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SHORT COMMUNICATION

Simulated ENSO's impact on tropical cyclone genesis over the western North Pacific in CMIP5 models and its changes under global warming

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El Niño–Southern Oscillation (ENSO) plays an important role in modulating the location of tropical cyclone (TC) genesis over the western North Pacific (WNP). This study evaluated the simulation of the ENSO's impact on WNP TC genesis in 10 CMIP5 models based on a TC detection method, and projected its changes under global warming using the historical and the representative concentration pathway 8.5 (RCP8.5) simulations. The observed southeast–northwest shift role of ENSO in the WNP TC genesis location can be well reproduced in most of the models, although the strength of the ENSO's impact is underestimated as the underestimated climatological TC genesis frequency in these models. Moreover, we found the WNP TC during both El Niño and La Niña events shows an apparent eastwards shift under global warming. However, this eastwards shift of WNP TC genesis could be associated with the changes in climatological TC genesis but not the changes in the ENSO's impact. The projected changes in the ENSO's impact on WNP TC genesis is not as certain as we expected based on the previous conclusions of the robust changes in ENSO's impact on large-scale environment. As a result, we suggest that both the TC genesis climatology and ENSO's impact on TC genesis simulated in the models need improvement in future to project the changes in ENSO's impact under global warming, and more models with 6-hourly outputs used to detect TCs are needed to increase the confidence of multi-model ensemble projections.

KEYWORDS

CMIP5, ENSO, global warming, WNP TC genesis

1 | INTRODUCTION

Tropical cyclones (TCs) are one of the most destructive synoptic systems. The western North Pacific (WNP), with the warmest sea surface temperature (SST) around the world, is the most active basin of TC genesis (Gray and Brody, 1968; Mcbride, 1995). About one third of the world's TC are generated over the WNP (Elsberry, 2004). The WNP TC genesis is pronouncedly modulated by large-scale circulation systems (Gray, 1979; Chan and Gray, 1982; Harr and Elsberry, 1995; Sobel and Camargo, 2005), such as monsoon trough (Cao *et al*., 2014), monsoon gyre (Lander, 1994b; Chen *et al*., 2004) and subtropical high (Harr and Elsberry, 1995). The anomalous large-scale circulation systems could induce dramatic TC genesis anomalies, including genesis frequency and location.

The El Niño–Southern Oscillation (ENSO), the most prominent inter-annual climate anomalies occurring in the equatorial Pacific (Rasmusson and Carpenter, 1982; Philander, 1983), plays an important role in modulating WNP TC genesis (Lander, 1994a; Chen *et al*., 1998; Chia and Ropelewski, 2002; Wang and Chan, 2002; Camargo *et al*., 2007a;

Hsu *et al*., 2009; Li and Zhou, 2012; Chen *et al*., 2018), intensity (Chan, 1985; Chan, 2000; Camargo and Sobel, 2005; Chen *et al*., 2006), track (Camargo *et al*., 2007b; Zhao *et al*., 2010) and landfall (Fudeyasu *et al*., 2006). The WNP TC genesis could be modulated by ENSO with two mechanisms (Chen *et al*., 2004). First, the upwards branch of the Walker circulation over the west of WNP with the WNP TC genesis frequency is suppressed during El Niño (EN) and enhanced during La Niña (LN). As a result, the WNP TC genesis exhibits a pronounced inter-annual east–west fluctuation. Second, an anomalous meridional teleconnection wave train emanates from the tropical western Pacific response to the central-eastern tropical Pacific SST anomalies during ENSO (Chen *et al*., 1998; Chen and Weng, 1998). This anomalous wave train can cause an inter-annual north–south variation in WNP TC genesis location. In sum, EN (LN) enhances TC genesis in the southeastern (northwestern) WNP (Chen *et al*., 1998; Wang and Chan, 2002).

In the recent decade, the impact of global warming on TC activity is an attractive topic owing to the enormous social and scientific interests in TC and global warming (e.g., Knutson *et al*., 2010; Sobel *et al*., 2016; Walsh *et al*., 2016). Many studies investigated future changes in TC genesis frequency and TC intensity (Knutson *et al*., 2010), in which most climate models tended to project a likely decrease in the globally averaged TC genesis frequency but with an increase in TC intensity (Murakami *et al*., 2012; Tory *et al*., 2013b; Camargo *et al*., 2014; Murakami *et al*., 2014; Bacmeister *et al*., 2018).

