Verification of the 2019 GloSea5 Seasonal Tropical Cyclone Landfall Forecast for East China

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ABSTRACT

A prototype climate service was developed and trialled in early 2019 to provide seasonal forecast of the June–July–August (JJA) tropical cyclone (TC) landfall risk for the East China region ahead of the forthcoming typhoon season. Test forecasts were produced in both March and April 2019 and a final forecast was released to the China Meteorological Administration (CMA) on 1 May 2019. The trial service was produced by using the Met Office Global Seasonal forecast system (GloSea5), and a forecast of the western Pacific subtropical high (WPSH) index was used to infer the TC landfall risk based on a simple linear regression between historical model WPSH indices and observed TC landfalls in East China. The forecast method shows significant skill for forecasting the JJA TC landfall risk in East China with up to three-month lead time, with the greatest skill for predictions initialized in May. The 2019 forecast provided good guidance of the near-average TC activity observed in East China in JJA 2019. Success of the forecast adds confidence to an improved climate service ahead of the 2020 typhoon season.

Key words: seasonal forecasting, typhoons, tropical cyclones (TCs), landfall risk, East China, western Pacific subtropical high (WPSH)

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1. Introduction

Tropical cyclones (TCs) can cause significant damage when they make landfall. China experiences the greatest annual average number of landfalling TCs in the world (Wen et al., 2018). In China, over 50% of societal and 18% of economic losses result from landfalling typhoons (Xiao and Xiao, 2010; Wang et al., 2016). The greatest losses occur along the coasts around the Yangtze River and Pearl River deltas, particularly in Zhejiang and Guangdong provinces (Wang et al., 2016, 2019). In 2019, East China was greatly impacted by Typhoon Lekima, which passed to the west of Shanghai. Lekima became the fifth most intense landfalling typhoon in the Chinese mainland since 1949 and lasted for 44 h on land—the sixth longest of all TCs in China on record—causing the daily average precipitation rates of 100 mm across 3.61 million km² (CMA, 2019) and 364,000 hectares of crops to be damaged (Reuters, 2019). Over one million people were evacuated, including those in Shanghai, and the total economic losses were estimated at 18 billion yuan (Reuters, 2019). Given the high impact of such events, seasonal forecasts of the TC landfall risk in East China are of significant benefit to decision makers and emergency management authorities to improve preparedness and minimize losses.

The TC landfall frequency in East China is strongly correlated with the strength of the western Pacific subtropical high (WPSH). When the WPSH is enhanced, TCs take a more westward track towards the South China Sea and landfall is reduced along the coast of East China. In contrast, when the WPSH is weakened and shifted fur-
ther towards the dateline, TCs can recurve northwards around the western periphery of the WPSH towards East China, Korea, and Japan. As a result, the TC landfall risk in East China is enhanced during periods with a weakened WPSH (Wang et al., 2013).

Camp et al. (2019) demonstrated that the UK Met Office Global Seasonal forecast system version 5 (GloSea5) shows significant skill for predictions of the strength of June–July–August (JJA) WPSH—as measured by using the WPSH index (Wang et al., 2013)—for forecasts issued on 1 May. For JJA seasons in the period of 1993–2013, the linear correlation between GloSea5 and the observed WPSH index exceeded 0.8 (significant at the 95% confidence level).

As the WPSH index is significantly correlated with the TC landfall frequency in East Asia ($r = -0.76$ for JJA 1979–2009; Wang et al. 2013), as well as the East China region used in the present study (Camp et al., 2019), the forecast WPSH index from GloSea5 can therefore be used as a broad-scale predictor of the TC landfall risk. Here, we use a simple linear regression model, which maps the relationship between historical values of the WPSH index predicted by GloSea5, and the observed East China TC landfall frequency, to provide a forecast of the TC landfall risk for the upcoming season. The East China region used in this study is shown in Fig. 1.

The statistical method follows that of the Yangtze River basin seasonal rainfall forecasts (Bett et al., 2018, 2020), which was the first climate service trial produced as part of the Climate Science for Service Partnership China (CSSP China) project in 2016 (Golding et al., 2017, 2019; Hewitt et al., 2020). Undertaking trials of climate services within CSSP China is proving to be an effective means of better understanding user needs and driving the development of additional scientific research. Here we provide verification of a new trial climate service produced through CSSP China: seasonal TC landfall risk forecasts for East China. The development of this trial climate service is described in Hewitt et al. (2020). The aim of the present study is to summarize the scientific capability underpinning the climate service.

