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Performance of Kilometer-Scale CARAS Precipitation Product Against Ground-based Observations During 2008–2021 over Hubei, China

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Abstract: Based on rain gauge data during 2008–2021 from national meteorological observation stations, this study investigated the performance of the precipitation field from the 1-km-resolution version of the China Atmospheric Realtime Analysis (CARAS) over Hubei from the perspective of climatology, multiple-time scale variations, as well as fusion accuracy and detection capability at multiple temporal scales. The results show that CARAS precipitation can reproduce the spatial distribution patterns of climatological seasonal precipitation and rainy days well over the whole of Hubei compared with observational (OBS) precipitation, albeit deviations exist between CARAS and OBS in terms of magnitude. Moreover, high correlation and consistency between CARAS and OBS can be found in multiple-time scale variations over Hubei, with correlation coefficients of interannual, seasonal, and diurnal variation generally exceeding 0.85, 0.98, and 0.95, respectively. Furthermore, CARAS has a relatively higher fusion accuracy in summer and winter, and stronger/weaker detection capability in spring/winter at a daily scale. However, the detection capability of CARAS at an hourly scale is weaker than that at a daily scale. With different precipitation intensity levels considered, CARAS daily precipitation shows relatively higher fusion accuracy in estimating moderate and heavy rain, and better detection capability in capturing no rain events. The variations of accuracy metrics and detection metrics under different precipitation intensities at an hourly scale generally resemble those at a daily scale. However, CARAS precipitation at an hourly scale shows a relatively lower fusion accuracy and weaker detection capability compared with that at a daily scale. This paper provides an insight into the characteristics of systematic deviations in CARAS precipitation over Hubei, which will benefit relevant applications of CARAS in meteorological operations over Hubei and the improvement of CARAS in the future.

Key words: China Atmospheric Realtime Analysis; kilometer-scale precipitation; climatology; multiple-time scale variations; accuracy and detection capability

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1 INTRODUCTION

Precipitation is not only an important component of the water cycle in the climate system but also a crucial indicator of climate change (Held and Soden [1]). Against the background of climate change, extreme drought and flood events are occurring in China with ever greater frequency, such as the 2022 summer record-breaking extreme drought and heatwave event and the 2020 extreme Meiyu event, which brought serious threats to ecosystems, agriculture, and economic development (Wang et al. [2]; Wang et al. [3]; Ding et al. [4]; Wang et al. [5]). However, accurate precipitation estimation is still challenging because of its marked discontinuity and variability in space and time (Herold et al. [6]). Therefore, obtaining accurate and high spatiotemporal resolution precipitation information is crucial for water resource management, agricultural production, and disaster prevention and mitigation.

The traditional approach to obtaining precipitation data

is through surface rain gauge observations, which have the main advantage of being highly accurate. Despite this reliability, however, the coverage of such observations is limited, especially in remote and mountainous areas with sparse rain gauge distributions (Zhang et al. [7]; Xin et al. [8]).

Since the 1990s, Japan, the European Union, and the United States have developed data fusion and assimilation techniques, which make comprehensive use of multiple sources of precipitation observation data to produce real-time gridded data of precipitation at high spatiotemporal resolution (Kalnay et al. [9]; Zhao et al. [10]; Sun et al. [11]; Hersbach et al. [12]). To date, such precipitation data have been widely used in various fields of meteorology, making up for the deficiency of the low spatial resolution of surface rain gauge observations (Zhang et al. [13]).

However, many studies have suggested that prominent systematic errors exist at a broad level in such gridded precipitation data (Cavalcante et al. [14]; Ye et al. [15]; Jiang et al. [16]; Li et al. [17]; Wang et al. [18]). For example, strong (weak) precipitation is underestimated (overestimated) in the precipitation data from the National Centers for Environmental Prediction/Department of Energy (NCEP/DOE), the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Japanese 25-year Reanalysis (JRA-25) (Dai et al. [19]). More recently, Ye et al. [15] pointed out that overestimation of precipitation in heavy rainfall regions in spring and summer can be found in the precipitation field of the Chinese Reanalysis-Interim (CRA-Interim), the fifth generation of ECMWF Reanalysis (ERA5), and the Japanese 55-year Reanalysis (JRA-55).

In 2013, the Public Meteorological Service Center (PMSC) of the China Meteorological Administration (CMA) introduced the Space and Time Multiscale Analysis System (STMAS) (Xie et al. [20]), which is a

three-dimensional variational analysis combining spatial and temporal observations to provide a temporally consistent surface gridded analysis. Moreover, the PMSC has also optimized and upgraded the core algorithms of STMAS, and then developed the China Atmospheric Realtime Analysis (CARAS), including products for precipitation and other meteorological variables (Li et al. [21]).

The highest resolution of CARAS precipitation is 1 km and 1 h, which is higher than similar products developed outside China, and has been in operation since 2020. So far, however, a comprehensive evaluation of the 1-km version of CARAS precipitation in China is still lacking, which is disadvantageous for the scientific application of this product in meteorological operations and research. Accordingly, this study performed a comprehensive evaluation of the applicability of CARAS precipitation over Hubei, thereby providing a scientific reference for improving CARAS and relevant applications in meteorological operations.

2 DATA AND METHODS

2.1 Study area

Hubei Province lies in the south of Central China (29°05'–33°20'N, 108°21'–116°07'E) and is located at the middle reaches of the Yangtze River and the north of Dongting Lake, covering an area of 185,900 km². Hubei is surrounded by mountains in the east, west, and north, and Jiangnan Plain in the middle, with the mountainous, hilly, and plain-lake areas accounting for 56%, 24%, and 20%, respectively. Meteorologically, Hubei is divided into Northwest Hubei (NWH), Southwest Hubei (SWH), Northeast Hubei (NEH), Southeast Hubei (SEH), and Jiangnan Plain (JHP), as shown in Fig. 1. Major river basins in Hubei include the Yangtze River Basin and the Han River Basin (Fig. 1).

