precipitation; shortwave radiation	0.1°	
CLDAS	forcing data set	2008-2014	2008-2016	precipitation; shortwave radiation	0.0625°	
GLDAS	forcing data set	2008-2014	2000-2016	precipitation; shortwave radiation	0.25°	
MWR	Observation data	2014	2014	precipitation		5490

Table 2. Basic information for shortwave radiation observation data used to validate the forcing data sets.

Name	Type	Analyzed period	Available period	Variables	Spatial resolution	Number of sites
CMA	observation data	2008-2010	Different at each site	shortwave radiation		625
CERN	observation data	2008-2014	Different at each site	shortwave radiation		35
HiWATER	observation data	Different at each site	Different at each site	shortwave radiation		8
TPE Database	observation data	Different at each site	Different at each site	shortwave radiation		2

Table 3. Statistical metrics summarizing the spatial average and variability of annual mean precipitation during 2008–2014.

Metrics	CN05.1	CMFD	CLDAS	GLDAS
Mean(mm yr^{-1})	612.09	637.65	508.58	609.44
SD(mm yr^{-1})	497.61	511.09	429.50	506.55
CV	0.81	0.80	0.84	0.83

Table 4. Statistical metrics summarizing the performance of monthly precipitation estimates based on forcing data sets in 2014 relative to MWR rain gauge observations (unit: mm mo^{-1} for monthly data and mm yr^{-1} for annual data).

Time	Bias				RMSE			
	CN05.1	CMFD	CLDAS	GLDAS	CN05.1	CMFD	CLDAS	GLDAS
Jan.	23.62	2.37	-1.85	-0.48	29.53	19.70	8.90	8.26
Feb.	48.04	31.53	4.74	20.43	59.13	59.87	26.19	37.15
Mar.	61.37	14.81	-9.26	12.50	77.02	37.54	36.43	59.47
Apr.	62.83	17.93	-8.47	12.39	79.06	47.63	35.86	67.15
May	66.23	24.72	13.32	39.51	93.05	66.51	52.63	105.35
June	40.11	23.59	0.49	19.48	74.53	67.77	50.06	87.73
July	18.68	7.38	-0.24	1.04	67.86	78.26	59.45	92.06
Aug.	22.37	-53.29	3.57	11.01	62.51	78.93	47.46	74.30
Sept.	4.58	-21.18	-8.57	1.74	36.81	45.66	32.35	44.09
Oct.	26.07	-17.59	5.56	8.72	37.11	38.95	27.76	32.35
Nov.	26.73	-21.04	-2.91	14.36	37.71	34.76	25.95	40.79
Dec.	8.99	-5.43	-4.33	-1.65	14.90	16.97	9.40	10.84
Annual	421.38	3.80	-7.93	139.06	403.16	273.68	234.39	427.71

Table 5. Statistical metrics describing the spatial average and variability of annual mean shortwave radiation during 2008–2014, along with the average difference, RMSE, bias and correlation coefficient relative to CMFD.

Metrics	CMFD	CLDAS	GLDAS
Mean(W m^{-2})	178.60	202.26	203.13
SD(W m^{-2})	31.13	28.82	20.99
CV	0.17	0.14	0.10
Average difference (W m^{-2})	--	23.72	24.57
RMSE(W m^{-2})	--	27.55	28.61
Relative bias	--	0.14	0.15
Correlation coefficient	--	0.89	0.92

Table 6. Statistical metrics for monthly-mean shortwave radiation anomalies among forcing data sets during 2008–2014.

Metrics	CLDAS-CMFD	GLDAS-CMFD
RMSE(W m^{-2})	5.14	5.79
Relative bias	1.14	1.66
Correlation coefficient	0.50	0.62

RMSE(W m^{-2})   5.14   5.79
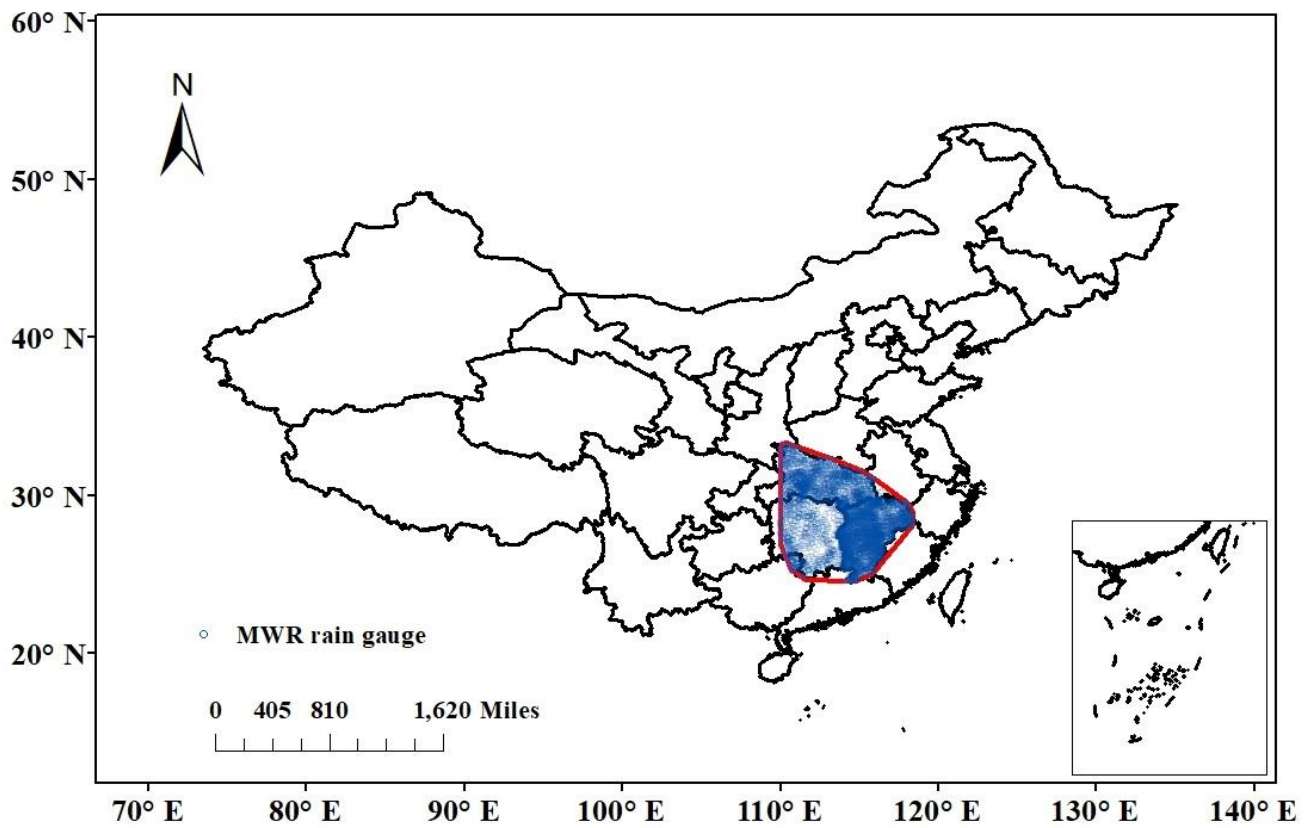
Figure 1: Locations of rain gauges operated by the Ministry of Water Resources of China, used as an independent source of precipitation data for validating the forcing data sets.
