Seasonal Rainfall Forecasts for the Yangtze River Basin in the Extreme Summer of 2020

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ABSTRACT

Seasonal forecasts for Yangtze River basin rainfall in June, May–June–July (MJJ) and June–July–August (JJA) 2020 are presented, following successful forecasts in previous years. The 3-month forecasts are based on dynamical predictions of an East Asian Summer Monsoon (EASM) index, which is transformed into regional-mean rainfall through linear regression. The June rainfall forecasts for the middle/lower Yangtze River basin are based on linear regression of precipitation. The forecasts verify well in terms of giving strong, consistent predictions of above-average rainfall at lead times of at least 3 months. However, the Yangtze region was subject to exceptionally heavy rainfall throughout the summer period, leading to observed values that lie outside the 95% prediction intervals of the 3-month forecasts. Our forecasts are consistent with other studies of the 2020 EASM rainfall, whereby the enhanced Meiyu front in early summer is skilfully forecast, but the impact of mid-latitude drivers enhancing the rainfall in later summer is not captured. This case study demonstrates both the utility of probabilistic seasonal forecasts for the Yangtze region, but also potential limitations in anticipating complex extreme events driven by a combination of coincident factors.

Key words: seasonal forecasting, flood forecasting, Yangtze basin rainfall, East Asian Summer Monsoon.

Article Highlights:

- Seasonal forecasts for Yangtze rainfall in June, MJJ and JJA 2020 are presented.
- The forecasts correctly predicted above-average rainfall with high confidence.

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- The observed values lie outside the 95% prediction interval of the 3-month forecasts.
- This partial success is consistent with the event being driven by teleconnections from multiple sources, not all of which were predicted.

1. Introduction

The UK Met Office, in conjunction with colleagues in China, has been producing seasonal forecasts of summer rainfall in the Yangtze River Basin since 2016. Forecasts for the summer period are produced from late winter into spring, and delivered to the China Meteorological Administration (CMA) each month to help inform their official forecast messages to users across China. Development of these forecasts grew out of research demonstrating significant forecast skill in the region from the Met Office GloSea5 seasonal forecast system (Li et al., 2016) and the identification of a clear user requirement (Golding et al., 2017a), and they have continued each year following positive feedback (Golding et al., 2019). The initial trial in 2016 followed the strong El Niño event in winter 2015–2016, which provided a clear driver for likely flood conditions the following summer. The forecasts predicted a high likelihood of above-average rainfall in the May–June–July (MJJ) period, and closer to average conditions in June–July–August (JJA). These were borne out by the observations (Wang et al., 2017; Yuan et al., 2017; Bett et al., 2018), and the forecast trial was run again in summer 2017 and 2018 (Bett et al., 2020).

For the 2019 season, the forecast system was upgraded, following research on the use of an East Asian Summer Monsoon (EASM) index to skilfully forecast smaller, sub-basin regions (Liu et al., 2018). This linked with further research based on user evaluation of the earlier forecasts (Golding et al., 2017b), showing a clear requirement for improved spatial resolution and longer lead times (Golding et al., 2019). Thus, the forecasts issued in 2019 and 2020 use an EASM index to give probabilistic predictions of mean rainfall in MJJ and JJA for the Upper and Middle/Lower Reaches of the Yangtze basin separately, as well as for the basin as a whole, from the preceding February. The 2019 forecasts gave good guidance for the modestly above-average conditions in MJJ 2019, and the near-normal conditions in JJA 2019 (Zeng et al., 2020; Bett et al., 2020).

For the 2020 season, the climate service was further extended to include forecasts of June mean rainfall in the Middle/Lower Reaches of the Yangtze basin. This was based on the demonstration of significant skill in GloSea5 for predicting June mean rainfall directly in this region (Martin et al., 2020), where much of the rainfall during June is contributed by the Meiyu rain band.

In this letter, we describe the forecasts produced for summer 2020, and how they compared to the subsequent observations. We briefly outline the forecast methodology and datasets used in section 2, before describing the forecast evolution and evaluation in section 3. We summarise our results and discuss what we can learn from 2020 from a seasonal forecasting perspective in section 4.

