Evaluation of the hourly rainfall in the ECMWF forecasting over southwestern China

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Abstract
The performance of the forecasts of the European Centre for Medium-Range Weather Forecasts’ (ECMWF) Integrated Forecasting System (IFS) with a horizontal resolution of 0.125° is assessed through comparison with station rain-gauge data in the warm season (May–October) in the period 2017–2018 over southwestern China. The mean state of rainfall amount, frequency and intensity, as well as the diurnal cycle of precipitation, are involved in the evaluation. The IFS can capture well the spatial distributions of rainfall amount, frequency and intensity in the gauge data, but the rainfall frequency is generally larger and the intensity is weaker in the IFS. The rainfall events of the IFS usually start and peak much earlier, and the afternoon rainfall peaks are over-estimated. The discrepancy between the gauge data and the IFS is larger over the western part of southwestern China. The results indicate that the IFS forecasts show considerable uncertainty when moving to the sub-daily scale, especially over areas with complex topography. When the IFS forecasts are applied operationally, the deviations (as revealed in this study) should be paid more attention.

KEYWORDS
ECMWF IFS, evaluation, hourly precipitation, orographic precipitation

1 | INTRODUCTION

Southwestern China, located to the east of the Tibetan Plateau (TP), has the most complex topography in the country. The TP comprises plateaus with elevations > 4,000 masl. Also, the elevations of the Sichuan Basin to the east of the TP are < 500 masl. Over the southeastern extension of the TP, the topography descends from north (> 4,000 masl in the main body of the TP) to south (around 1,000 masl) and a series of steep, north–south-oriented parallel ridges and rivers make the topography even more complex. As shown in Figure 1, the gap between the elevations over southwestern China amounts to > 5,000 m. Influenced by these dramatic changes in topography, the rainfall variations over southwestern China are rather unique.

Simulating rainfall in areas with a complex topography is a great challenge for models (Gulizia and Camilloni, 2015). Most models in the Coupled Model Intercomparison Project Phase 5 (CMIP5) overestimate precipitation over regions of complex topography (Mehran et al., 2014). Both regional and global models...
produce excessive precipitation over the ridges of mountains in both South and North America (Cavalcanti et al., 2002; Solman et al., 2008; Alves and Marengo, 2010). Over the TP, the ensemble mean of the CMIP3 models overestimates the precipitation by up to 100% (Xu et al., 2010). Despite substantial improvements to models in other respects, the updated models in the CMIP5 still overestimate the annual mean precipitation over the eastern TP by 62–183% (Su et al., 2013). Larger wet biases also exit in both reanalysis rainfall data and high-resolution weather research and forecasting model (WRF) simulations (Gao et al., 2015).

The overestimation of precipitation is mainly contributed by the category of light rain. Many studies have shown that model simulations produce light rain (1–10 mm) too frequently, leading to a weaker rainfall intensity (Dai, 2006; Wilcox and Donner, 2007; Brown et al., 2010). Biases have been reported in the simulations of warm clouds associated with unrepresentative microphysical parameterizations (Lebsock et al., 2013). Although the ratio of light rainfall in a super-parameterized CAM5 simulation was found to be still overestimated over China, it was far more reliable than the traditional version of the model (Zhang and Chen, 2016). Also, it was found that rainfall intensity could be improved over the eastern periphery of the TP and eastern China by using a convection-permitting model (Li et al., 2020).

Meanwhile, the diurnal cycle of precipitation in both weather and climate simulation models is incorrectly predicted. Generally, weather forecast models simulate the initiation of convection several hours earlier than observed, meaning precipitation is also simulated several hours in advance (Wulfmeyer et al., 2008). In the earlier version of the short-term forecasts of the European Centre for Medium-Range Weather Forecasts (ECMWF) model, in a study focusing on the region of Amazonia, precipitation was found to have started shortly after sunrise in the model, which was several hours earlier than observed (Betts and Jakob, 2002), and close to local noon in mid-altitudes (Betts et al., 1998), although the mean daily precipitation compared well with the observations. With the development of convection parameterization, the diurnal cycle of convection has been greatly improved in the Integrated Forecasting System (IFS), but representing late-night convection over land remains a challenge (Bechtold et al., 2014). These errors in model simulations also exist over China. For instance, Xu et al. (2017) evaluated the GRAPES-Meso4.0 model (one of the operational models in China) with resolutions of 3 and 10 km. With a resolution of 10 km, the model greatly overestimated the daytime rainfall frequency, but showed improvements in the 3 km version. However, the diurnal peak in the early morning was still weak and the triggering of deep convection was earlier than observed.