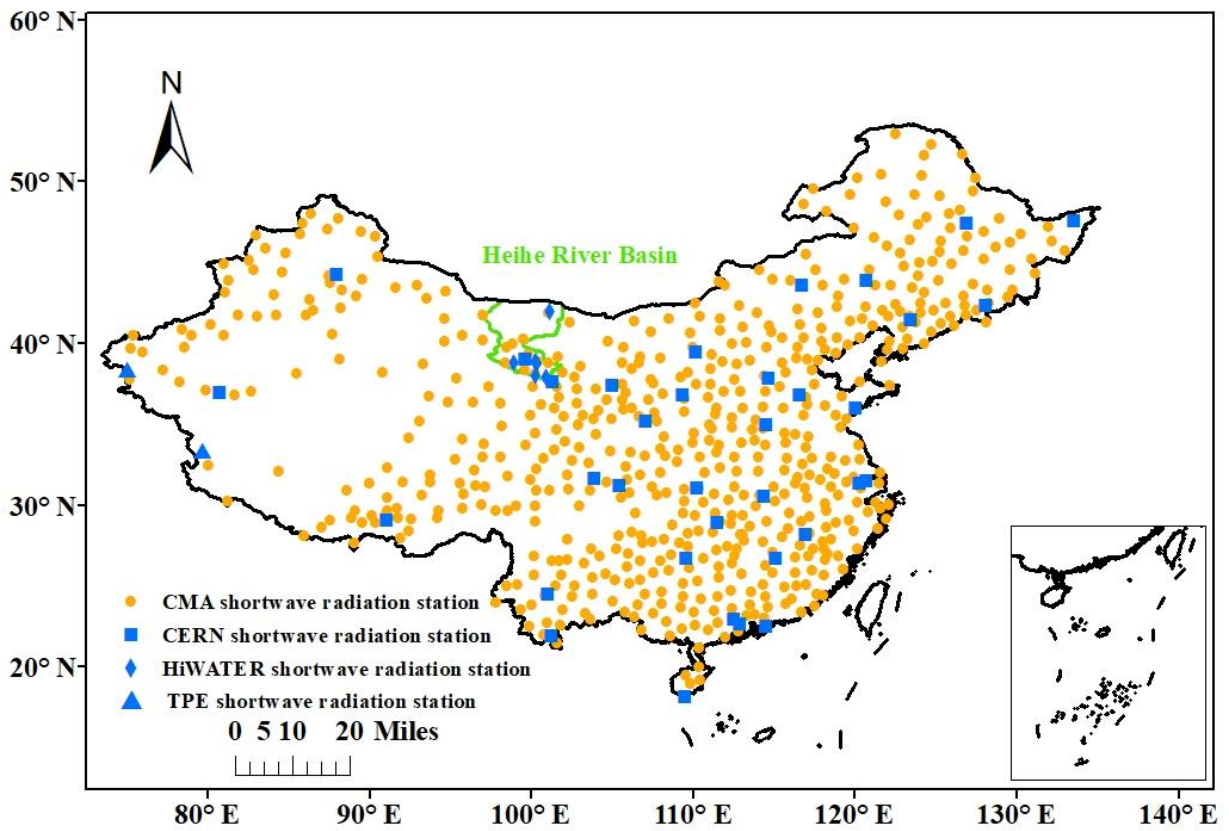
Figure 2: Locations of shortwave radiation stations in mainland China used to validate the forcing data sets.