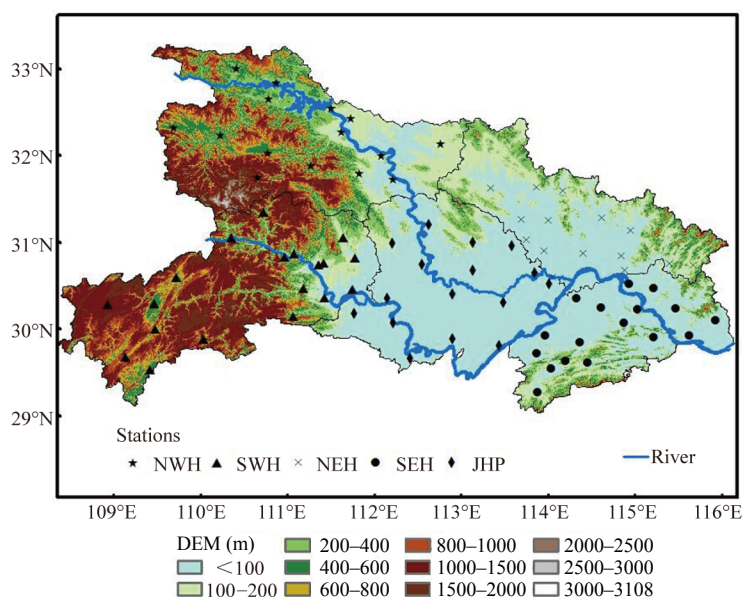


Figure 1. Topography and distribution of national meteorological observational stations over Hubei Province.

2.2 Data

The hourly precipitation field of CARAS is provided by the PMSC, CMA, which merges multiple sources of observations (e.g., automatic meteorological station, radar, satellite, wind profiler, and GPS-Met water vapor observations). The CARAS precipitation product covers the period from 0000 UTC January 1, 2008 to 2300 UTC December 31, 2021, and has a horizontal resolution of $0.01^\circ \times 0.01^\circ$. Based on these hourly precipitation data, we calculated the daily precipitation.

The hourly precipitation data from 82 national meteorological observation stations in Hubei Province, provided by the Hubei Meteorological Information and Technological Support Center, are used to evaluate the applicability of CARAS precipitation. The observational precipitation data, covering the period from 0000 UTC January 1, 2008, to 2300 UTC December 31, 2021, have been quality controlled. Then, observational daily precipitation can be calculated.

The Digital Elevation Model (DEM) data, with a horizontal resolution of 90 m, are from the Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences. The DEM data are used to depict the topographic features of Hubei Province.

2.3 Methods

To facilitate the comparison of CARAS and observational precipitation data, the CARAS data are interpolated to the locations of national meteorological stations using the bilinear interpolation method. Furthermore, the Cressman objective analysis method is used to clearly display the spatial distribution of CARAS and observational precipitation (Cressman [22]). The Cressman objective analysis method is a gradually revised interpolation method that interpolates discrete points to regular grids and causes less error. Thus, it is widely used in meteorological research.

In this paper, temporal correlation coefficient (TCC), root mean square error (RMSE), and relative error (RE) are adopted to analyze the fusion accuracy of CARAS. The formulae are as follows:

$$TCC_i = \frac{\sum_{j=1}^N (x_{i,j} - \bar{x}_i)(y_{i,j} - \bar{y}_i)}{\sqrt{\sum_{j=1}^N (x_{i,j} - \bar{x}_i)^2 \sum_{j=1}^N (y_{i,j} - \bar{y}_i)^2}} \quad (1)$$

$$RMSE_i = \sqrt{\frac{\sum_{j=1}^N (x_j - y_j)^2}{N}} \quad (2)$$

$$RE_i = \frac{\sum_{j=1}^N (x_j - y_j)}{\sum_{j=1}^N y_j} \times 100\% \quad (3)$$

where x and y denote the values of CARAS and observational data, respectively, N is the total number of time series, and subscript i represents a national

meteorological station.

Probability of detection (POD), false alarm ratio (FAR), and critical success index (CSI) are used to quantitatively evaluate the ability of CARAS to detect rainfall events (Yu et al. [23]). POD measures the proportion of rainfall events correctly captured. FAR represents the proportion of rainfall events detected by CARAS but actually did not happen. CSI is a comprehensive evaluation of CARAS about hit and false rates, indicating the true ability of CARAS in detecting actual rainfall events. The formulae are as follows:

$$POD = \frac{N_{11}}{N_{11} + N_{01}} \quad (4)$$

$$FAR = \frac{N_{10}}{N_{11} + N_{01}} \quad (5)$$

$$CSI = \frac{N_{11}}{N_{11} + N_{01} + N_{10}} \quad (6)$$

where N_{11} is the number of rainfall events identified by CARAS and observation, N_{01} denotes the number of rainfall events detected by observation but not by CARAS, and N_{10} represents the number of rainfall events identified by CARAS but not actually occurring.

To evaluate the applicability of CARAS under different daily precipitation intensity, precipitation is divided into five levels of $<0.1 \text{ mm d}^{-1}$, $0.1\text{--}10 \text{ mm d}^{-1}$, $10\text{--}25 \text{ mm d}^{-1}$, $25\text{--}50 \text{ mm d}^{-1}$, and above 50 mm d^{-1} , corresponding to no rain, light rain, moderate rain, heavy rain and rainstorm. For hourly scale, precipitation is separated into five levels of $<0.1 \text{ mm h}^{-1}$, $0.1\text{--}1.5 \text{ mm h}^{-1}$, $1.5\text{--}7 \text{ mm h}^{-1}$, $7\text{--}15 \text{ mm h}^{-1}$, and above 15 mm h^{-1} , corresponding to no rain, light rain, moderate rain, heavy rain, and rainstorm (Yu et al. [23]).