The problems surrounding the simulation of rainfall intensity, frequency and its diurnal cycle strongly limit the application of operational models for decision-makers. Consequently, improving quantitative precipitation forecasts is a key cross-cutting issue. Quantifying the biases and uncertainties in simulations of precipitation is thus fundamental to understand the reliability of simulations for forecasting operations. Over southwestern China, the reliability of forecasting is relatively low when compared with eastern China, and comprehensive evaluations are rare. The present paper evaluates the accuracy of the forecasts of the ECMWF’s IFS in terms of the distributions of rainfall amount, frequency and intensity, and their diurnal cycles over southwestern China. Highlighting discrepancies between the IFS and gauge data at the sub-daily time scale provides essential feedback to both users and model developers on the quality of the forecasting system verification statistics to evaluate the accuracy of its forecasts and to provide a comprehensive understanding of the strengths and weaknesses of the forecasting system.

The paper is structured as follows. The data and methods are described in Section 2. The results are described in detail in Section 3. Finally, a discussion and summary are provided in Sections 4 and 5, respectively.
2 | DATA AND METHODS

2.1 | Data

Hourly rainfall data from 709 rain gauges covering southwestern China in the warm seasons (May–October) of the period 2017–2018 were used. This data set was collected and quality controlled by the National Meteorological Information Centre of the China Meteorological Administration (CMA).

The forecasts made by the IFS were used, and the model was run at a horizontal resolution at about 9 km (for full documentation, see https://www.ecmwf.int/en/research; and Malardel et al. 2016 [winter 2015]). The spatial resolution of data used is 0.125 × 0.125° (Figure 1). The other was the topography with a horizontal resolution of 1 km used in Figure 8 from the USGS/NASA SRTM (Shuttle Radar Topography Mission, ftp://e0srp01u.ecs.nasa.gov/srtm/).

2.2 | Methods

For a better comparison between the gauge observations and the IFS forecasts, the hourly rain gauge records were accumulated every 3 hr and the IFS simulations were interpolated to stations. For most of the stations (668), there was only one station in each grid, so the nearest IFS grid point to this station was taken. For the other 41 stations (marked in Figure 1), the least-squares fit was used for the interpolation. Because the model simulations usually produce light rain too frequently, the threshold of the IFS data was set at 0.3 mm·(3 hr)^{-1} and that of the gauge data was 0.1 mm·(3 hr)^{-1}. Some sensitivity tests were performed by employing thresholds of 0.1 and 0.5 mm·(3 hr)^{-1}, and it was found that the conclusions were not sensitive to the choice of threshold. A higher threshold was associated with a lower frequency and stronger intensity of rainfall, but no significant change in the diurnal cycle (data not shown).

Rainy hours were defined as being greater than or equal to the threshold of 3 hr-accumulated rainfall. The mean rainfall amount (the mean rate of accumulated rainfall in all observational hours), frequency (the percentages of observational hours having measurable precipitation) and intensity (the mean rate of accumulated rainfall in rainy hours) were calculated every 3 hr and averaged in the warm seasons for the period 2017–2018. Hourly rainfall events were further classified according to their durations of continuous rainfall, which meant that rainfall after a period of intermittence was considered to belong to a new event, but only if the dry period lasted for ≥ 6 hr (two time slices) (Yu et al., 2007). The number of hours between the start and end of an event was defined as the duration. The calculation of the diurnal cycles of rainfall events with different durations was based on each single event.

3 | RESULTS

3.1 | Mean rainfall amount, frequency and intensity

The rainfall amount, frequency and intensity of the gauge data and IFS simulations are compared in Figure 2. For the rainfall amount (Figure 2a), maximum rainfall is near the southern border of China and along the eastern periphery of the TP. The rainfall frequency is larger over the TP, the southeastern extension of the TP and some coastal regions (Figure 2d). On the contrary, stronger rainfall intensity is mainly located in the regions with lower elevations (Figure 2g). The IFS simulations can generally reproduce well the spatial distributions of the rainfall amount, frequency and intensity of the gauge data, and the spatial correlations reach 0.76, 0.82 and 0.56, respectively. However, the rainfall amount (Figure 2b) and frequency (Figure 2e) are overestimated and the intensity (Figure 2h) is underestimated in the IFS when compared with the station rainfall data. For the rainfall amount, the overestimation is found at > 60% of all stations (Figure 2c). Over the Sichuan Basin and eastern periphery of the TP (one of the large rainfall centres), rainfall in the IFS is generally overestimated, while rainfall is underestimated at most stations along the majority of the southern boundary. The rainfall frequency is larger in the IFS at nearly 80% of stations when compared with the gauge data, but is weaker at 65% of stations with respect to the intensity. The underestimated rainfall frequency and the overestimated rainfall intensity are mainly found in the northern part of southwestern China where the rainfall is relatively low. Over areas with large rainfall amounts, the overestimated rainfall frequency and underestimated intensity are prominent.
To compare further the contributions of rainfall with different intensities with the total rainfall, Figure 3 illustrates the ratio of the rainfall of different intensities in the gauge data and IFS output. Weak rainfall occupies a considerably larger ratio for the rainfall amount in the IFS when compared with the station rainfall. For the rainfall amount in the IFS, rainfall with an intensity of $< 3 \text{ mm h}^{-1}$ can comprise $> 41\%$ of the total rainfall, while it is $15.8\%$ in the gauge data (Figure 3a). The ratios of weak rainfall frequency ($< 3 \text{ mm h}^{-1}$) to total rainfall are similar to each other (92% versus 88% in Figure 3b), which indicates that the intensity of weak rainfall in the IFS is even weaker than that in the gauge data. For heavy rainfall (with intensity $> 20 \text{ mm h}^{-1}$), it only occupies 0.7% and 0.2% of the total rainfall frequency in the gauge data and IFS output, respectively, but the ratio of rainfall amount can reach 22.7% in the gauge data, whilst in the IFS it is only 4.8%. Heavy rainfall is highly underestimated in the IFS simulations.