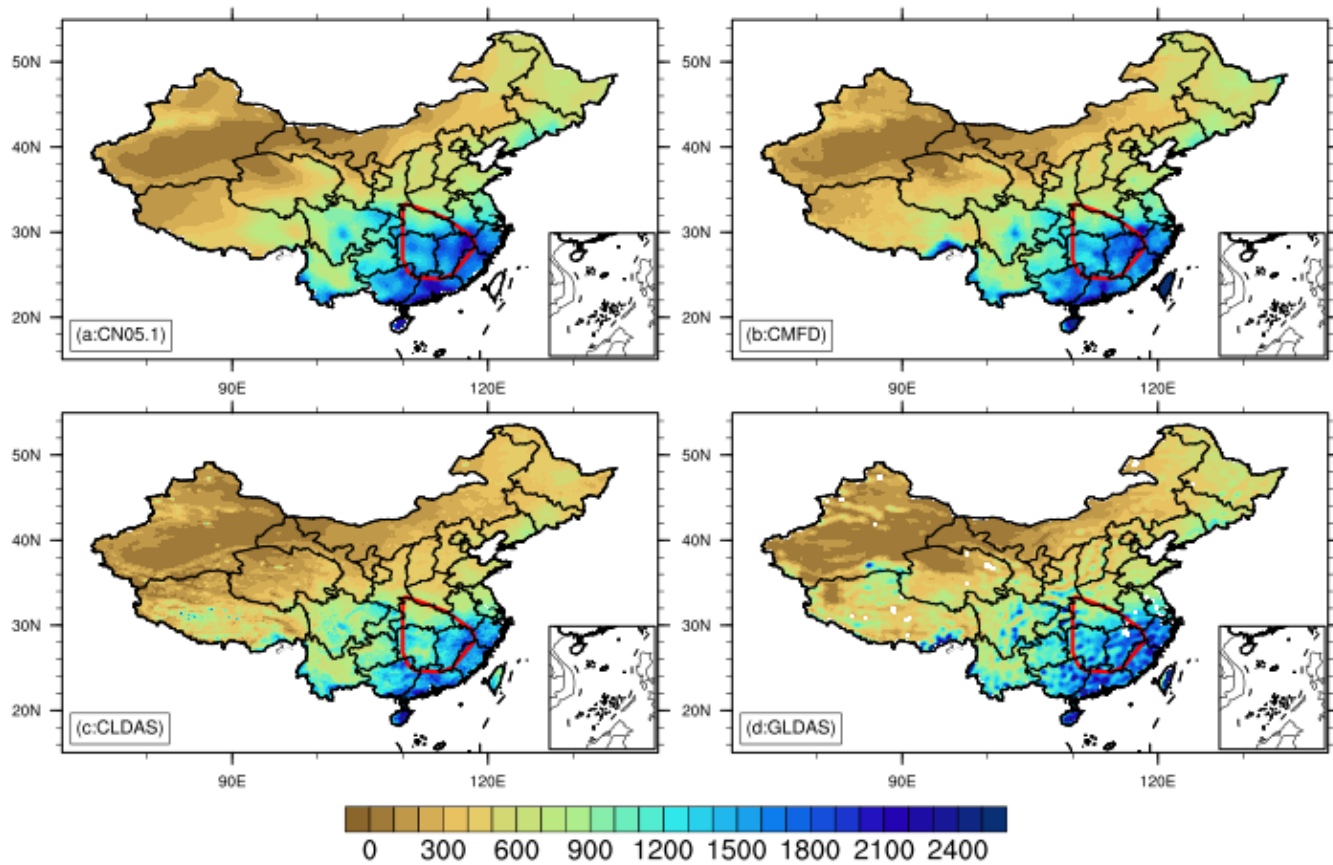
Figure 3: Spatial distributions of annual-mean precipitation over 2008–2014 (unit: mm yr-1) **from (a) CN05.1, (b) CMFD, (c) CLDAS, and (d) GLDAS.**
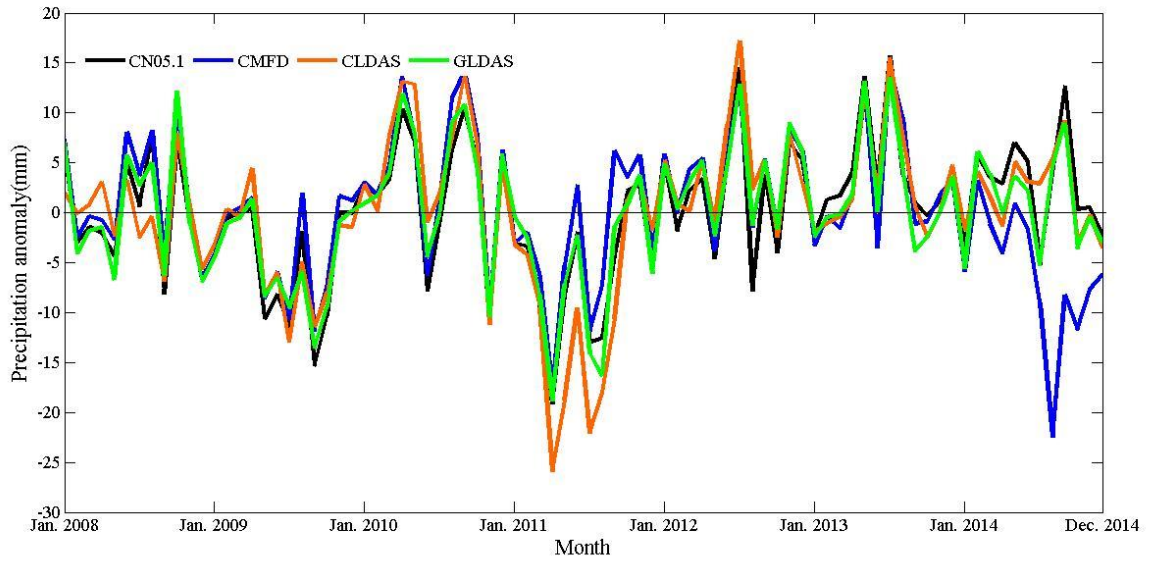
Figure 4: **Time series of monthly-mean precipitation anomalies from CN05.1 (black), CMFD (blue), CLDAS (orange) and GLDAS (green).**
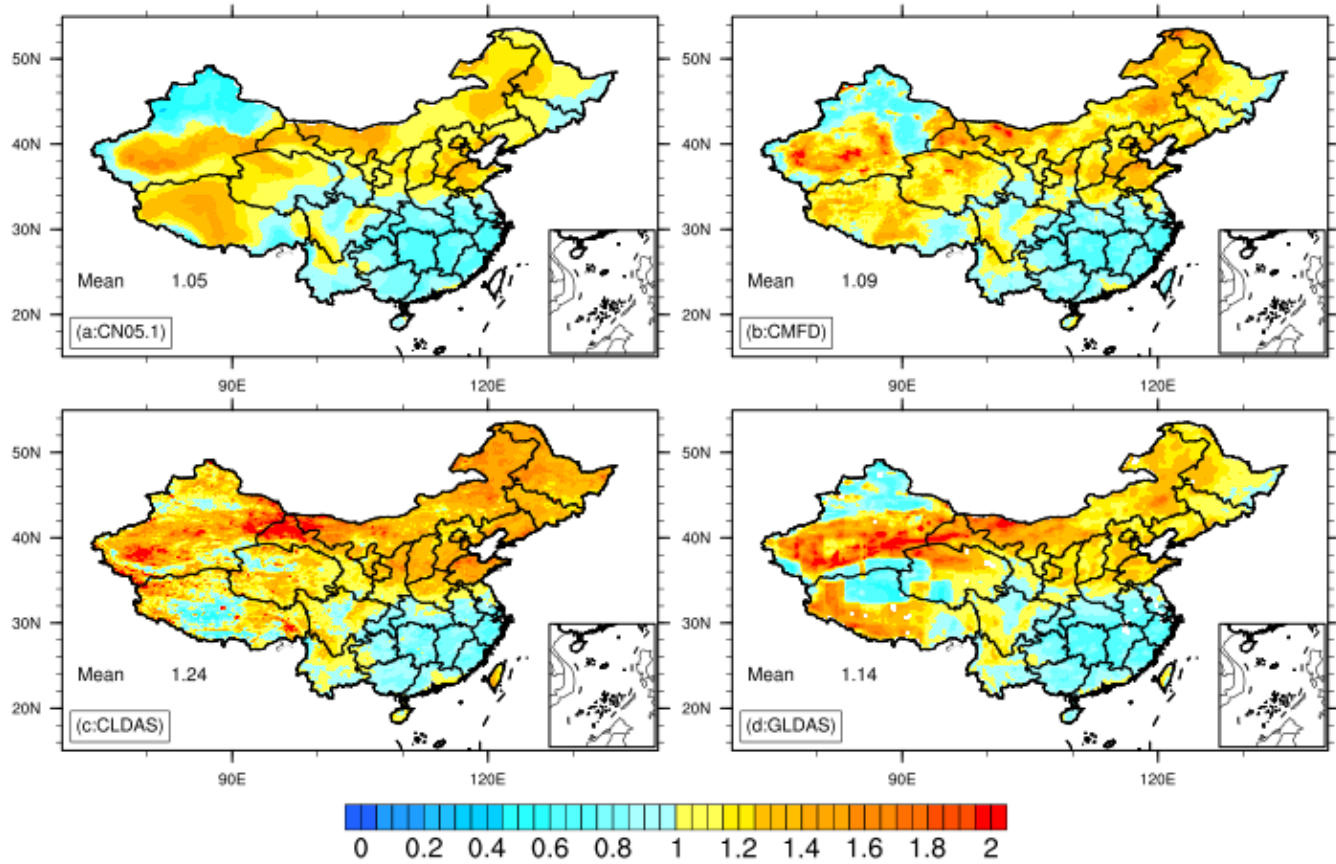