In this study, we extend the original analysis of Camp et al. (2019) to examine the skill of GloSea5 over the longer hindcast period (JJA 1993–2016) and verify the forecast of TC landfall risk in East China issued to the China Meteorological Administration (CMA) in May 2019. As an extension to this analysis, we also examine the skill of GloSea5 forecasts of the WPSH index at 2- and 3-month lead times (on 1 March and 1 April) and demonstrate the significant skill prior to 1 May. Plans for further improvements to the forecast ahead of the 2020 typhoon season (including the increased lead time) are also discussed.

Models and data used in the study are outlined in Section 2. Verification of the WPSH index forecasts and TC landfall risk forecast for East China for JJA 2019 are provided in Section 3. Plans for future improvements to the forecasts are discussed in Section 4. A summary of the results and discussion are provided in Section 5.

Fig. 1. The East China landfall region (boxed; thick black line) used to forecast the tropical cyclone (TC) landfall risk. The red star shows the location of Shanghai. This is a subset of the East Asian region used in Wang et al. (2013) and Camp et al. (2019).
2. Model, data, and analysis

The model used in this study is the UK Met Office GloSea5 (MacLachlan et al., 2015) with the Global Coupled model 2.0 (GC2; Williams et al., 2015; Walters et al., 2017) configuration. GloSea5 is a fully coupled ocean–atmosphere–land–sea ice ensemble prediction system and is used to produce operational seasonal forecasts at the Met Office, including forecasts of TCs (Camp et al., 2015, 2018a). The atmospheric model horizontal resolution is 0.83° longitude × 0.55° latitude (corresponding to approximately 60 km in the midlatitudes), with 85 vertical levels extending into the stratosphere. The ocean model has a global resolution of 0.25° (27 km on the equator) on a tripolar grid with 75 vertical levels. The GloSea5 system utilizes the Even Newer Dynamics for General atmospheric modelling of the environment (ENDGame; Wood et al. 2014) dynamical core, and shows significant skill for predictions of the TC activity from subseasonal (Camp et al., 2018b; Camargo et al., 2019; Gregory et al., 2019) to seasonal (Camp et al., 2015, 2018a; Klotzbach et al., 2019) timescales.

The skill of GloSea5 in predicting the WPSH index and TC landfall risk is examined in JJA seasons over the 24-yr hindcast period of 1993–2016. Each hindcast ensemble member is started on one of four dates centered around 1 May: 17 April, 25 April, 1 May, and 9 May. Each of these four start dates has 7 ensemble members, which are then combined to provide a 28-member hindcast ensemble per year. The hindcasts are initialized by using the ECMWF interim reanalysis (ERA-Interim; Dee et al., 2011). The ocean and sea ice are initialized from historical reanalysis by using the NEMOVAR system (Waters et al., 2015). We also examine the skill of real-time forecasts for JJA 2017–2019 from 1 March, 1 April, and 1 May. The forecast ensemble combines the previous 21 days of forecast runs leading up to the issue date (for example, a forecast for 1 May uses ensemble members dating back to 10 April). There are two ensemble members per day, providing a combined 42-member forecast ensemble each year.

The WPSH index is calculated by using the method of Wang et al. (2013) and Camp et al. (2019), and is defined as the normalized 850-hPa geopotential height (GPH) averaged over the region 15°–25°N, 115°–150°E. This region experiences the greatest interannual variability in JJA 850-hPa GPH within the subtropical western North Pacific (see Fig. S3A of Wang et al., 2013) and is significantly correlated with the TC frequency in East Asia.

For comparison with GloSea5, the monthly 850-hPa GPH are retrieved from ERA-Interim reanalysis (Dee et al., 2011) at a grid resolution of 0.75° × 0.75° covering the period of JJA 1993–2019. The WPSH index is calculated for ERA-Interim by using the same method as that for GloSea5.

The observed sea surface temperature (SST) anomalies for the equatorial Pacific Niño3.4 region (5°S–5°N, 120°–170°W, ) are from the U.S. NOAA Climate Prediction Center (CPC, 2020) for the period of JJA 1993–2016.

The observed TCs in the western North Pacific basin are from the U.S. Navy’s Joint Typhoon Warning Center (JTWC) best-track database (Chu et al., 2002). The real-time observations for the 2019 season are from the operational best-tracks from JTWC, as provided through the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al., 2010). It is noted that the final location and strength of TCs may change following a post-season analysis. TCs must have a 1-minute maximum sustained wind speed of at least 34 kt (i.e., 39 mph or 17.5 m s⁻¹). The observed TC landfall frequency in East China is calculated as the total number of observed TC tracks that intersect the East China region (indicated by the black box in Fig. 1).