### 3.2 Diurnal features of rainfall events

Figure 4 presents the most frequent start, peak and end times of rainfall events in the gauge data and IFS simulations. The rainfall over most stations in southwestern China shows apparent nocturnal features in the gauge data. Rainfall events at these stations usually start during midnight and last to the early morning (Figure 4a), reach a peak shortly after (Figure 4c), and end in the period between morning and noon (Figure 4e). For the stations with afternoon rainfall peaks in the gauge data, the start time of events mainly occurs in the afternoon and ends shortly after. In the IFS, rainfall events at most stations start during the morning and last till noon; and the
rainfall at stations in the Sichuan Basin starts in the late evening (Figure 4b), which is much earlier when compared with the gauge data. The peak time in the IFS can be treated in two parts separately (Figure 4d). For the stations with afternoon diurnal peaks in the gauge data, the IFS can reproduce the peak time well. However, the IFS overestimates the afternoon peaks excessively. Over the eastern part of the southeastern extension of the TP, nocturnal peaks in the gauge data turn out to be at noon and the afternoon in the IFS. In the Sichuan Basin, the nocturnal peaks occupy a much smaller region than in the gauge data; plus, they are ahead of time. Rainfall events at most stations to the east of 105° E in the IFS usually end in the afternoon. To the west of 105° E, some stations present early morning end times, but which are still earlier than those in the gauge data.

Three typical regions are selected and outlined in Figure 4, which are the Sichuan Basin, the eastern part of the southeastern extension of the TP, and a region with afternoon peaks (from north to south). The Sichuan Basin and the eastern part of the southeastern extension of the TP are typical regions with a nocturnal rainfall feature in China, which differs from most of the inland regions that have afternoon rainfall peaks (Yu et al., 2007; Zhou et al., 2008). Some studies have suggested that the eastwards propagation of convective systems from the TP is important to the nocturnal rainfall over the leeward side of the TP (Wang et al., 2004; Qian et al., 2015). Chen et al. (2010) demonstrated that the diurnal cycles of low-level jets and the mid-level temperature advection from the TP favour the initialization and development of rainfall systems. Influenced by complex topography and many factors, the simulations of nocturnal rainfall over the leeward side of the TP are difficult. In the Sichuan Basin, the mean leading start and peak time in the IFS (Figure 5b) is 3 hr earlier than those in the gauge data (Figure 5a), and there are secondary peaks in the afternoon in the IFS. In the eastern part of the southeastern extension of the TP, the diurnal cycle of the start, peak and end time of rainfall events is out of phase between the gauge data (Figure 5c) and IFS simulations (Figure 5d). In the gauge data, rainfall events mainly begin and peak around midnight and end in the morning. The chance of a rainfall event starting is lowest in the afternoon, but is highest in the IFS. Although a slight increase is found in the diurnal variations of peak time at 1700 BJT (Beijing Time, UTC+8) in the gauge data, it is much weaker when compared with the IFS. In a typical region with afternoon rainfall peaks, the diurnal variations of the start and peak times in the IFS (Figure 5f) are consistent with those in the gauge data (Figure 5e), but the ratio of rainfall events starting around noon is still larger in the IFS. In all three regions, the time lag between the most frequent peak and the end time of rainfall events is shorter in the IFS. In the gauge data, the time lag is about 3 hr, while the most frequent peak and end time are usually simultaneous in the IFS.