3 RESULTS

3.1 Climatology

The spatial distributions of the 14-year-averaged (2008–2021) seasonal precipitation in CARAS and observation (OBS), and corresponding bias percentage are shown in Fig. 2. It can be seen that the distribution patterns of CARAS precipitation in different seasons agree well with those of OBS precipitation (Figs. 2a–2h). Specifically, CARAS precipitation in spring (March–April–May) and summer (June–July–August) is characterized by more precipitation over SWH, SEH, and southern NEH, and less precipitation over NWH and northern NEH, being similar to OBS precipitation. In autumn (September–October–November), CARAS precipitation exhibits more precipitation over southwestern SWH and less precipitation over eastern NWH, northern JHP, and most of NEH; OBS precipitation shows a similar distribution pattern, though a discrepancy exists over eastern NEH. In winter, OBS precipitation is featured with relatively more precipitation over SEH, the eastern edge of JHP, and southern NEH, and less precipitation over other regions of Hubei. For CARAS precipitation in winter, relatively more precipitation can

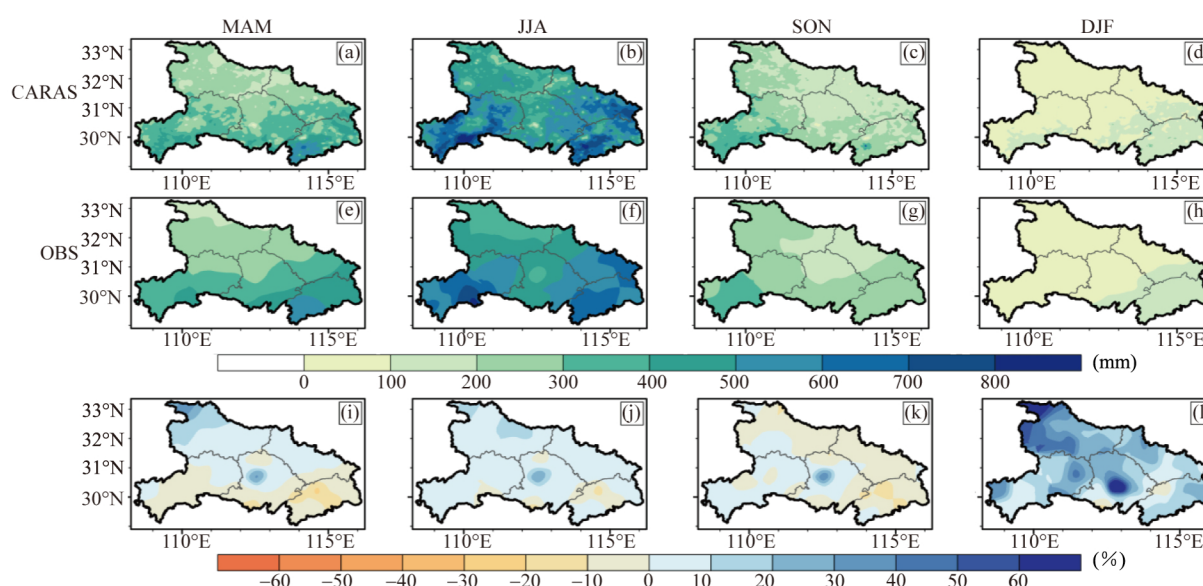


Figure 2. Distribution of the 14-year-averaged seasonal precipitation during 2008–2021 in (a, e) spring, (b, f) summer, (c, g) autumn, and (d, h) winter. (a–d) CARAS precipitation and (e–h) observational precipitation (OBS). Bias percentages of climatological total precipitation for CARAS against OBS in (i) spring, (j) summer, (k) autumn, and (l) winter. Note that (a–d) are plotted using original CARAS precipitation data without interpolation.

also be seen over the eastern edge of SWH.

It should be noted that differences exist between CARAS and OBS precipitation in a level of sophistication and concerning the intensity (Fig. 2). Firstly, CARAS shows more detailed characteristics of the spatial distribution, especially in summer, because of its high spatial resolution. Secondly, CARAS overestimates or underestimates the seasonal precipitation compared with OBS over Hubei (Figs. 2i–2l). In particular, in spring, CARAS generally overestimates precipitation over NWH, eastern SWH, NEH, and northern JHP, with bias percentage mainly concentrating in (0, 10%) except the region over northwestern NWH and northern JHP, while underestimates precipitation over other areas of Hubei, with bias percentage generally being in the range of (0, –10%) except for the region over central SEH (Fig. 2i). In summer, CARAS shows positive bias percentage over most of Hubei, with its value mainly ranging from 0 to 10% (Fig. 2j). In autumn, CARAS overestimates precipitation over most of SWH and JHP with the maximal bias percentage located over western JHP, while underestimates precipitation over other regions of Hubei (Fig. 2k). In winter, CARAS basically overestimates precipitation over Hubei, and the center of bias percentage locates over central JHP, with its value more significant than 60% (Fig. 2l).

Figure 3 further displays the spatial distribution of multi-year total rainy days from 2008 to 2021 and the corresponding difference between CARAS and OBS for different precipitation intensities. Both CARAS and OBS show a prominent declining trend of total rainy days as precipitation intensity increases (Figs. 3a–3h). Furthermore, the distribution pattern of total rainy days

in CARAS is generally consistent with that in OBS. Specifically, with respect to light rain, both CARAS and OBS show a more significant frequency of total rainy days over western SWH and central JHP compared with that over other regions of Hubei (Figs. 3a and 3e). For moderate rain, relatively larger total rainy days occur over western and central SWH, southeastern JHP, and SEH in both CARAS and OBS, with values ranging from 300 to 400 d (Figs. 3b and 3f). For heavy rain, both CARAS and OBS are characterized by a homogeneous pattern of total rainy days over Hubei, with total rainy days being in the range of (100, 200) d (Figs. 3c and 3g). Compared with other precipitation intensities, the total rainy days of CARAS and OBS for rainstorms are the least, with its value concentrating in (10, 100) d (Figs. 3d and 3h). Moreover, the center of total rainy days for rainstorm is located over central SWH, eastern JHP, SEH, and southern NEH in both CARAS and OBS, with its value ranging from 50 to 100 d (Figs. 3d and 3h).