3. Results

In this section, we examine the skill of predictions of the WPSH index in GloSea5 for JJA 1993–2016 and provide verification of forecasts of the TC landfall risk in East China for JJA 2017–2019. The 2019 forecasts were made in real time, but the 2017 and 2018 forecasts were produced retrospectively, by using archives of the real-time forecast data for those years. A summary of the observed TC activity in the western North Pacific during JJA 2019 is also provided.

3.1 Skillful predictions of the WPSH index

We first explore the skill of predictions of the WPSH index. Figure 2 shows the GloSea5 ensemble-mean WPSH index versus ERA-Interim for the period of JJA 1993–2016, alongside forecasts (red dots) and verification (ERA-Interim; black dots) for JJA 2017–2019 issued on 1 May. GloSea5 predicts the interannual variability of the WPSH index, with a linear correlation between the GloSea5 ensemble-mean and ERA-Interim WPSH index of 0.80 (significant at the 95% confidence level) for the period of JJA 1993–2016. In particular, GloSea5 captures the enhanced WPSH index in 1998 and 2010, as well as the weakened WPSH index in 2004.

Forecasts for JJA 2017 and 2018 (red dots; Fig. 2) also performed well. These seasons had contrasting predic-
tions of the WPSH index. GloSea5 was able to correctly predict the tendency for an above-average WPSH index in JJA 2017 and a below-average WPSH index in JJA 2018.

For the trial climate service issued on 1 May 2019, GloSea5 forecasts a near-average WPSH index for JJA 2019 with a value of −0.06, which verified well against the ERA-Interim reanalysis value of −0.40 (standardized with respect to JJA 1993–2016).

3.2 2019 TC landfall risk forecast for East China

We now examine the real-time prediction of the TC landfall risk in East China for 2019 by using GloSea5. Figure 3 shows the relationship between the GloSea5 hindcast WPSH index and observed TC landfall frequency in East China for JJA 1993–2016, together with the forecast for JJA 2019 issued on 1 May 2019. The observed TC landfall frequency in East China is significantly correlated with the GloSea5 WPSH index for the period of JJA 1993–2016 ($r = −0.59$; significant at the 95% confidence level). To estimate the landfall risk for JJA 2019, we first construct a linear regression model between the GloSea5 hindcast ensemble-mean WPSH index and observed TC landfall frequency in East China, following the method of Bett et al. (2018, 2020), assuming a normal distribution. The 75% and 95% prediction intervals are then calculated to provide an estimate of the uncertainty of a future forecast about the linear fit: they describe the conditional probability distribution for a future observation, given the GloSea5 WPSH forecast, and accounting for the uncertainty in the regression due to sampling (Wilks, 2011). In Fig. 3, the linear regression model is illustrated by a solid grey diagonal line, with shaded grey bands showing the 75% and 95% prediction intervals.

To create the forecast for JJA 2019, we take the GloSea5 forecast ensemble-mean WPSH index (as predicted by the 42-member ensemble) for JJA 2019 (−0.06) and map this to the linear regression model, with the uncertainty in landfall risk estimated from the prediction intervals. In Fig. 3, the forecast (light red) is shown as a central estimate (dot with vertical line), with the boxed regions showing the 75% and 95% prediction intervals, respectively.

In May 2019, the forecast WPSH index for JJA 2019, and thus the landfall rate for East China, was predicted to be very close to the climatological mean (vertical and horizontal dashed lines in Fig. 3) of around 3 TC landfalls. Indeed, the forecast predicted a 50% chance of the above-normal TC landfalls in East China during this period. In the event, three TCs made landfall; namely, Tropical Storm Danas, Super Typhoon Lekima, and Tropical Storm Bailu. Tracks of these TCs, as well as others observed in JJA 2019, are shown in Fig. 4. The forecast from 1 May therefore provided good guidance of the near-average TC landfall frequency observed in East China in JJA 2019.

For completeness, we also note that forecasts performed well from 1 May 2017 and 2018 (figures omitted). Indeed, GloSea5 predicted a 40% chance of the above-average TC landfalls in East China during JJA 2017, in contrast to a 70% chance of the above-average TC landfalls in JJA 2018. In the event, two TCs made landfall in JJA 2017 and seven in JJA 2018. GloSea5 was therefore able to correctly predict the tendency of reduced TC landfall risk in 2017 relative to 2018.