Because the rainfall events in the IFS simulations usually start much earlier than those in the gauge data, the rainfall events generally last longer than they do in the gauge data (Figure 6). At 570 of 709 stations, the mean duration of rainfall events is longer in the IFS simulation, and the largest deviation is 2.5 hr. The deviation is larger over the southeastern extension of the TP. To the west of 105° E, the mean bias is about 0.64 hr, but it drops to 0.22 hr to the east of 105° E. Aside from the duration, the coverage of rainfall is also an important factor in operational forecasting. The coverage of rainfall is usually linked to the duration, such as the convective rainfall is likely to last for a shorter duration and occupy a smaller spatial coverage. We simply use the number of rainy stations within a 0.5° radius of the target rainy station to represent the coverage of rainfall. Figure 7a first illustrates the number of stations within a 0.5° radius of each station, and the stations with no neighbour within a 0.5° radius are excluded in Figures 7b–d. As shown in Figure 7b, the mean rainfall coverage is large in the IFS at all stations when compared with the gauge data. Because 1400–2000 and 0200–0800 BJT are found to be...
the two periods with relatively higher levels of rainfall (data not shown), the deviations during the daytime (1400–2000 BJT) and night-time (0200–0800 BJT) are calculated. The deviation of rainfall coverage in the daytime (1.52) is larger than that at night-time (1.21) averaged for southwestern China.

4 | DISCUSSION

The results show that large uncertainties exist in the IFS simulations over the main body and the southeastern extension of the TP, where the topography is highly complex. On the one hand, it is harder to simulate rainfall over such areas with complex topography, whilst, on the other, uncertainties can also be found in the gauge data over mountainous areas. Using the topography data with a horizontal resolution of 1 km, the standard deviations of elevations in the grid boxes (0.125 × 0.125°) around each station were calculated. Over the main body and the southeastern extension of the TP, the variations of the elevations are quite large in the 0.125 × 0.125° boxes, and the standard deviations can reach 654 m (Figure 8a). To the west of 105° E, the mean standard deviation is about 203.9 m, while it is only 101.5 m to the east. Meanwhile, Figure 8b shows the deviations between the elevation of a station and the mean in the 0.125 × 0.125° grid box around it. To
FIGURE 5  Mean diurnal variations (in BJT (Beijing Time)) of the start times (blue lines), peak times (black lines) and end times (red lines) of rainfall events in the gauge data (a, c, e) and Integrated Forecasting System (IFS) simulations (b, d, f) averaged in the regions shown in Figure 4: (a, b) Sichuan Basin (103–106° E, 28–31° N); (c, d) eastern part of the southeastern extension of the Tibetan Plateau (TP) (103–106° E, 26–28° N); and (e, f) region with afternoon peaks (107–111° E, 22–25° N)

FIGURE 6  Mean duration (coloured dots; units: hr) of rainfall events in the gauge data (a) and Integrated Forecasting System (IFS) (b), and the deviations between the IFS and the gauge data (c). The elevations over southwestern China are indicated by the grey shading (units: masl)
the west of 105°, only 28 stations show positive deviations, indicating that most of the stations are located in valleys. Since the distributions of station gauges are sparse and most of the station gauges in mountainous regions are generally situated in valleys, the actual areal-averaged rainfall may also be underreported (Huffman et al., 2007).

5 | CONCLUSIONS

The performance of the Integrated Forecasting System (IFS) forecasts with a horizontal resolution of 0.125° in simulating the warm-season mean and diurnal cycle of precipitation over southwestern China was assessed. The simulated hourly rainfall features were evaluated against
corresponding results based on station rain-gauge data. The findings can be summarized as follows:

- The IFS can capture well the spatial distributions of rainfall amount, frequency and intensity, as seen in the gauge data, and the spatial correlations can reach 0.76, 0.82 and 0.56, respectively. The rainfall frequency is generally larger and the intensity weaker in the IFS compared with the gauge data.
- Rainfall events in the IFS usually start and peak much earlier than in the gauge data, and the period between the peak and the end of events in the IFS is shorter. The evolution of rainfall events with afternoon peaks in the gauge data is relatively well simulated in the IFS, but the afternoon rainfall peaks in the IFS are overestimated. The stations with nocturnal peaks in the IFS are far fewer than those in the gauge data. The duration and coverage of rainfall events are longer and larger in the IFS. The discrepancy between the gauge data and the IFS is larger over the western part of southwestern China.

The results indicate that the IFS forecasts show considerable uncertainty when moving to the sub-daily scale, especially over areas with complex topography. Therefore, when the IFS forecasts are applied operationally, the deviations revealed in this paper should be paid more attention. Meanwhile, uncertainties also exist in gauge data over mountainous areas, so more data should be involved in future validations.

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