Prediction and attribution of quiescent tropical cyclone activity in the early summer of 2016: case study of lingering effects by preceding strong El Niño events

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Abstract
We investigated mechanisms contributing to the quiescent tropical cyclone (TC) activity in the western North Pacific (WNP) during the early summer (May–July) of 2016 by conducting and analysing seasonal predictions and sensitivity experiments with an atmosphere–ocean coupled model. In the seasonal prediction experiment, the model successfully predicted the inactive TC condition. Sensitivity experiment simulations, in which the warmer-than-normal sea surface temperature (SST) in the Indian Ocean (IO) was restored to the climatology, represented a weakened lower-tropospheric anticyclonic anomaly and near-normal TC activity over the WNP. These results suggest that the quiescent TC activity is attributable to the warm IO SST anomalies induced by the preceding 2015/2016 El Niño. Verification and analysis of reforecasts indicated that the TC count in early summer is highly predictable due to IO warming, a lingering effect of preceding El Niño events.

Keywords: tropical cyclone; seasonal prediction; Indian Ocean; El Niño

I. Introduction

The western North Pacific (WNP) is the most active basin for tropical cyclones (TCs), and its TC activity has a profound socio-economic influence on Asian countries (Zhang et al., 2009; Weinkle et al., 2012). Accurate seasonal prediction of TCs is expected to contribute to mitigate the risk of human and economic losses caused by TCs.

Much effort has been made in developing and improving seasonal TC predictions (Vitart, 2006; Camargo et al., 2007; Takaya et al., 2010; Vecchi et al., 2014; Camp et al., 2015). Some operational and research institutes currently issue seasonal TC predictions (Camargo et al., 2007). A better understanding of the interannual variability of the TC activity and improving the predictive performance of seasonal prediction systems are important in facilitating the improved use of forecast information.

Recent studies provide a promising perspective on the seasonal prediction of WNP monsoon and TC activity in boreal summer on the basis of the potential predictability originating from lingering effects of preceding strong El Niño events (Xie et al., 2009; Kosaka et al., 2013; Wang et al., 2013; Xie et al., 2016). Two mechanisms have been proposed to explain these lingering effects on the WNP monsoon (Wang et al., 2003; Xie et al., 2009). This study focuses on one of the mechanisms: the ‘Indian Ocean capacitor effect’ put forward by Xie et al. (2009). Strong El Niño events trigger sea surface temperature (SST) warming in the Indian Ocean (IO) during their mature and decay phases (boreal winter–spring) through oceanic Rossby wave and wind–evaporation feedback mechanisms (Xie et al., 2002; Du et al., 2009), and the warmed SSTs and enhanced convectons in the IO in turn induce an anticyclonic anomaly in the lower troposphere and suppressed convections over the WNP. These conditions often persist through the summer.

Moreover, a few studies have investigated impacts of preceding El Niño events on TCs in the WNP. Such work has found that the IO warming by preceding strong El Niño events inhibits WNP TC activity in the following summer and pointed out a possible IO contribution to the high predictability of seasonal TC activity (Du et al., 2011, hereafter DYX11, Zhan et al., 2011a, hereafter ZWL11, Zhan et al., 2011b). DYX11 examined the relationship between TC activity and SST in the IO basin during July–September and showed that TC activity is suppressed in summers following El Niño events. DYX11 reported that the warm tropical IO induced by a preceding El Niño causes an inactive TC condition during July–September. ZWL11 examined the relationship between the eastern IO SST and TC activity during June–October.

The early summer (May–July) of 2016 exhibited profound quiescent TC activity. The year also marked the second latest record of the first typhoon genesis date of the year since 1951 (the first named Typhoon “Nepartak” formed on 3 July 2016). From the results of previous studies (DYX11, ZWL11), the quiescent
TC activity was likely associated with a warmed IO induced by the preceding El Niño.

As reviewed above, a few studies have focused on the relationship between TC activity and IO SST; however, to our best knowledge, the feasibility of the seasonal TC prediction has not been studied in this context. Moreover, the seasonal dependence of seasonal TC predictability and its link to the IO have not been reported. Here we analyse a set of numerical simulations for the early summer of 2016 using a state-of-the-art atmosphere–ocean coupled model with a special focus on the early summer. Furthermore, we analyse reforecasts and discuss underlying mechanisms and the seasonal dependence of seasonal TC predictability.