2. Data and methods

Our Yangtze seasonal forecasts are produced using a hybrid statistical–dynamical method, designed to make the best use of the skill available in a seasonal climate prediction model, while also following a relatively straightforward approach that makes the forecast uncertainty clear, reliable and explicit to users.

The forecasts for MJJ and JJA are based on a seasonal mean forecast of the Wang & Fan (1999) East Asian Summer Monsoon (EASM) index, calculated from zonal wind at 850 hPa, u_{850}, produced by the GloSea5 seasonal forecast system (MacLachlan et al., 2015). Liu et al. (2018) demonstrated that GloSea5 could forecast this index skilfully. The forecasts for June mean rainfall in the Middle/Lower Reaches of the Yangtze basin are based on the GloSea5 rainfall output for that month. The operational GloSea5 system running in 2020 used the Global Coupled 2 configuration of the HadGEM3 climate model, described in detail in Williams et al. (2015). Two forecast ensemble members are produced each day, and a full 42-member forecast ensemble can be constructed for a given start date by pooling together the runs from the three weeks prior to that date. A hindcast ensemble is produced alongside the forecasts for calibration, covering the 24 years 1993–2016. Seven hindcast ensemble members are produced on four fixed dates each month, and a full hindcast ensemble corresponding to a given forecast is assembled from the hindcast start dates closest to the forecast members' start dates, as described in MacLachlan et al. (2015).

The EASM index is defined as the difference between the mean u_{850} in two boxes, one centred on the South China Sea minus one centred on the East China Sea (Bett et al., 2020), and is closely related to the West Pacific Subtropical High. Low values of the index correspond to anomalously anticyclonic circulation in the western North Pacific, acting to enhance the northward advection of moisture that occurs as part of the Meiyu front: this leads to increased rainfall in the Yangtze basin. High values of the EASM index on the other hand, corresponding to anomalously cyclonic circulation in the western North Pacific, act against this northward flow over China, resulting in less rainfall over the Yangtze, but more rainfall in southern China.

We use the linear regression between the hindcast ensemble-mean EASM index and the historical observed precipitation as the basis for calibrated forecasts for MJJ and JJA, and between the hindcast ensemble-mean and the observed mean precipitation for the June forecasts. We use data from the Global Precipitation Climatology Centre (GPCC, Schneider et al., 2011, 2015) as the observations. The linear regression is shown as a scatter plot in the issued forecasts, together with a contingency table describing the hit rate and false alarm rate for forecasts of above-average precipitation. (An example of a forecast document is provided as Supplementary Information.) This provides a very clear demonstration of both the skill and the uncertainty in the forecast: for example, while the linear regression shows that negative values of our EASM index often result in enhanced rainfall, the uncertainty shows that this outcome is of course is not guaranteed.

A probabilistic forecast is then produced by applying the linear regression to a new ensemble mean forecast value of the EASM index from GloSea5. The forecast central estimate is given by the regression line itself, with the forecast uncertainty given by the prediction interval on the regression. This method automatically bias-corrects for the mean and variance, and calibrates the forecast probabilities (Bett et al., 2020), within the limitations given by the length of the hindcast data set.

Bett et al. (2020) demonstrated that rainfall in the Middle/Lower Reaches of the Yangtze basin can be skilfully predicted in this way for the MJJ period, and the Upper Reaches in JJA. These regions are defined in terms of the Yangtze watershed, divided in two by a line at 111°E (shown later in Figure 4). Bett et al. (2020) also showed there was skill for the whole basin average in both periods. In all cases, forecasts could skilfully be produced at lead times of at least 3 months, i.e. from February for MJJ, and from March for JJA. Martin et al. (2020) demonstrated that June mean rainfall in a box over the Middle/Lower reaches of the Yangtze basin (25°–32.5°N, 110°–120°E) can be skilfully predicted directly by GloSea5 from February onwards, a lead time of 4 months.

Operationally, forecasts were produced every Sunday from February to June for internal monitoring. They were issued to CMA in the first week of each month, on 4th February, 3rd March, 1st April and 4th May (produced on the Sundays 2nd February, 1st March, 29th March, and 3rd May).

Finally, the observational rainfall data for summer 2020 were obtained from the GPCC monthly monitoring data set (Schneider et al., 2018).