It can also be seen that deviation exists between CARAS and OBS and varies with different precipitation intensities. For light rain, total rainy days in CARAS are overestimated over the whole of Hubei, with the center of bias located over central JHP and southeastern SEH and the maximal deviation exceeding 300 d (Fig. 3i). While for other precipitation intensities, total rainy days are underestimated over most of Hubei, with its value mainly concentrating in the range of (–15, 0) days (Figs. 3j–3l). Although deviation of total rainy days exists between CARAS and OBS, CARAS can reproduce the distribution pattern of total rainy days for different precipitation intensities.

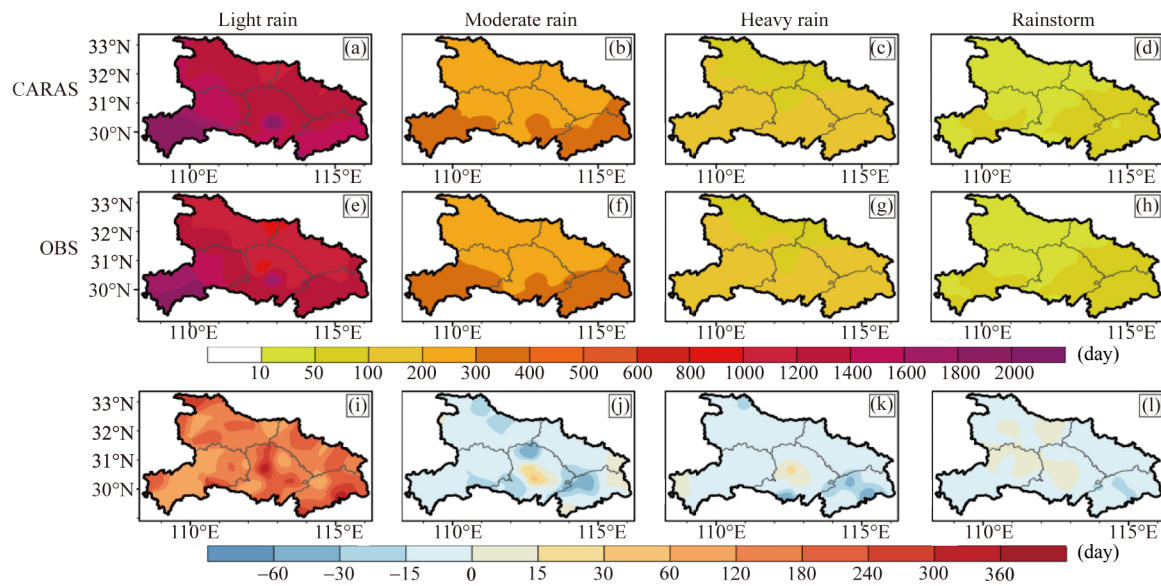


Figure 3. Distribution of multi-year total rainy days (units: d) during 2008–2021 for (a, e) light rain, (b, f) moderate rain, (c, g) heavy rain, and (d, h) rainstorm. (a–d) CARAS precipitation and (e–h) observational precipitation (OBS). The difference in total rainy days between CARAS and OBS (i.e., CARAS minus OBS) for (i) light rain, (j) moderate rain, (k) heavy rain, and (l) rainstorm.

3.2 Multiple-time scale variations

3.2.1 INTERANNUAL VARIATION

Figure 4 presents the time series of area-mean annual precipitation from 2008 to 2021 over five regions and the whole of Hubei. CARAS agrees well with that of OBS over each region and the whole of Hubei, reflecting a high correlation between CARAS and OBS at interannual timescale, as suggested by the correlation coefficients of 0.847, 0.949, 0.870, 0.874, 0.883, and 0.867 over NWH, NEH, SWH, SEH, JHP, and HB, respectively (Fig. 4). It should be noted that CARAS notably deviates from OBS for the year 2016 over each region and the whole of Hubei. As suggested by previous studies, the forecast field of the CMA-MESO model is used as an initial field during the process of producing CARAS (Li et al. [21]), and the CMA-MESO model has relatively poor performance in rainfall forecast for rainstorms (Xu et al. [24]). Meanwhile, in 2016, an extreme Meiyu event attacked the Yangtze River Valley, including Hubei (Zhao et al. [25]). Therefore, the notable deviation in 2016 shown in Fig. 4 may be related to the relatively larger forecast bias of precipitation in the CAM-MESO model compared with that in other years.

Moreover, CARAS generally exhibits weak positive deviation over NWH, NEH, and SWH (Figs. 4a–4c) while showing weak negative deviation over SEH, JHP, and HB (i.e., Hubei) for most years (Figs. 4d–4f). Generally speaking, there is good consistency between CARAS and OBS in terms of interannual variation, with high correlation and weak deviation over Hubei.

3.2.2 SEASONAL VARIATION

For a further understanding of the performance of CARAS in temporal variability, the seasonal evolution of monthly total precipitation over five regions and the whole of Hubei is illustrated in Fig. 5. It is clear that CARAS

matches well with OBS in terms of seasonal trends with a general rise from January to July and a decline from July to December over each region and the whole of Hubei in general. Meanwhile, a high correlation between CARAS and OBS can be seen over each region and the whole of Hubei, as indicated by the correlation coefficients of 0.993, 0.989, 0.998, 0.985, 0.992, and 0.992 over NWH, NEH, SWH, SEH, JHP, and HB, respectively (Fig. 5). However, it should be noted that the maximum precipitation appears in June instead of July over SEH and JHP (Figs. 5d and 5e). Furthermore, CARAS obviously underestimates the precipitation from April to October over each region and the whole of Hubei. To sum up, CARAS has a good estimation capacity in seasonal variation, with precipitation being in line with OBS.