Figure 5: Distribution of TCV for precipitation products from (a) CN05.1, (b) CMFD, (c) CLDAS, and (d) GLDAS during 2008–2014.
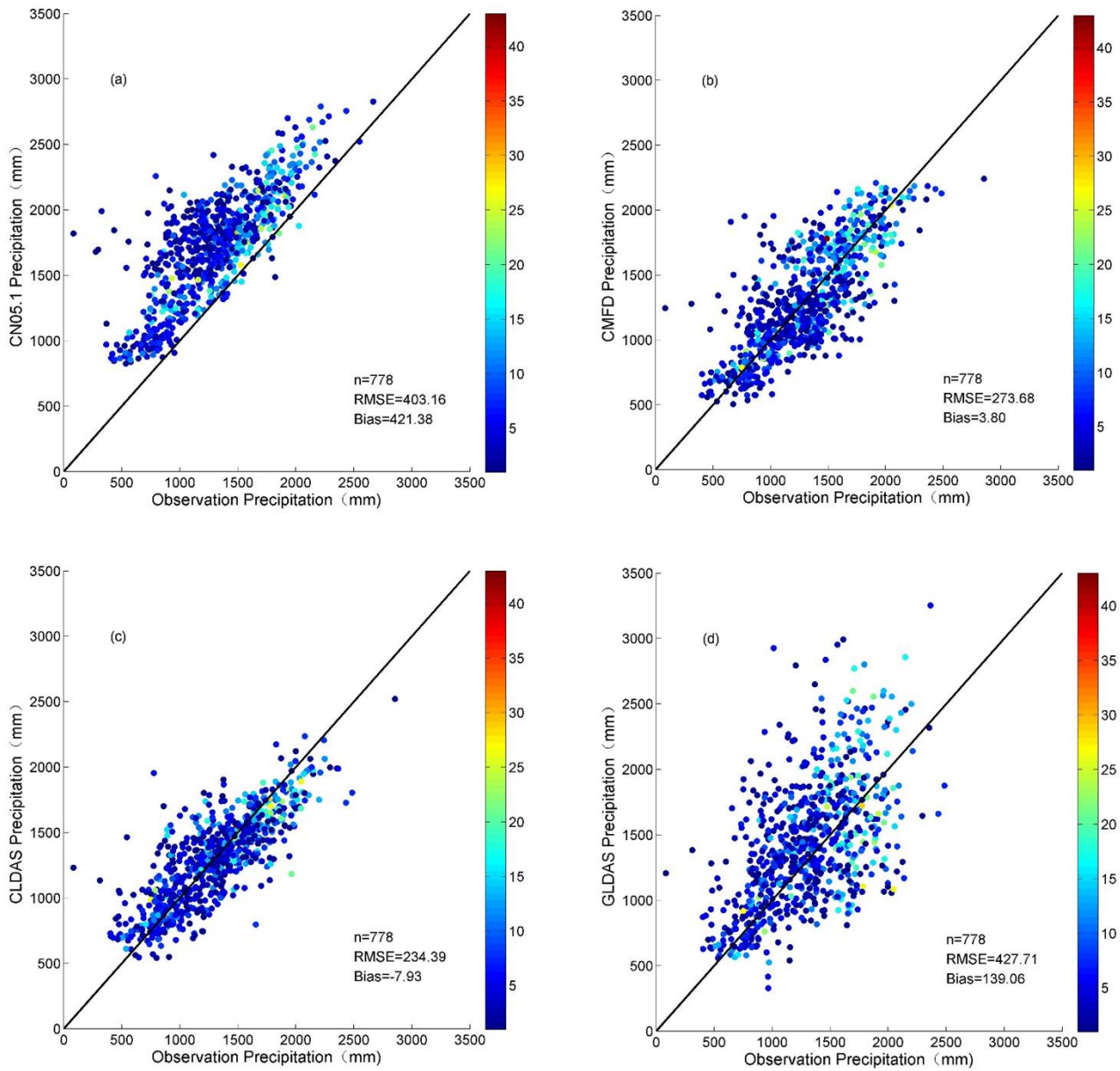
Figure 6: Comparison of the precipitation from (a) CN05.1, (b) CMFD, (c) CLDAS, and (d) GLDAS against mutually-independent rain gauge observations from MWR. The color bar on the right indicates the number of MWR rain gauges in the corresponding 0.25°×0.25° grid cell.