3. Forecasts and verification

Figure 1 shows the evolution of the weekly forecasts of MJJ-mean rainfall in the Middle/Lower Reaches in 2020. The skill as measured by the correlation between hindcast and observations is consistently high (around 0.6), and the forecasts give consistently high probabilities of above-average rainfall in the region (>60%), irrespective of lead time. The probabilities of above-average rainfall increase as the lead time reduces, with the final forecast issued (end of March) having a probability of over 70% for above-average rainfall. However, Figure 1 also shows that the actual observed value from the GPCC data set is outside the 95% prediction interval of the forecast: the forecast central estimates remain within $\pm 1\sigma$ of the historical observations, while the observed value of 10.2 mm day^{-1} is $\approx 3.5\sigma$ away from the 1993–2016 mean (6.5 mm day^{-1}). In fact, the 2020 observed value lies above the 99th percentile of the prediction interval distribution for the forecast issued on 1st April – i.e. a value this extreme would be highly unlikely to occur according to the forecast. Forecasts for the whole basin in MJJ show very similar behaviour (Figure 5 in the Appendix).

The corresponding results for the forecasts for the Upper Reaches in JJA are shown in Figure 2. The skill from the hindcast is lower in this case, although it remains statistically significant at the 5% level throughout. The forecast probability of above-average rainfall in the region is again >60% at all lead times, and indeed rises to >80% in the weeks after the final forecast was issued in early May. The skill also increased in this period, and the forecast central estimate reaches about $+1\sigma$ above average. Nevertheless, the observed value, 7.1 mm day^{-1}, is over 3.5σ above average, outside the 95% prediction intervals of the forecasts. Again, a similar pattern of behaviour is seen in JJA for the basin as a whole (Figure 6 in the Appendix).

Figure 3 shows the evolution of the weekly forecasts of June mean rainfall for the box covering the Middle/Lower Reaches in 2020. The skill is statistically significant at the 5% level for all forecasts until mid-April, and the forecasts give consistently high probabilities of above-average rainfall in the region (>60%) at all lead times from late February onwards. In contrast with the MJJ and JJA forecasts, the probabilities decrease from above 80% to just over 60% as the lead times reduce, returning to higher values for the final two forecasts in May. This is thought to be related to the increasing influence of less-predictable sub-seasonal variability on monthly mean rainfall predictions as the target month approaches, reducing the signal to noise ratio. In contrast with the MJJ and JJA forecasts, the actual observed value from the GPCC data set is within the 95% prediction interval of all the forecasts from March onwards.

The breakdown of the observations by month and season is shown in Figure 4. There are strong above-average anomalies in the Upper Reaches in all four months, and in the Middle/Lower Reaches in June and July. Outside the Yangtze Basin itself, it is clear that there was also heavy rainfall in north-eastern China in May, and again in August; and in southern China in July and August.

The latitudinal progression of the monsoon rainband (Meiyu) exhibited some particular features in summer 2020, which can be seen in Figure 4 but have been investigated in detail by Liu et al. (2020): Initially, the Meiyu rainband moves north from May to June, such that the June average map shows the peak rainfall lying north of the Yangtze River itself. However, in July, the rainfall peak shifted southwards again, and can be seen lying on the Yangtze River in our figure. In August the rainband returned to its usual progression north of the Yangtze basin. Clearly, this remarkable temporary reversal in the usual monsoonal flow in July contributed significantly to the extremely high net rainfall totals over the Yangtze basin in 2020.

4. Discussion and conclusions

The rainfall in China throughout summer 2020 was truly exceptional, resulting in heavy flooding, and significant pressures on water control infrastructures such as the large hydroelectric dams along the Yangtze River. The seasonal forecasts for rainfall in June, MJJ and JJA 2020 described here provided good advice in terms of warning of the enhanced risk of above-average rainfall for both the Upper and Middle/Lower Reaches of the basin, as well as for the basin overall, at lead times of up to 3–4 months.