3.2.3 DIURNAL VARIATION

As diurnal variation is one of the most crucial aspects of representing regional climate, Fig. 6 is plotted to show the performance of CARAS hourly precipitation in diurnal variation in different seasons and over different regions of Hubei. A high correlation between CARAS and OBS can be found from the perspective of the correlation coefficient, with its value generally exceeding 0.95. In spring, the diurnal trends of CARAS and OBS hourly precipitation are consistent, though there exist differences in intensity, especially for the region over SEH and JHP (Figs. 6a0–6a4). Meanwhile, the range of diurnal variation is relatively small over most of Hubei, except the region over SWH (Figs. 6a0–6a4). The peaks of both CARAS and OBS precipitation intensity over SWH appear at 2300–0100 Beijing Time (BJT, BJT=UTC+8 hours), manifesting an obvious nocturnal precipitation characteristic (Fig. 6a1).

In summer, the diurnal variation is remarkable for



Figure 4. Time series of area-mean annual precipitation (units: mm) of CARAS and observational data (OBS) during 2008–2021 over (a) NWH, (b) NEH, (c) SWH, (d) SEH, (e) JHP, and (f) HB (i.e., Hubei). The r in the figure represents the correlation coefficient between CARAS and OBS for the time series of area-mean annual precipitation.

both CARAS and OBS precipitation over Hubei. Moreover, the differences in precipitation intensity between CARAS and OBS are very small (Figs. 6b0–6b4). It is clear that the diurnal variations of CARAS and OBS precipitation over NWH, SWH, NEH, and JHP are generally characterized by single-peak structure, with peaks occurring at 1000–1200, 0800–1100, 2200–0100, and 0000–0200 BJT, respectively (Figs. 6b0, 6b1, 6b2, and 6b4). By contrast, a double-peak structure appears over SEH for CARAS and OBS precipitation, with peaks occurring at 0700–0800 and 2300–0100, respectively (Figs. 6b3).

In autumn, the diurnal trends of CARAS and OBS hourly precipitation are also consistent over Hubei (Figs. 6c0–6c4). Note that the differences in precipitation intensity between CARAS and OBS are relatively large over NWH and SEH, compared with that over other regions of Hubei. Furthermore, significant diurnal variations only appear over SWH and SEH, characterized by single-peak and double-peak structures,

respectively (Figs. 6c1 and 6c3). In winter, there are no obvious diurnal variations of CARAS and OBS hourly precipitation over Hubei (Figs. 6d0–6d4).

Generally speaking, the diurnal variations of CARAS and OBS hourly precipitation are consistent over Hubei. Moreover, the range of diurnal variations is largest in summer while smallest in winter. Moreover, there is generally a small gap between CARAS and OBS hourly precipitation over most of Hubei. It is worth noting that significant regional difference in diurnal variation of precipitation exists over Hubei, which may be related to complicated topography, local thermal forcing, and eastward movement of weather systems indicated by previous studies (Hu et al. [26], Yu et al. [27], Lin et al. [28]).

3.3 Analysis of accuracy and detection capability

3.3.1 FOR DIFFERENT SEASONS

Figure 7 displays the variations of assessment metrics over five regions of Hubei for different seasons at a daily scale. TCC in each season exceeds 0.92 over the whole of Hubei, manifesting a high correlation between CARAS