2. Data and methods

We conducted seasonal prediction and sensitivity experiments using the Japan Meteorological Agency/Meteorological Research Institute-Coupled Prediction System version 2 (JMA/MRI-CPS2, Takaya et al., 2017b), which is the latest operational seasonal prediction system of JMA. The system adopts an atmosphere–ocean–land–sea-ice coupled model with an atmospheric resolution of 110 km and ocean resolution of 1°×0.5°. Further details are described in Takaya et al. (2017b). We verified the performance of the system in predicting seasonal TCs and found that it is comparable to that of its precedent system (JMA/MRI-CPS1, Takaya et al., 2017a, 2010).

In the control seasonal prediction experiment (CTRL), a total of 52-member ensembles were integrated from initial dates of 11, 16, 21, and 26 April 2016 (13 members from each initial date). In the sensitivity experiment (IOclim), the experimental settings were almost the same as those of CTRL, except that SST in the IO basin (illustrated in Figure 1(e)) was strongly nudged to the model climatology of the same system; specifically, the Newtonian nudging term with a coefficient of 2400 W m⁻² K⁻¹ was added to the surface layer so that SST was sufficiently restored to the climatology of reforecasts during 1981–2010 (c.f. Morioka et al., 2014).

In this study, we analysed TCs classified in categories stronger than the tropical storm, which have sustained winds exceeding 34 knots (17.2 m s⁻¹). We detected simulated TCs using an objective algorithm (Takaya et al., 2010, Appendix A). We set parameters in the detection algorithm so that the model produces a realistic climatological number of TC genesis. Validation of the algorithm using the JRA-25 analysis (Onogi et al., 2007) showed a reasonable agreement between the detected TCs and best track data (Takaya et al., 2010).

Analysis data used in this study were the JRA-55 reanalysis (Kobayashi et al., 2015) for atmospheric analysis, CPC Merged Analysis Precipitation (CMAP,
The pronounced quiescent TC activity during May–July 2016 was associated with large-scale atmospheric and oceanic conditions in the Indo-Pacific basin. Figure 1 shows the observed and predicted SST, precipitation, and 850-hPa stream function anomalies during May–July 2016. The negative anomalies spread broadly in the WNP, a lower-tropospheric anticyclonic anomaly and deficit precipitation were observed as a forced atmospheric response to the IO (Watanabe and Jin, 2003). The prediction (CTRL) successfully captured these conditions with a 0-month lead time (Figures 1(c) and (d)).

Figure 2(a) illustrates anomalies of the TC count in 5° × 5° boxes in CTRL during the period May–July 2016. The negative anomalies spread broadly in the WNP in response to the above-mentioned weak WNP monsoon conditions is consistent with ZWL11.

Figure 3 shows the observed and predicted time-series of the TC count in the WNP (0°–60°N, 100°E–180°E) during May–July. During May–July 2016, the observed TC activity was extremely weak compared with the climatology and only four TCs were determined in the RSMC Tokyo analysis. This inactive TC condition was well captured by CTRL with an ensemble mean TC count of 4.3. The interannual variability of TC genesis is well captured by the 10-member reforecasts, in particular, the inactive TC years following strong El Niño events such as 1998 and 2010, indicating strong lingering effects of the preceding El Niño events. The correlation coefficient of the total TC counts between the best track analysis and the prediction is 0.69 during 1981–2010, which is higher than that of the other summer periods (Table 1). These results indicate that the TC count is highly predictable especially during May–July.

The inactive early TC season (May–July 2016) is likely to have resulted from the IO warming (Figure 1(a)), which was plausibly forced by the tropical teleconnection of the preceding El Niño event in the 2015/2016 winter (Klein et al., 1999; Lau and Nath, 2000). To attribute the inactive early-summer TC to the warm IO condition, we conducted an idealized experiment (IOclim). Figures 1(e) and (f) display the simulated SST, precipitation anomalies and 850-hPa stream function anomalies in IOclim. The SST anomalies in the IO were close to zero, indicating that the SST in the IO is sufficiently constrained by the model climatology. Below-normal precipitation is seen in the IO in contrast to CTRL, and the anticyclonic anomaly in the WNP is rather weak compared with that of CTRL.

Figure 2 compares anomalies of the TC counts in CTRL and IOclim. As expected from the large-scale atmospheric conditions over the WNP, CTRL presents broad negative anomalies of TC genesis over the WNP, whereas IOclim presents near-normal TC genesis. Correspondingly, the total TC count was close to the climatology in IOclim in contrast to the remarkably small TC count in CTRL (Figure 3). Our results presented herein suggest that the quiescent TC activity observed in the 2016 early TC season is mostly attributable to the IO warming.