However, the 3-month forecasts, based on the EASM index, under-predicted the magnitude of the rainfall anomalies, and our model did not predict 2020 to be an exceptional year with respect to the 1993–2016 period (see the scatter plots in the forecast document attached as Supplementary Information). Li et al. (2021) have examined the wider behaviour of the GloSea5 forecast model data, and they demonstrate that the raw model precipitation forecasts gave anomalies of a similar magnitude, about 1σ. They also showed that the sea surface temperature (SST) anomalies in the Indian Ocean and tropical Pacific were well forecast by GloSea5, leading to successful forecasts of the atmospheric circulation in the west north Pacific, as seen in the WPSH and characterised by our EASM index. This is consistent with Takaya et al. (2020), who showed how the 2019 extreme positive Indian Ocean Dipole (IOD) event led to basin-wide Indian Ocean warmth by early summer 2020. Their forecasting experiments demonstrated that without this Indian Ocean warmth, the WPSH would have been weaker and there would have been much reduced Meiyu rainfall. However, the seasonal forecasting model they used (JMA/MRI-CPS2) also significantly underpredicted the rainfall anomaly, to a similar degree as GloSea5.

A consequence of GloSea5's successful forecasts of the EASM circulation is that our forecasts of June rainfall contained the observed value within their 95% prediction interval. Indeed, our targeting of June alone for 1-month forecasts is because of the high levels of skill originating in the EASM circulation (Martin et al., 2020). This also points towards the errors in the 3-month forecasts lying in the later summer.

Both Li et al. (2021) and Liu et al. (2020) identified a southward flow from north China towards the Yangtze basin, corresponding to the temporarily retreating Meiyu front in July (Liu et al. 2020) and the resulting extreme persistence in the Yangtze rainfall. Li et al. (2021) showed that this circulation feature was not forecast by GloSea5. Considering the June–July average, Li et al. (2021) related this southward flow to an intensification of the westerly jet stream over Asia, which GloSea5 was not able to reproduce. This is consistent with the investigation by Liu et al. (2020) on subseasonal timescales, which traced the phenomena further back to a period of negative anomalies in the summer North Atlantic Oscillation (NAO), occurring from late June and throughout July. They demonstrated that the ECMWF Extended Range Forecast model (i.e. on subseasonal timescales) was able to forecast the enhanced rainfall anomalies during the northward-advancing phase in the early summer, but was unable to capture the circulation features leading to the southward movement in July.

Although the teleconnection between the spring/summer NAO and the East Asian Summer Monsoon is well known (e.g. Linderholm et al., 2011; Bao-Qiang and Ke, 2012), this represents a problem for subseasonal and seasonal forecasts, as the summer NAO itself is not currently well predicted by models. Indeed, as emphasized by Liu et al. (2020), the most skilful forecast components are the tropical circulation, whereas the skill falls away when the midlatitude circulation becomes the dominant driver. One possibility might be to use SST patterns in the North Atlantic as an additional predictor in our forecasts, as it has been shown that these can drive the Eurasian wave patterns that modulate the EASM rainfall (e.g. Yuan et al., 2017; Li et al., 2018).

Our forecasts gave good warnings for above-average rainfall in the Yangtze basin in summer 2020, and particularly in June, based on successful forecasts of the East Asian Summer Monsoon circulation in the west north Pacific, as a correct response to the warm Indian Ocean (present in the initial conditions, but deriving ultimately from the extreme positive IOD event in autumn 2019). However, the forecast model failed to capture the midlatitude drivers that particularly affected the circulation in later summer, manifesting in changes in the East Asian Jet, which caused the Meiyu front to persist for longer over the basin resulting in the extreme rainfall and severe impacts. It is interesting that the forecast models used by Takaya et al. (2020) and Liu et al. (2020) seem to have similar drawbacks, as well as successes. It is clear therefore that further research is required to improve forecasts of extreme events driven by multiple climate factors.

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Appendix

Forecast timeseries for the whole Yangtze River Basin are presented here for MJJ (Figure 5) and JJA (Figure 6).