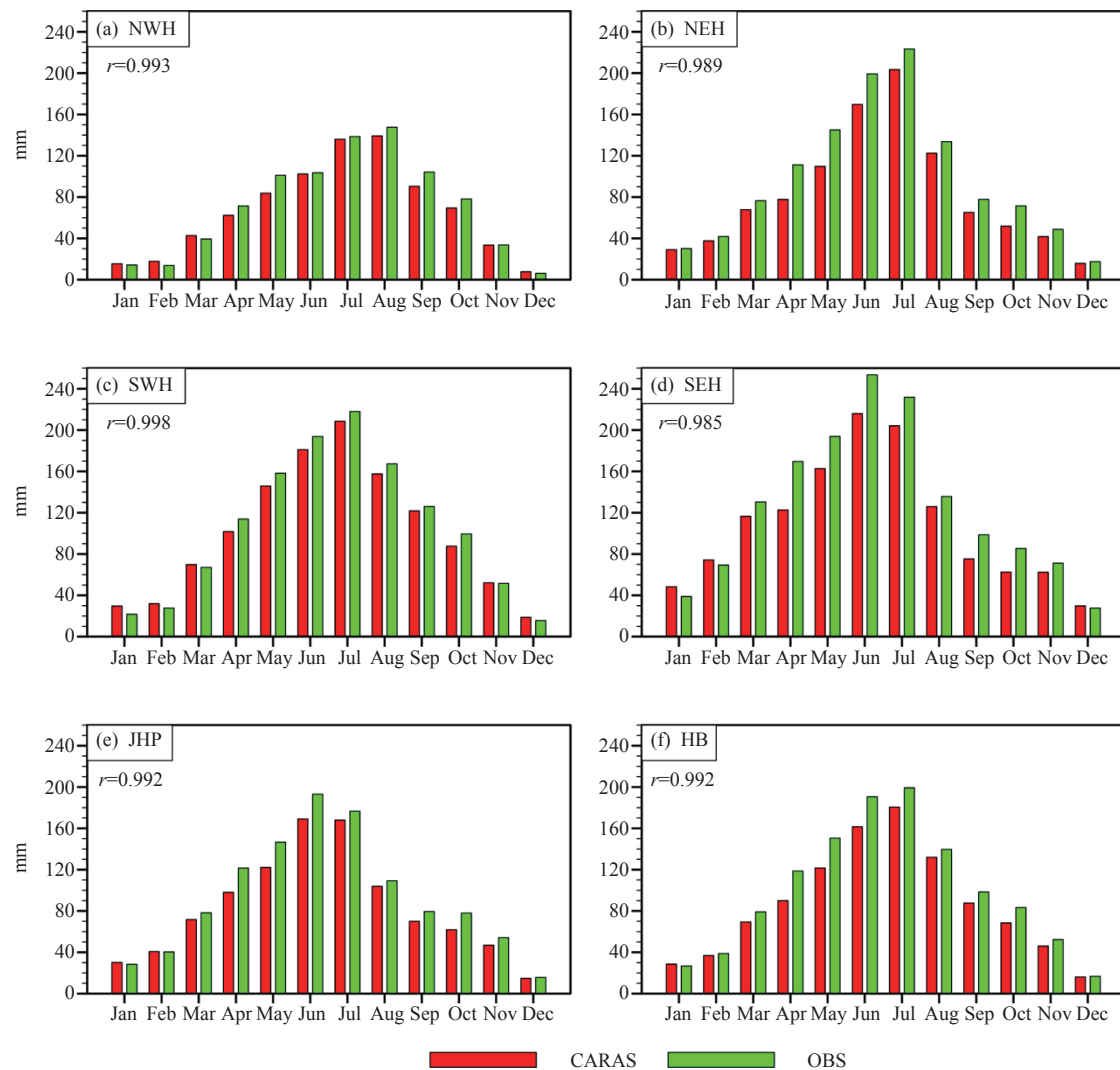


Figure 5. Climatological monthly total precipitation (units: mm) of CARAS and observational data (OBS) during 2008–2021 over (a) NWH, (b) NEH, (c) SWH, (d) SEH, (e) JHP, and (f) HB (i.e., Hubei). The r in the figure represents the correlation coefficient between CARAS and OBS for the time series of climatological monthly total precipitation.

and OBS precipitation on a daily scale (Fig. 7a). Moreover, TCC is relatively higher in summer compared with that in other seasons. RMSE generally decreases from spring to winter except in the region over NWH (Fig. 7b). Noted that the maximum of RMSE appears in spring over SEH, with its value above 4 mm d^{-1} . The minimum of RMSE occurs in winter over NWH, with its value below 0.5 mm d^{-1} (Fig. 7b). With regard to RE, negative bias dominates Hubei in both spring and autumn, and positive bias dominates most of Hubei in winter (Fig. 7c). In summer, RE over NWH, SWH, and NEH is positive and slightly deviates from 0. At the same time, RE over SEH and JHP is less than -3% (Fig. 7c). According to the above results of accuracy metrics at a daily scale, CARAS has a relatively higher accuracy in summer and winter.

With respect to detection metrics, the detection capability of CARAS at a daily scale varies significantly/slightly in different seasons/regions (Figs. 7d–7f). POD is larger than 0.9 in all seasons over Hubei, with maximum/minimum occurs in summer/autumn (Fig.

7d). FAR is generally less than 0.2 over Hubei, characterized by relatively lower value in spring and autumn, and higher value in winter (Fig. 7e). CSI changes from ~ 0.9 (spring) to ~ 0.8 (winter) over Hubei, indicating relatively stronger/weaker detection capability in spring/winter (Fig. 7f).

The variations of TCC, RMSE, RE, POD, FAR, and CSI for different seasons at an hourly scale generally resemble those at a daily scale (figure not shown). However, RMSE over the whole of Hubei reaches its peak in summer (figure not shown), differing from that at a daily scale (Fig. 7b). In comparison, the detection capability of CARAS at an hourly scale is relatively weaker than that at daily scale, indicating a relatively weaker capability in detecting rainfall events (figure not shown).

3.3.2 UNDER DIFFERENT PRECIPITATION INTENSITY

Figure 8 shows the variations of accuracy and detection metrics versus precipitation intensity on a daily scale. TCC generally has a rising trend over the whole of