Due to the impact of ENSO on WNP TC genesis location, any changes in ENSO in a warmer climate are likely to influence the inter-annual variability of WNP TC (Walsh *et al*., 2016). The ENSO-induced tropical Pacific rainfall anomalies are likely enhanced under global warming due to the non-uniform mean-state SST increase (Power *et al*., 2013; Cai *et al*., 2014). Huang and Xie (2015) suggested that the ENSO-induced Pacific rainfall anomalies could be shifted eastwards under global warming, and resultantly the ENSO-induced atmospheric circulation anomalies over the northern Pacific could also be shifted eastwards (Kug *et al*., 2010; Zhou *et al*., 2014). These studies implied that the impact of ENSO on WNP TC genesis could also be changed under global warming. For example, Chand *et al*. (2016) projected that Pacific TCs would be more frequent during future EN than present EN, and less frequent during future La Niña based on 12 CMIP5 models.

Climate models are widely used to investigate the TC changes in a warmer climate. However, the CMIP5 models, the state-of-the-art climate models often used in climate change studies, cannot explicitly produce TC. In this condition, several methods were developed to detect TC genesis and activity from the coarse outputs of the climate models, such as the statistic detection methods (Manabe *et al*., 1970; Wu and Lau, 1992; Bengtsson *et al*., 1995; Vitart *et al*., 1997; Camargo and Zebiak, 2002; Walsh *et al*., 2007; Murakami and Sugi, 2010; Strachan *et al*., 2013; Tory *et al*., 2013a; Horn *et al*., 2014) and the statistical or dynamical downscaling method (Emanuel *et al*., 2008; Emanuel, 2013). Based on the detected TC data sets, theses climate models can reproduce a realistic climatological global TC spatial distribution and annual-mean TC frequency, but the TC intensity is systematically underestimated (Biasutti *et al*., 2009; Strachan *et al*., 2013; Walsh *et al*., 2013). The impact of ENSO on WNP TC genesis has been simulated in a coarse model since Wu and Lau (1992), and it has been improved in high-resolution coupled climate models in recent years (Matsuura *et al*., 1999; Iizuka and Matsuura, 2008; Bell *et al*., 2014; Li and Wang, 2014; Krishnamurthy *et al*., 2015; Han *et al*., 2016; Zhang *et al*., 2016; Patricola *et al*., 2018). Chand *et al*. (2016) evaluated the ENSO and global TC relationship simulated in 20 CMIP5 models based on the TC detection method developed in Tory *et al*. (2013a). Due to the large uncertainty of the TC-detection method (Horn *et al*., 2014; Walsh *et al*., 2016), it is necessary to evaluate the ENSO–WNP TC relationship in CMIP5 models using other detection method for further investigating the possible changes in ENSO's impact on WNP TC activity under global warming.

Previous studies reported that TC tracks and genesis are projected to shift eastwards in the future in the WNP (Yokoi and Takayabu, 2009; Murakami *et al*., 2011; Yokoi *et al*., 2012; Yokoi *et al*., 2013; Colbert *et al*., 2015), leading to reduced frequency of landfalling events. Although these studies investigate mean changes in TC tracks between present-day climate and future climate, it is not clear to what extent changes in ENSO–WNP TC relationship contribute to the eastwards shift in TC tracks. The present study first evaluated the global TC climatological distribution and the ENSO–WNP TC relationship in 10 CMIP5 models, based on the TC activity detected by the Murakami and Sugi (2010) and Murakami *et al*. (2014) method. This TC detection method uses maximum relative vorticity at 850 hPa, temperature anomaly, surface maximum wind speed, and the duration as criteria, and the detected TC activity data sets have been widely used to study the mean-state changes in TC frequency. Then, we investigated the changes in ENSO's impact on WNP TC genesis location under global warming based on the detected TC genesis data sets. The results show the 10 CMIP5 models can well reproduce the observed ENSO–WNP TC relationship in the historical runs, but there are large inter-model spreads in the ENSO–WNP TC relationship changes under global warming. This paper is organized as follows. Section 2 provides a brief description of data, models and analysis methods. The results are shown in sections 3 and 4. Conclusions and discussion are given in section 5.