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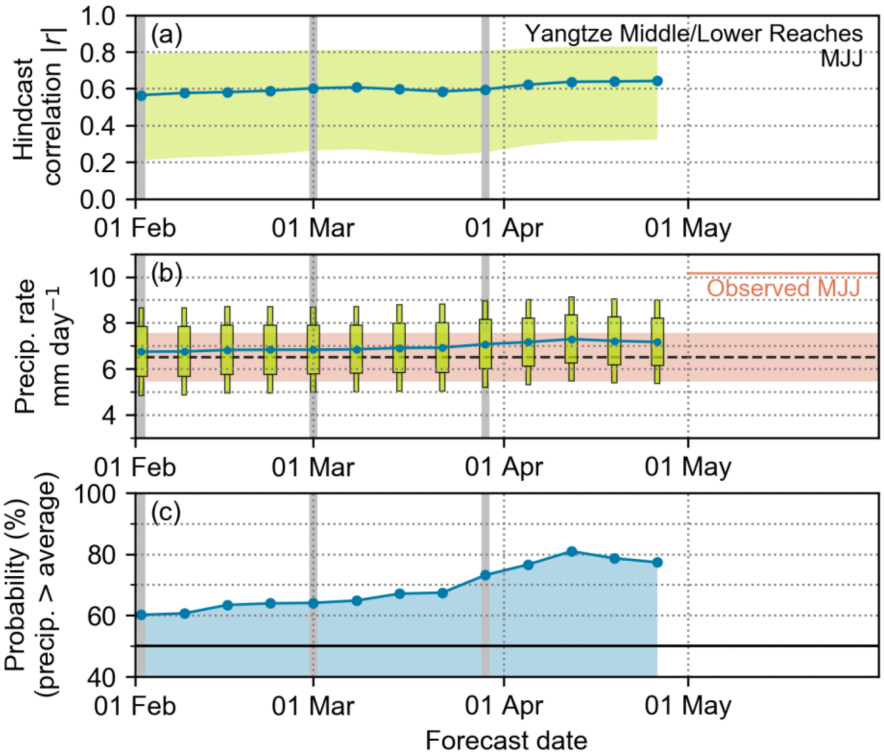


Figure 1. Forecasts for the Middle/Lower Reaches in MJJ 2020, as a function of lead time. The forecasts produced each week are shown as points, with grey vertical bars highlighting the monthly releases to CMA. Top (a): Absolute correlation between observations and the operational hindcasts available each week. The shading indicates the 95% confidence intervals on the correlation using a Fisher z test. Middle (b): The forecast signal from the linear regression, shown as the central estimates (blue line) and the 95% and 75% prediction intervals (green boxes). The observed mean over 1993–2016 is shown as a horizontal dashed line, with ±1 standard deviation shown as orange shading. The observed value for MJJ 2020 is shown as a horizontal orange line from May. Bottom (c): The forecast probability of MJJ rainfall in this region being above the 1993–2016 average.