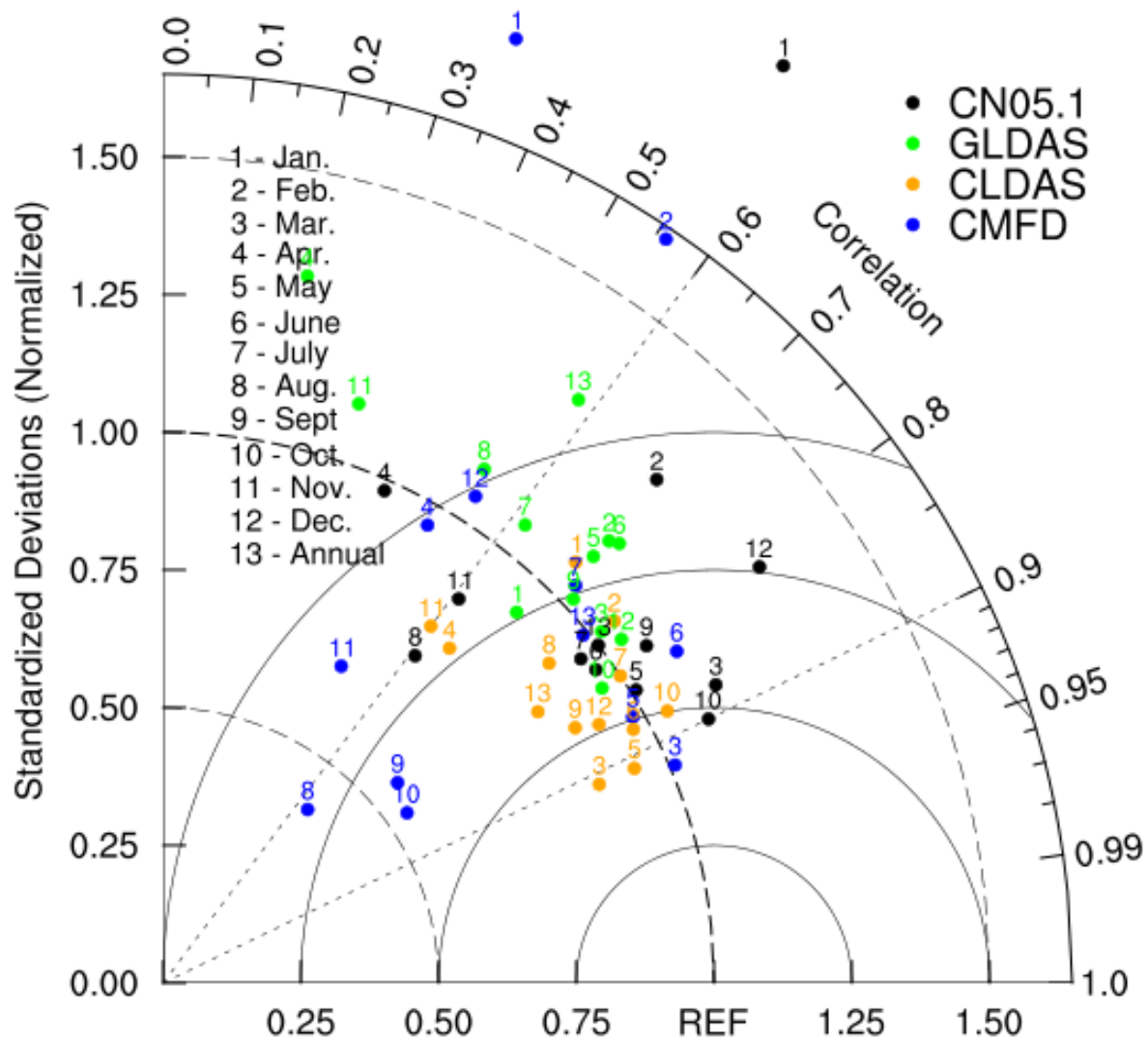
Figure 7: Taylor diagram summarizing the performance of monthly and annual mean precipitation from CN05.1 (black), CMFD (blue), CLDAS (orange), and GLDAS (green) relative to mutually-independent rain gauge observations from MWR.
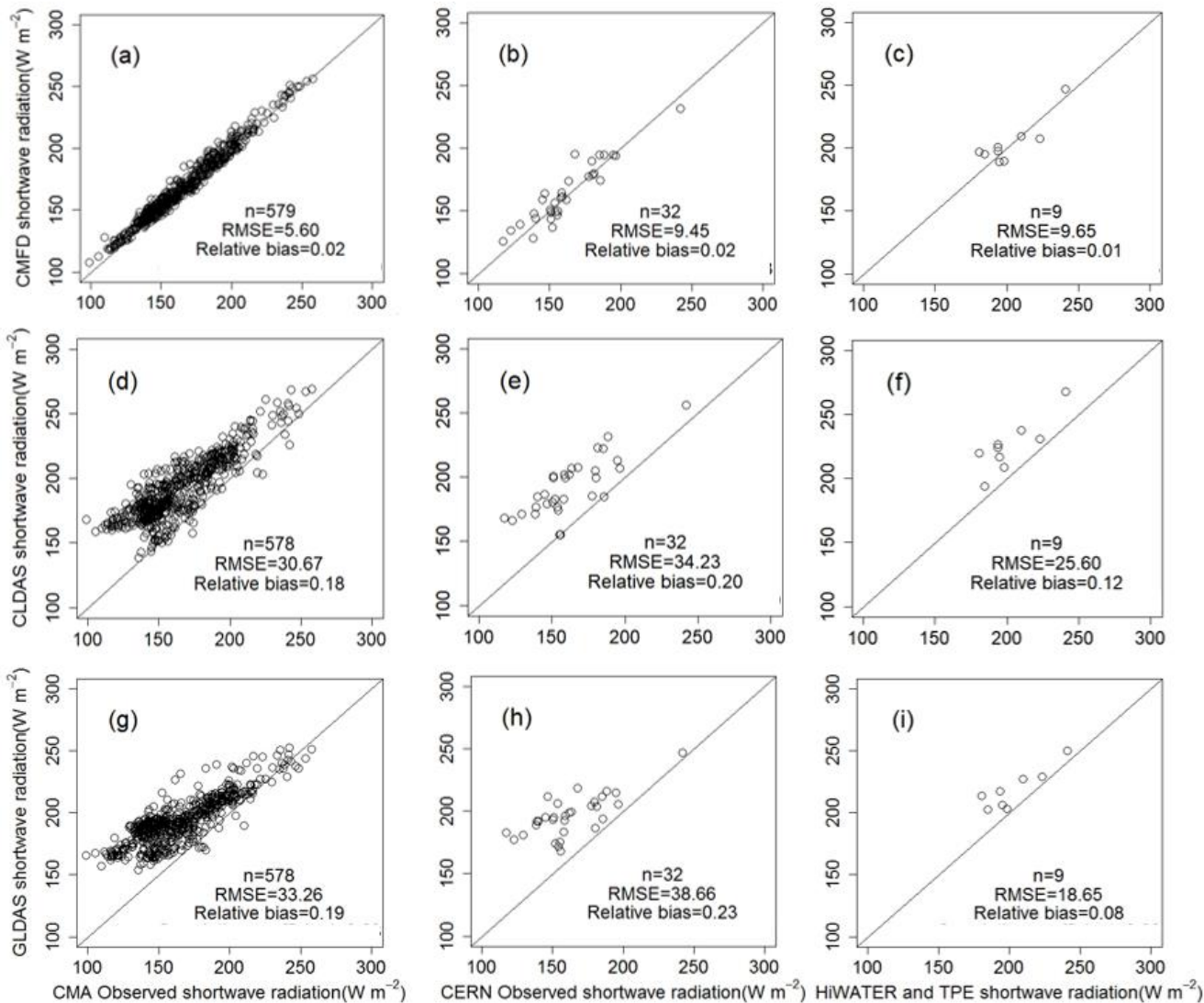
Figure 8: Relationships between shortwave radiation from forcing data and shortwave radiation based on station observations.