4. Conclusions and discussion

We have presented results of seasonal TC simulations for the early summer (May–July) of 2016. The latest JMA seasonal prediction system well predicted the quiescent TC activity in the season. Our verification (Table 1) suggested that the predictive skill of the TC count for the early TC season is high (correlation coefficient of 0.69), and it is higher than that for the other consecutive 3-month periods during the TC season. Kosaka et al. (2013) presented the lagged correlation between the NINO3 (5°N–5°S, 150°–90°W) SST during December–February and the monthly TC counts, which shows the largest negative correlation in June (Figure 1 in their paper). Together with their finding, our results suggest that the lingering effect of an El Niño on the TC activity is stronger in the early summer and TC activity is more predictable during the early summer than other 3-month periods during the TC season. We note that JMA/MRI-CPS2 has a high predictive skill (correlation coefficient of >0.8) for the TC
Figure 3. Time-series of total TC counts during May–July. Red line indicates the best track analysis and the black line indicates the predictions with a 0-month lead time. Whiskers represent the maximum and minimum ranges of 10 member ensembles, except for those of 52 members from the real-time operational predictions for 2015 and 2016 (CTRL experiment). The blue dot and whiskers show the result of the IOclim experiment.

Table 1. Correlations between TC counts for 3-month periods in the best track analysis and those of the predictions with a 0-month lead time. The 10-member ensemble mean predictions were verified for a 30-year period (1981–2010).

| Initial month | Target months | Correlation |
|---------------|---------------|-------------|
| May           | May–July      | 0.69        |
| June          | June–August   | 0.53        |
| July          | July–September| 0.42        |
| August        | August–October| 0.17        |

We also elucidated the attribution of the quiescent TC activity in the early summer of 2016 by conducting and analysing the prediction and sensitivity experiment. The prediction experiment (CTRL) represented a broad decrease in TC genesis over the WNP in contrast to the sensitivity experiment, in which the IO SST was restored to the model climatology. The anomaly pattern in CTRL differs from that expected for an El Niño/La Niña response in summer, which is characterized by a northwest–southeast shift of genesis location (Wang and Chan, 2002; Takaya et al., 2010). Our results are consistent with the results of ZWL11, who pointed out that a warm eastern IO SST reduces the total number of TCs in the WNP during the TC season (June–October).

It is worth comparing the 2016 case with other cases following El Niño events. Figure 4 shows composites of the anomalies of TC counts in the best track analysis and predictions during the years following El Niño events (1983, 1988, 1992, 1998, 2003, and 2010). The anomalies are given relative to the reforecast climatology of each dataset during 1981–2010.

The observed inactive TC condition in the early summer following El Niño events was well reproduced in the reforecasts of JMA/MRI-CPS2, supporting the hypothesis that the preceding El Niño and lingering IO warming are sources of the predictably of early summer TC activity in the WNP. The results presented in this early summer following El Niño events was observed in the historical record, as seen in Figure 3. Nakazawa (2001) pointed out that inactive TC genesis in the WNP in 1998 was related to anomalous lower-tropospheric anticyclonic circulation and subsidence over the WNP, which was induced by the anomalous IO convective activity and ascending motion, associated with the 1997–1998 El Niño. This is a recursive situation in summers following El Niño events (DYX11, ZWL11). The observed inactive TC condition in the early summer following El Niño events was well reproduced in the reforecasts of JMA/MRI-CPS2, supporting the hypothesis that the preceding El Niño and lingering IO warming are sources of the predictably of early summer TC activity in the WNP. The results presented in this
paper indicate high predictably of seasonal TC activity and feasibility of operational seasonal TC prediction during early summer.

**Appendix A: TC detection algorithm**

The TC detection algorithm used in this study is briefly described here. TCs in the model simulations are objectively detected using model outputs at $1.5^\circ \times 1.5^\circ$ resolution according to the following conditions and criteria.

1. A grid point with a local sea level pressure (SLP) minimum within $6^\circ \times 6^\circ$ over the ocean between the equator and $30^\circ$N is searched to detect the center of a candidate TC.
2. At any point within $3^\circ \times 3^\circ$ of the center of the TC, the relative vorticity at 850-hPa is below $5 \times 10^{-5}$ s$^{-1}$.
3. A warm core exists near the local SLP minimum. The thickness between 200 and 500 hPa geopotential height at the center of the TC is 7 gpm higher than the average thickness within grids surrounding the center of the TC within a $9^\circ \times 9^\circ$ box, excluding the center grid (24 grids).
4. At the center of the TC, the wind speed at 200 hPa is lower than that at 850 hPa.
5. The four conditions listed above continue for at least 12 h.

The parameters were chosen so that the number of detected TCs was reasonably close to that for analysed TCs (maximum wind exceeding 17.2 m s$^{-1}$) in the RSMC Tokyo best track analysis.

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