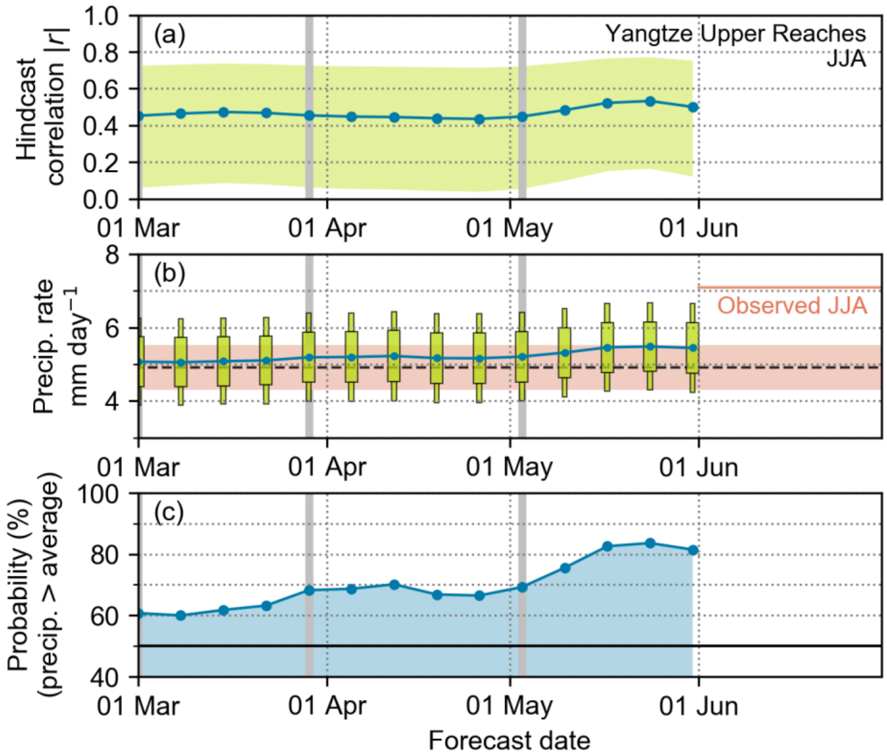
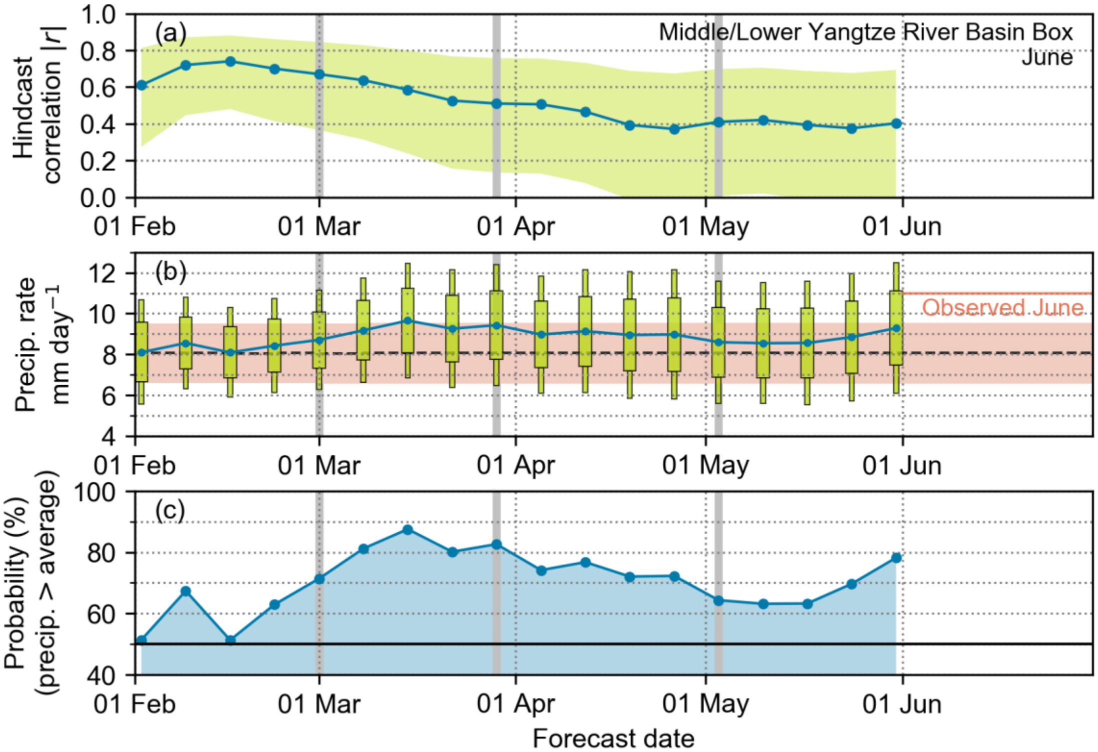


Figure 2. Forecasts for the Upper Reaches in JJA 2020, as a function of lead time, as in Figure 1.



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350 Figure 3. Forecasts for June 2020 mean rainfall in the box covering the Middle/Lower
351 Reaches (25°–32.5°N, 110°–120°E), as a function of lead time, as in Figure 1.