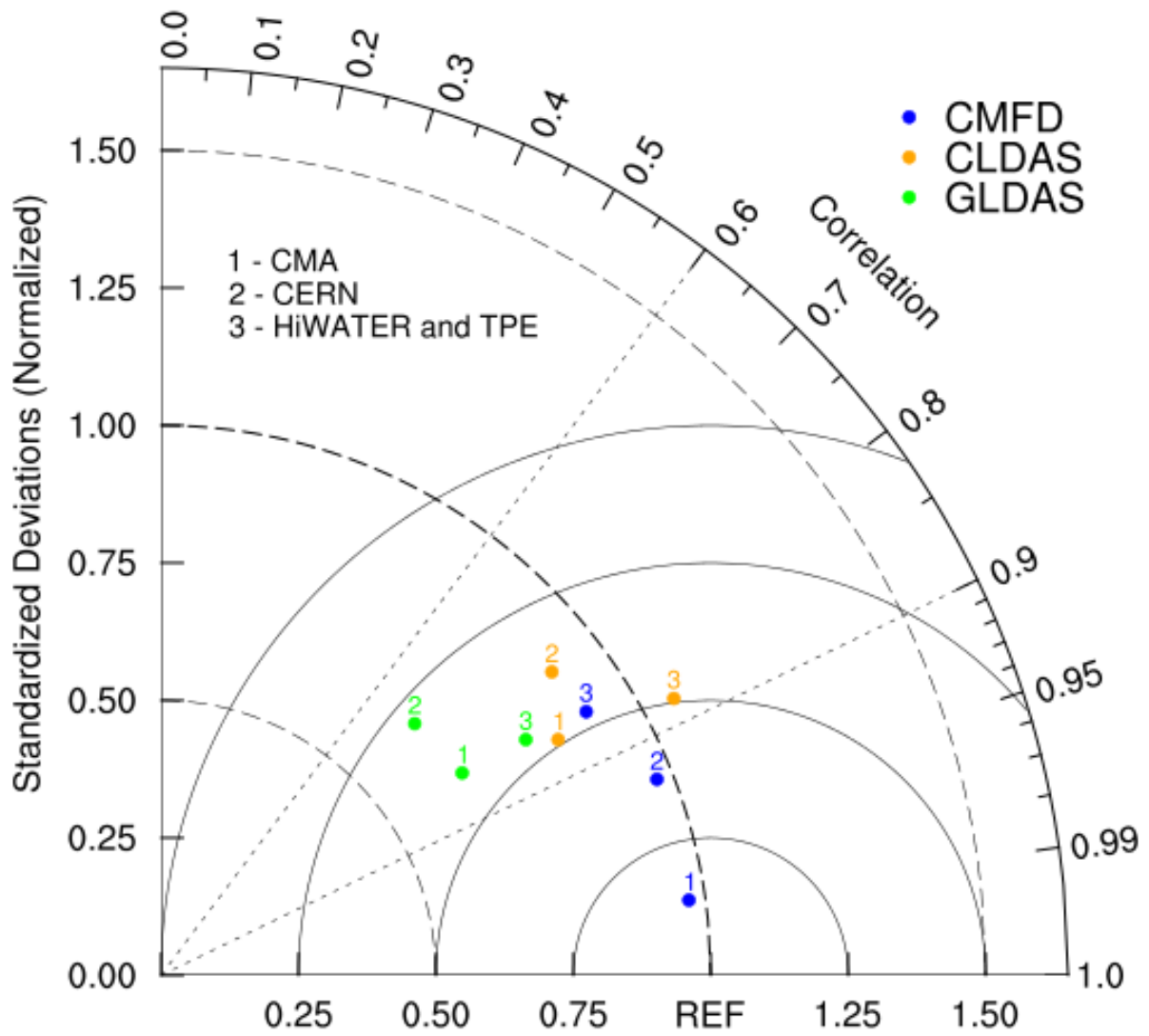
Figure 9: Taylor diagram summarizing the performance of shortwave radiation estimates from CMFD (blue), CLDAS (orange), and GLDAS (green) relative to station observations.