3.3 The 2019 typhoon season

There were 11 TCs in the western Pacific during JJA 2019 and, as described above, 3 intersected the East China region (Fig. 1): Tropical Storm Danas, Super Typhoon Lekima, and Tropical Storm Bailu.
June saw the formation of only one TC (Sepat), which formed close to and impacted Japan. In July, two Tropical Storms (Mun and Wipha) affected the South China coast and Tropical Storm Danas made landfall in South Korea. The most significant typhoon to impact East
China (including the Yangtze River Delta) was Typhoon Lekima in August 2019, whose center passed to the west of Shanghai. Lekima made landfall in Wenling in the eastern coastal province of Zhejiang and was the fifth most intense typhoon to impact the Chinese mainland since the records began in 1949 (CMA, 2019). The typhoon resulted in extreme heavy rain in the eastern provinces of Zhejiang, Jiangsu, and Shandong, with Zhejiang recording the daily average precipitation rates of 165 mm, the second highest on record for the province (CMA, 2019). It is estimated that the daily rainfall rates of over 100 mm occurred over an area of 3.61 million km$^2$ (CMA, 2019). In Zhejiang Province, the heavy rain led to flooding and landslides and caused buildings to collapse. The total economic loss from Typhoon Lekima in China has been estimated at 18 billion yuan (US$2.55 billion), including damage to 364,000 hectares of crops (Reuters, 2019). Three other TCs also formed in August: Typhoon Krosa made landfall in Japan, and Tropical Storms Bailu and Podul impacted South China and Vietnam, respectively.

4. Improved TC landfall risk forecast for 2020

We now discuss possible areas of development of the scientific capability underpinning this climate service (i.e., seasonal TC landfall risk forecasts for East China) ahead of the 2020 typhoon season. These developments aim to provide an improved service of greater benefit to CMA, both in terms of the increased lead time as well as through improvements in the forecast skill.

Following the early evaluation and feedback of the 1 May 2019 forecast in June 2019, it was found that a key benefit to CMA would be a skillful forecast released at a longer lead time to allow more time to prepare and to enable input to the existing institutional procedures (Hewitt et al., 2020). For the TC landfall risk forecast specifically, it is preferable that the initial predictions are released during March to coincide with seasonal forecast meetings held by CMA prior to the typhoon season. This would enable the forecast to be used alongside predictions from the Beijing Climate Center and the Shanghai Typhoon Institute (Hewitt et al., 2020). To examine whether GloSea5 is able to provide forecasts at this longer lead time, we analyze the skill of GloSea5 hindcasts of the WPSH index for JJA 1993–2016 from both a 2- (1 April) and a 3-month (1 March) lead time. Time series of the GloSea5 ensemble-mean WPSH index versus ERA-Interim are shown for both 1 March and 1 April for hindcasts covering JJA 1993–2016, as well as forecasts for JJA 2017–2019, in Fig. 5. The corresponding linear correlations between GloSea5 and ERA-Interim are provided in Table 1 (for brevity this table also includes the skill of forecasts issued on 1 May).

GloSea5 shows significant skill for predictions of the JJA WPSH index from both 1 March (linear correlation $r = 0.72$) and 1 April (0.74), with the greatest skill from 1 May (0.80; all correlations are significant at the 95% confidence level). Nevertheless, it is worth noting that the forecast performance for JJA 2017–2019 from 1 March and 1 April was mixed. In 2018, GloSea5 correctly predicted the below-average WPSH index from 1 March and 1 April; however, in 2017 (2019), GloSea5 underestimated (overestimated) the size of the WPSH index with respect to the 1993–2016 climatology (Fig. 5). Thus, in these two years, the best guidance was provided by forecasts issued on 1 May (Fig. 2). This suggests that even though forecasts from 1 March and 1 April exhibit certain skill and would provide useful information for decision-makers, a further forecast update around 1 May would likely be beneficial to providing the most skillful

![Fig. 5. As in Fig. 2 but for the ERA-Interim (black) and GloSea5 WPSH index (Wang et al., 2013) from 1 March (red) and 1 April (blue).](image-url)
and up-to-date guidance to users ahead of the forthcoming season.

To address improvements in the skill of seasonal forecasts, we explore two key areas as part of ongoing research for CSSP China: the East China forecast region and underlying statistical model used to forecast TC landfall risk. Firstly, the East China region currently used to provide an indication of the landfall risk (Fig. 1) is large, extending towards both northern coastal China and the Taiwan Island. The eastward boundary of the box is also far offshore, allowing TCs that pass through the region but do not make a direct landfall in East China, to be included in the landfall forecast (e.g., Tropical Storm Danas in July 2019), which is not desirable. Research is currently underway to examine whether adjustments to the East China region (to focus more on the coast of East China specifically) will improve the skill of TC landfall forecasts and make them more relevant for CMA. Finally, attempts are also being made to improve the underlying statistical model used to create the forecast. The statistical model used to predict the TC landfall risk in this study assumes that the historical observed WPSH index and TC landfall frequency in East China are Gaussian distributed. However, this assumption does not hold for the TC landfall frequency, which is positive definite and is better approximated by a Poisson process. We have identified that allowing the TC landfall frequency to be modeled as a Poisson process can improve the skill of landfall forecasts, in agreement with previous studies (e.g., Zhang et al., 2017; Zhang and Villarini, 2019). Forecasts of the landfall risk for the 2020 typhoon season will therefore use this improved statistical method to provide a better estimate of the landfall risk for CMA.