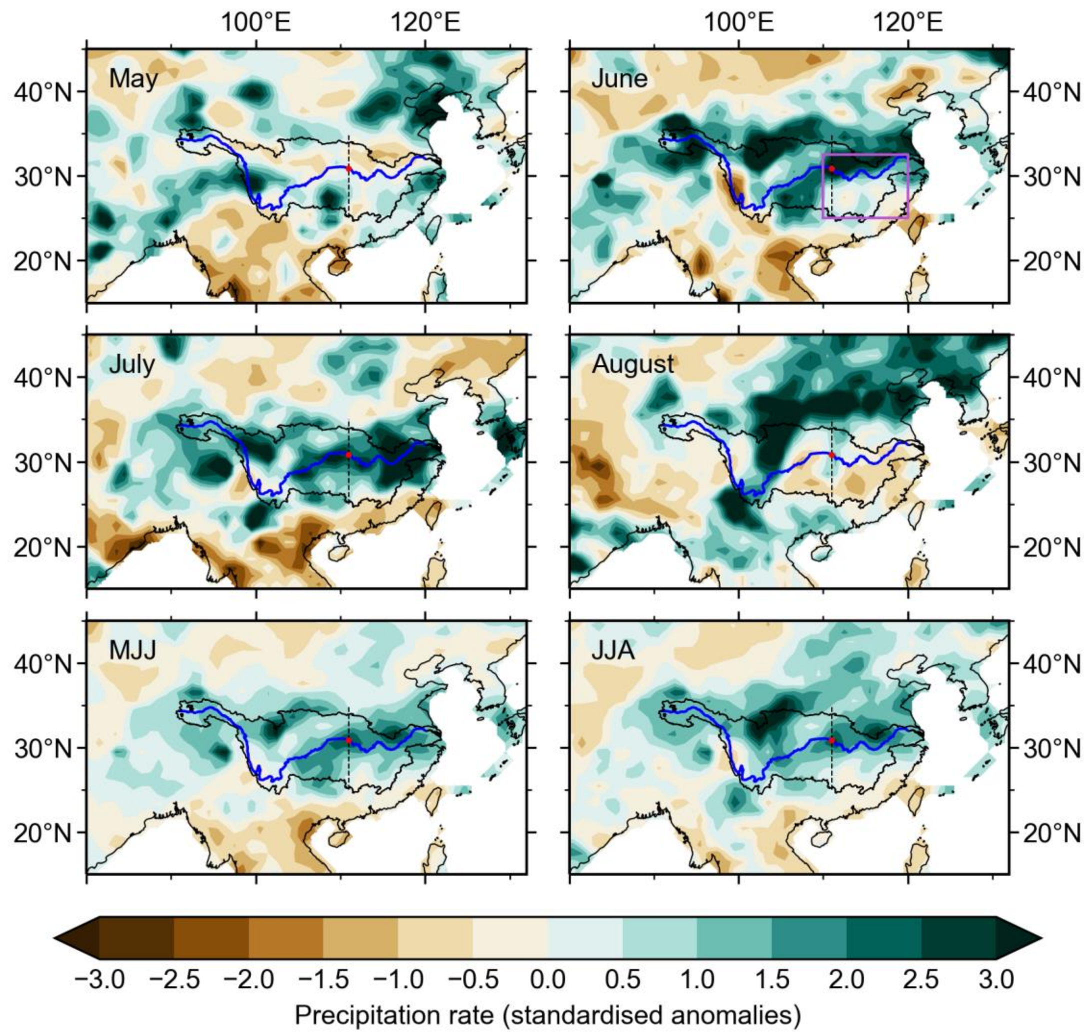

Figure 4. Precipitation maps for summer 2020, based on GPCC monitoring data (Schneider et al., 2018). Each month and season (see labels) are shown as standardized anomalies with respect to their 1993–2016 mean and standard deviation from the latest GPCC full data reanalysis (Schneider et al., 2020). The Yangtze River is marked in blue, and the basin is outlined in black, with a black dashed line showing our separation into the Upper Reaches and Middle/Lower Reaches. The box used for the Middle/Lower Reaches forecasts in June is marked in purple on the June map. The location of the Three Gorges Dam is marked in red.