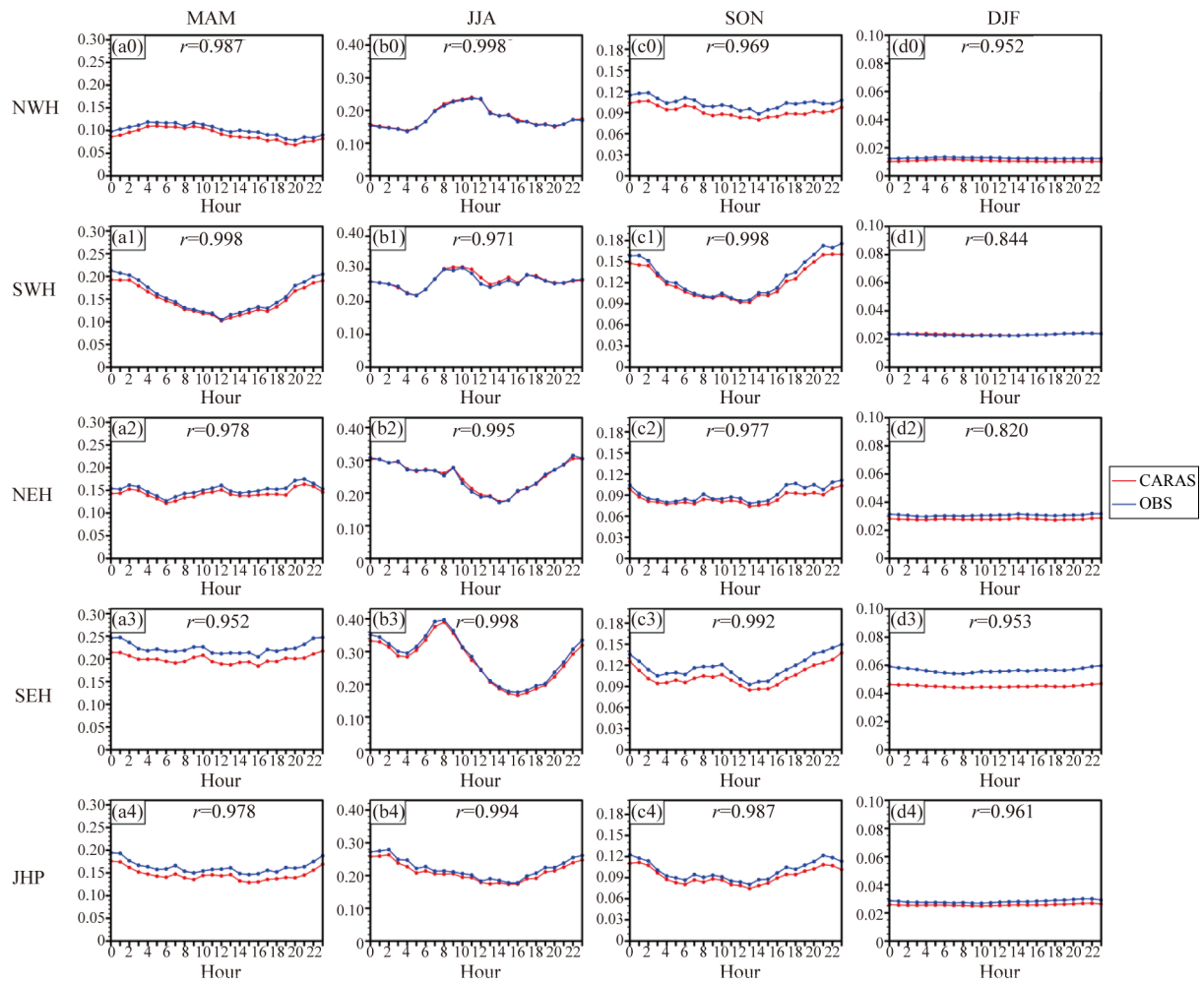


Figure 6. Diurnal variations of CARAS and OBS hourly precipitation (units: mm) in (a0–a4) spring, (b0–b4) summer, (c0–c4) autumn, and (d0–d4) over different regions of Hubei. The first to the fifth rows are for the regions over NWH, SWH, NEH, SEH, and JHP, respectively. The abscissa is Beijing time (BJT) for each hour of the day. The r in the figure represents the correlation coefficient between CARAS and OBS for the time series of diurnal variations of hourly precipitation.

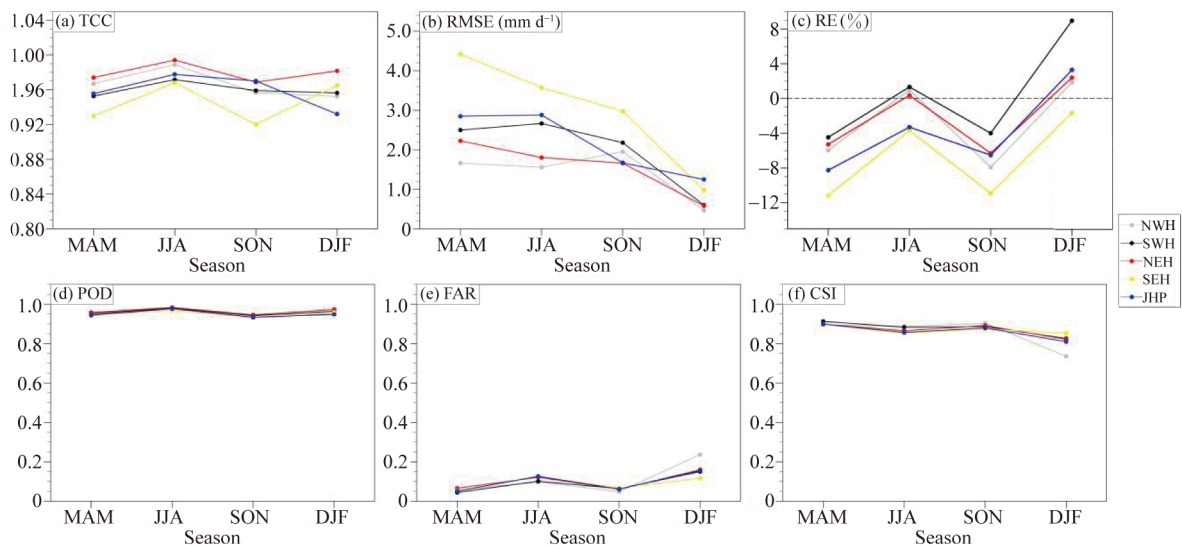


Figure 7. Variations of (a) TCC, (b) RMSE, (c) RE, (d) POD, (e) FAR, and (f) CSI for different seasons at the daily scale over Hubei.

Hubei with the increase of precipitation intensity, but the variation of TCC in the range of $[10, 50] \text{ mm d}^{-1}$ is not remarkable (Fig. 8a). With respect to RMSE, an overall increasing trend over the whole of Hubei can also be seen in Fig. 8b, while the change of RMSE in the range of $[0.1, 25] \text{ mm d}^{-1}$ is not prominent. In terms of RE, it is clear that RE has a significant rising trend against precipitation intensity within the range of $<25 \text{ mm d}^{-1}$ over the whole of Hubei (Fig. 8c). While the variation of RE is tiny in the range of $>25 \text{ mm d}^{-1}$, with its value concentrated around 0. On the basis of the above results of accuracy metrics at a daily scale, CARAS precipitation shows relatively better performance in estimating moderate and heavy rain and low fusion accuracy in estimating no rain. From the perspective of detection metrics at a daily scale, CARAS precipitation performs best in detecting no rain, featuring the highest POD and CSI and lowest FAR (Figs. 8d–8f). In addition, CARAS also has a good performance in capturing other precipitation intensity events, with CSI generally exceeding 0.75 (Fig. 8f).