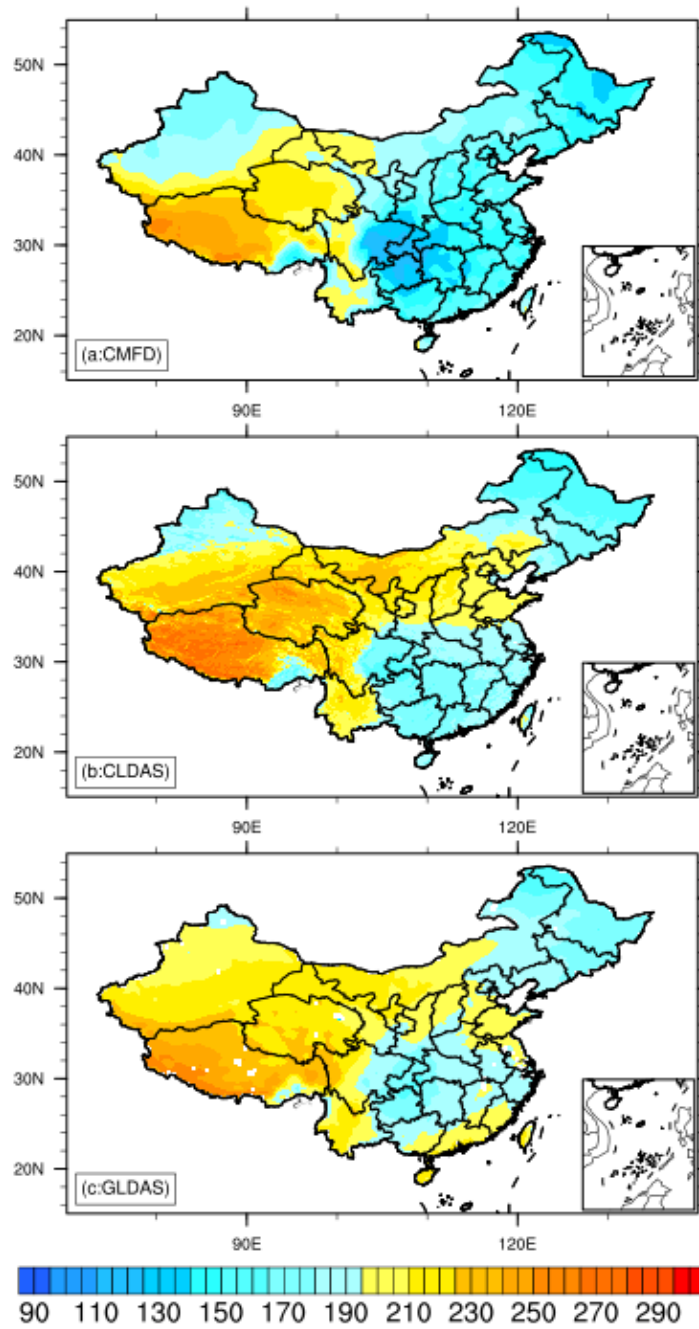
Figure 10: Spatial distributions of annual-mean shortwave radiation based on the three forcing data sets over 2008–2014 (unit: W m^{-2}).
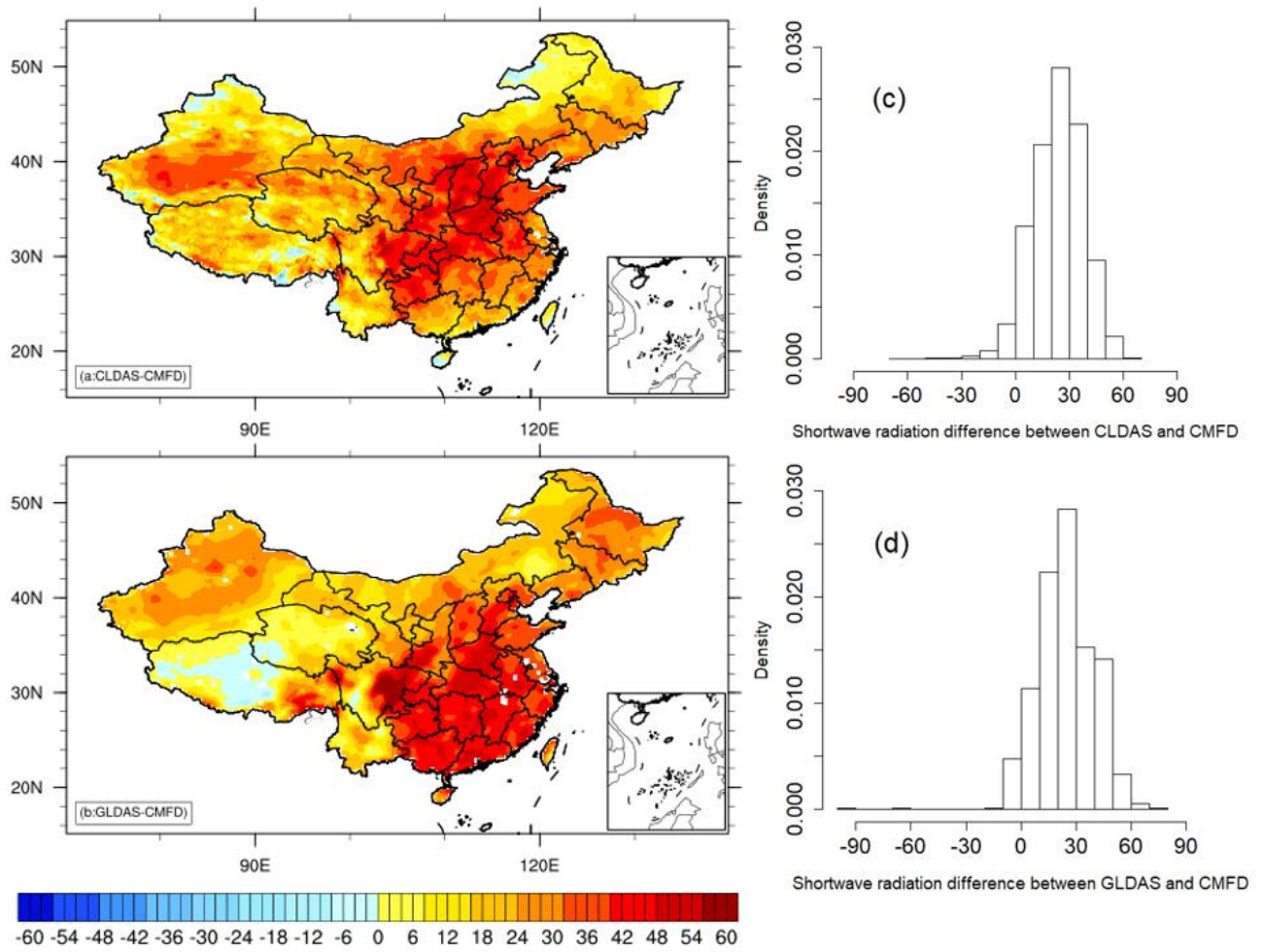
Figure 11: Spatial distributions of differences in mean shortwave radiation between (a) CLDAS and CMFD and (b) GLDAS and CMFD. The corresponding histograms are shown in (c) for CLDAS–CMFD and (d) for GLDAS–CMFD.