Finally, although not considered in detail as part of CSSP China at present, the underlying predictors used to forecast the TC landfall risk for East China could also be re-examined. To date, we have based the seasonal forecast of the TC landfall risk solely on predictions of the WPSH index (i.e., 850 hPa GPH), following the studies of Wang et al. (2013) and Camp et al. (2019). However, recent studies have shown that SSTs in both the North Atlantic (Gao et al., 2018; Zhang and Villarini, 2019) and Pacific Ocean (Zhang and Villarini, 2019) could also provide skillful indicators of the TC landfall risk for East Asia. Tian and Fan (2019) also demonstrated that SSTs in Southwest Indonesia, as well as summer atmospheric predictors (such as divergence and vorticity), were important for skillful forecasts of the TC landfall risk specifically in China. Further consideration of these predictors (either individually or in combination) could be beneficial, as this may further improve the forecast skill and predictability at longer lead times. Examining the role of El Niño–Southern Oscillation (ENSO) on the TC landfall frequency, such as in studies of Wu et al. (2004) and Zhang et al. (2012), could also extend predictability of the TC landfall risk in East China from JJA into autumn (September–November) in the future.

Table 1. The linear correlation between the GloSea5 ensemble-mean predicted WPSH index and ERA-Interim reanalysis for JJA 1993–2016 for forecasts initialized on 1 March, 1 April, and 1 May 2019. For all the three start dates, the skill is significant at the 95% confidence level.

| Forecast date | 1 March | 1 April | 1 May |
|---------------|---------|---------|-------|
| Linear correlation | 0.72 | 0.74 | 0.80 |

5. Summary and discussion

In this study, we examine the skill of GloSea5 to predict the WPSH index (Wang et al., 2013) and provide verification of the TC landfall risk forecast for East China issued on 1 May 2019 for the period of JJA 2019. This paper extends the analysis of Camp et al. (2019), and applies the statistical approach used by Bett et al. (2018, 2020) for seasonal rainfall forecasts for the Yangtze River basin, to develop a trial climate service of the TC landfall risk for East China during the boreal summer (JJA).

GloSea5 shows significant skill ($r = 0.80$) for predictions of the WPSH index during JJA 1993–2016 (significant at the 95% confidence level) for forecasts issued on 1 May. On 1 May 2019, the first trial TC landfall risk forecast using GloSea5 was released to CMA ahead of the forthcoming typhoon season. This forecast predicted a near-average WPSH index and a 50% chance of the above-average TC landfall frequency in East China during JJA 2019. In the event, 11 TCs formed during JJA 2019, 3 of which (Danas, Lekima, and Bailu) intersected the East China landfall region (Fig. 1). GloSea5 therefore provided good guidance of the near-average TC landfall activity observed in East China in JJA 2019.

Two key improvements to the forecast have been identified to be of benefit to CMA following the early feedback and evaluation of the service in June 2019 (Hewitt et al., 2020): (1) a forecast released at a longer lead time (preferably in March to coincide with seasonal forecast meetings held by CMA prior to the typhoon season) and (2) continued improvements in the skill of seasonal forecasts. Research into increasing the lead time of forecasts shows that GloSea5 skill decreases slowly with lead time and predictions of the JJA WPSH index from both 1 March and 1 April are skillful. This suggests the poten-
tial for a trial forecast for the 2020 typhoon season to be released at a 3-month lead time in March 2020, greatly improving on the 1-month lead time given for forecasts for JJA 2019 from 1 May 2019. Secondly, two methods for improving the forecast skill have been identified: adjustments to the East China forecast region (meanwhile making it more applicable for CMA) and the underlying statistical method used to generate the TC landfall forecast. The latter would enable the observed TC landfall frequency to be modeled as a Poisson process as opposed to Gaussian, which would provide a more skillful forecast of the TC landfall risk for East China. When combined, these improvements will allow an improved climate service to be provided to CMA ahead of the 2020 typhoon season.

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