The variations of accuracy and detection metrics under different precipitation intensities at an hourly scale are generally consistent with those at a daily scale (figure not shown). However, CARAS hourly precipitation shows a relatively weak fusion accuracy and detection capability compared with CARAS daily precipitation (figure not shown).

4 SUMMARY AND DISCUSSION

Based on rain gauge data from national meteorological observation stations, this paper systematically investigated the applicability of the 1-km resolution version of the CARAS precipitation product during 2008–2021 over Hubei. This study evaluated the performance of CARAS in climatology, multiple-time scale variations, and fusion accuracy and detection capability at multiple temporal (daily and hourly)

scales by adopting accuracy metrics and detection metrics. The main findings of this study are as follows.

CARAS can reproduce the spatial distribution of seasonal precipitation and rainy days, though different degrees of deviation exist between CARAS and OBS in different seasons and under different precipitation intensities, respectively.

The time series of area-mean annual precipitation in CARAS during 2008–2021 fits well with that of OBS, with correlation coefficients of 0.847, 0.949, 0.870, 0.874, 0.883, and 0.867 over NWH, NEH, SWH, SEH, JHP, and HB, respectively. However, CARAS dramatically deviates from OBS for the year 2016 over all regions of Hubei.

CARAS agrees well with OBS in terms of seasonal variation, with a general rise from January to July and a decline from July to December over Hubei. However, precipitation in CARAS is generally underestimated from April to October over the whole of Hubei.

For diurnal variation, CARAS can describe the diurnal trends and peak patterns of precipitation over Hubei, with correlation coefficients generally exceeding 0.95 over the whole of Hubei. The gap between CARAS and OBS in terms of intensity is tiny over most of Hubei.

From the perspective of performance in different seasons, CARAS has a relatively higher fusion accuracy in summer and winter and stronger/weaker detection capability in spring/winter at a daily scale. Although the variations of accuracy metrics and detection metrics at an hourly scale are much similar to those at the daily scale, the detection capability of CARAS at an hourly scale is weaker than that at the daily scale.

Considering different precipitation intensity levels, CARAS daily precipitation shows relatively higher fusion accuracy in estimating moderate and heavy rain and better detection capability in capturing no rain events. The variations of accuracy metrics and detection metrics under

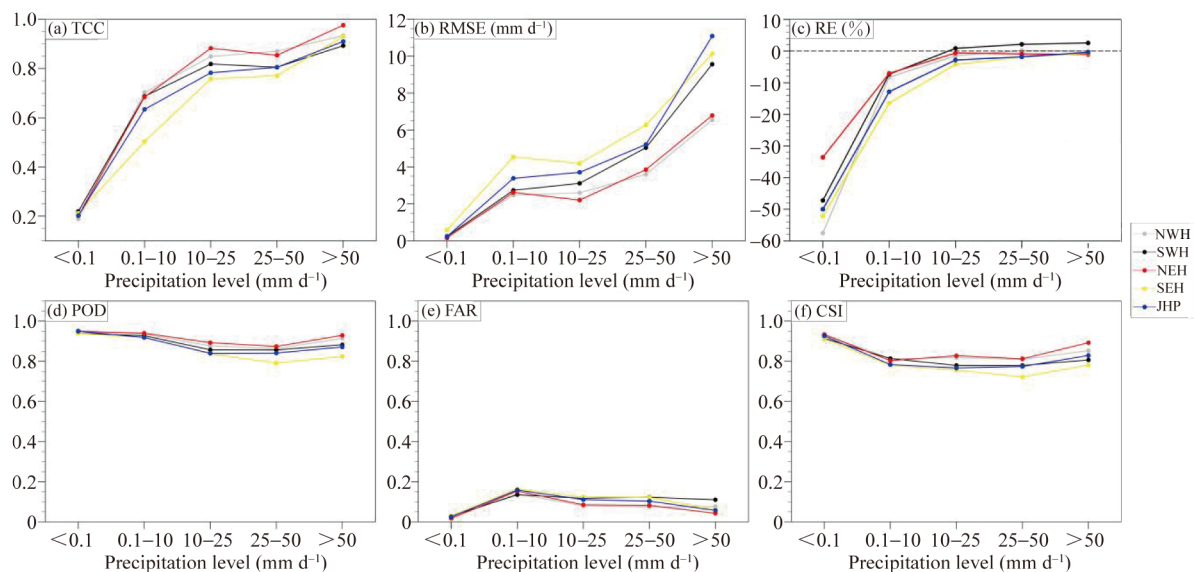


Figure 8. Variations of (a) TCC, (b) RMSE, (c) RE, (d) POD, (e) FAR, and (f) CSI for different precipitation intensity levels at the daily scale over Hubei.

different precipitation intensities at an hourly scale generally resemble those at a daily scale. However, CARAS precipitation at an hourly scale shows a relatively lower fusion accuracy and weaker detection capability compared with that at a daily scale.

This paper aims to reveal the characteristics of systematic deviations in CARAS precipitation for different time scales and over different regions of Hubei, which will benefit the application of CARAS in meteorological operations and the advancement of CARAS in the future to some extent. However, the sources and causes of systematic deviations in CARAS precipitation have not been explored in this article. Li et al.^[21] reported that a 1-km version of CARAS in China is produced by a multi-source data assimilation system named STMAS, and the forecast field of CMA-MESO is regarded as the initial field during the process of producing CARAS. Consequently, the systematic deviations of CARAS precipitation may derive from the forecast bias of CMA-MESO or the data assimilation algorithm of STMAS. As suggested by evaluation studies on the forecast performance of CMA-MESO, forecast bias of CMA-MESO exists in many meteorological elements, such as precipitation, temperature, wind, and so on (Huang et al.^[29], Zhong et al.^[30], Cai et al.^[31]). In the future, further work is needed to investigate the inherent sources and causes of deviations in CARAS. Furthermore, the applicability of CARAS in other regions of China, especially in areas with complicated terrain and weather, also needs to be explored.

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