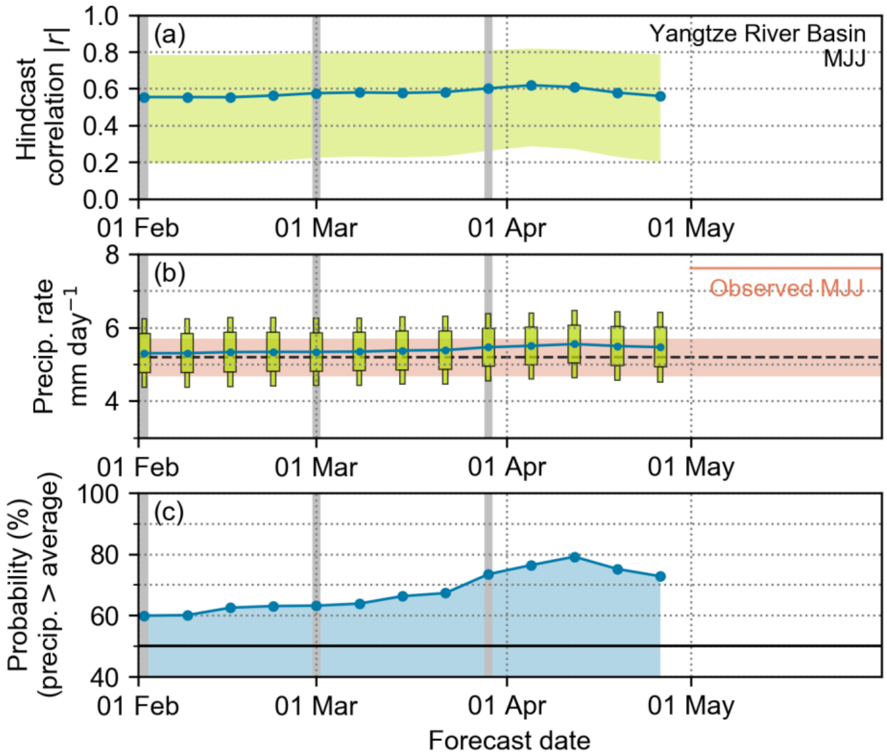

Figure 5. Forecasts for the whole Yangtze River Basin in MJJ 2020, as a function of lead time, as in Figure 1.

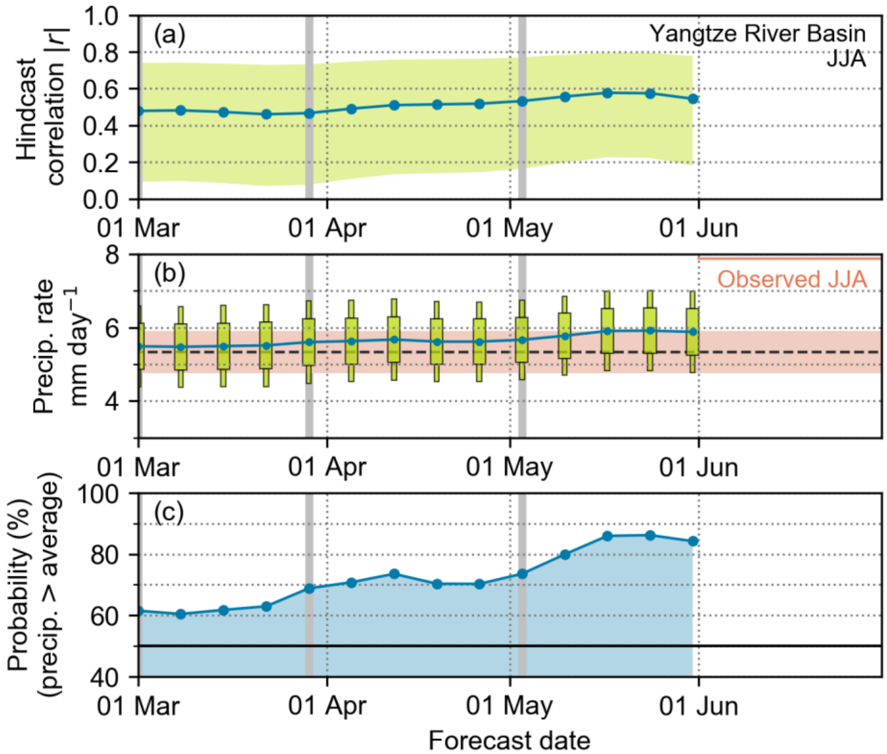

Figure 6. Forecasts for the whole Yangtze River Basin in JJA 2020, as a function of lead time, as in Figure 2.