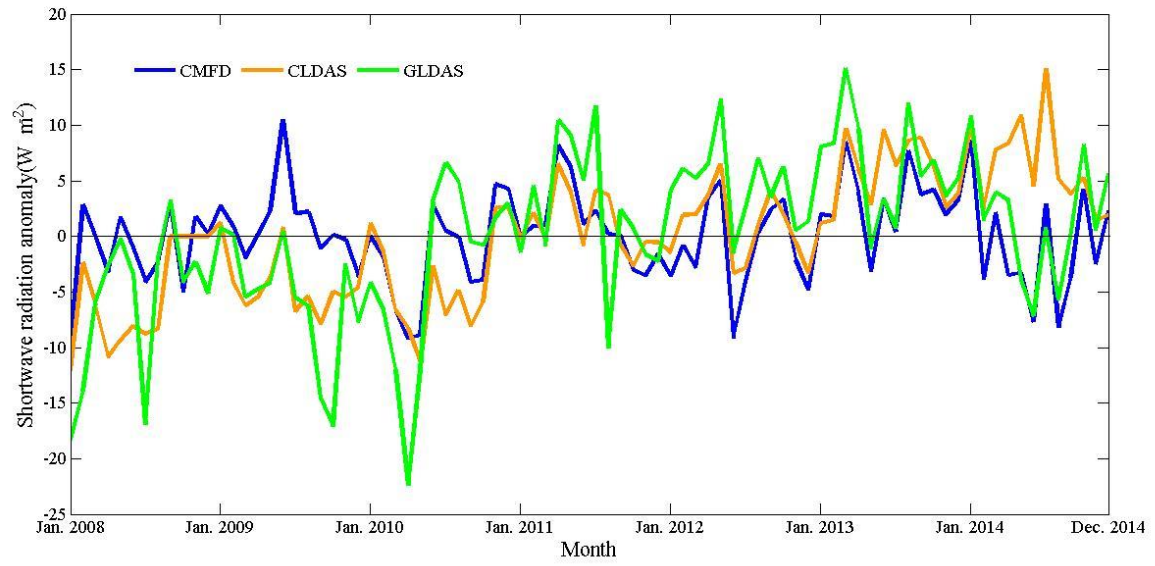
Figure 12: **Time series of monthly mean shortwave radiation anomalies relative to the mean annual cycle from CMFD (blue), CLDAS (orange) and GLDAS (green) (unit: W m⁻²).**
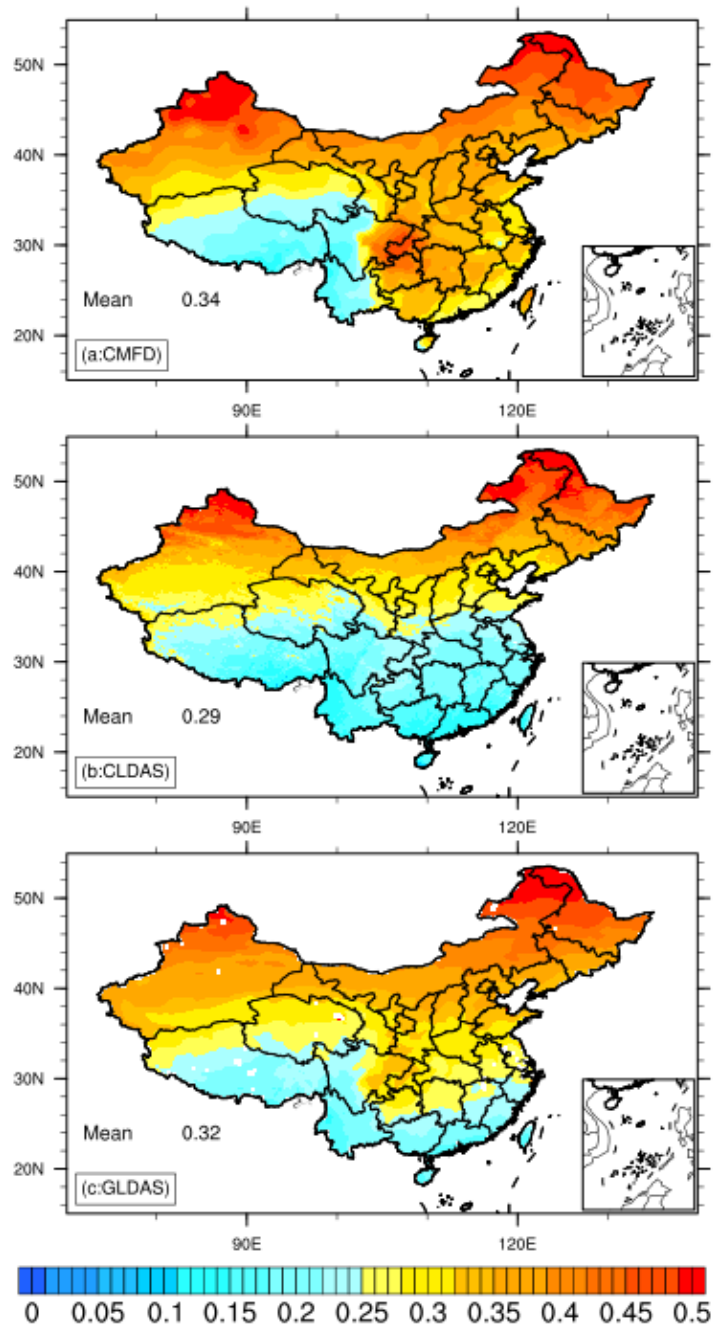
Figure 13: Spatial distributions of TCV for shortwave radiation products from the three forcing data sets.