2 | MODELS, DATA AND METHODS

2.1 | CMIP5 models

We used the TC activity detected by Murakami and Sugi (2010) and Murakami *et al*. (2014) from the 6-hourly output of 10 CMIP5 models in historical runs (1965–2004) and the representative concentration pathway 8.5 (RCP8.5) runs (2060–2099). The 10 models are: CCSM4, CMCC-CM, CNRM-CM5, CSIRO-Mk3-6-0, HadGEM2-CC, HadGEM2-ES, MIROC5, MPI-ESM-LR, MPI-ESM-MR, and MRI-CGCM3 (Taylor *et al*., 2012). To illustrate the spatial distribution of TC genesis frequency, we count the TC genesis into 5°×5° grid boxes following the previous studies (Camargo *et al*., 2005; Wang *et al*., 2014a; Han *et al*., 2016; Kossin *et al*., 2016; Zhang *et al*., 2016). The 5°×5° grid boxes are quite rough in the studies of tropical climate change, but the spatial scale of the issue studied here, the location shift of TC genesis from around 120°E to 180°, is much larger than the grid scale 5°. Thus, the conclusions are not dependent on the selection of grid boxes to count TC genesis frequency. Together with the analysis of TC activity, we also used the monthly output of SST and wind velocity at 850 hPa from the 10 CMIP5 models. The monthly data are interpolated into 2.5 × 2.5° gird to calculate the multi-model ensemble mean (MME).

2.2 | Observational data sets

The observed TC data are obtained from the International Best Track Archive for Climate Stewardship (IBTrACS v03r10; Knapp *et al*., 2010). We only used TCs with intensity stronger than tropical storm, that is, TCs with 1-min sustained surface winds greater than 35 kt (≈18 m/s), during the period 1965–2004. The large-scale wind velocity is from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 (Kalnay *et al*., 1996), and the sea surface temperature is from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) data set (Rayner *et al*., 2003).

2.3 | Definitions of climatology and ENSO events

The long-term mean of 1965–2004 in historical runs defines the historical climatology, whereas the mean of 2060–2099 for the future climate. The EN and LN events are defined based on the Niño3.4 index (the averaged SST anomalies in the Niño3.4 region, 5°S–5°N and 170°–120°W) during the peak season of the WNP TC (July–September, JAS), as in previous ENSO–TC relationship studies (Chen *et al*., 1998; Camargo and Sobel, 2005; Chen *et al*., 2006). The year with Niño3.4 index greater than one standard deviation of the Niño3.4 index is defined as an EN year, whereas the year with Niño3.4 index smaller than one negative standard deviation is defined as a LN year. Analogous analyses were also performed based on the ENSO definition of the Niño3 index, and consistent results were obtained (not shown), indicating the conclusions are independent on the ENSO definition here.

3 | EVALUATING THE WNP TC CLIMATOLOGY, INTER-ANNUAL VARIABILITY AND ITS RELATIONSHIP WITH ENSO

3.1 | Climatology and inter-annual variability

The climatology of TC genesis frequency in observations and the simulations in CMIP5 historical runs are shown in Figure 1a,b. The spatial patterns of WNP TC frequency in the MME of CMIP5 models (Figure 1b) are similar to observations (Figure 1a), although the modelled TC geneses show some discrepancies with the observations. For example, the climatological TC genesis frequency is generally underestimated; the modelled TC geneses extend farther eastwards than observations and the observed maximum TC genesis frequency over around 140°E is underestimated in the models; the observed TC geneses over the South China Sea is overestimated; and an observed maximum centre located at the southwest of WNP (around 15°N, 145°E) is not apparent in models.

Figure 1c,d shows the inter-annual variance of WNP TC genesis frequency during 1965–2004 in observations and the MME of historical runs. Generally, the pattern of the inter-annual variance is realistically reproduced in the models with comparable magnitude. Similar to the climatological distribution, the modelled inter-annual variance of WNP TC genesis frequency is underestimated over around 140 °E and extends farther eastwards. Therefore, the ability of the CMIP5 models for the inter-annual variability of WNP TC genesis is close to their ability for simulating the climatological distribution.

3.2 | WNP TC association with ENSO

We further evaluated the location shift role of ENSO in WNP TC genesis in the models. Figure 2 shows the composited WNP TC genesis frequency and 850-hPa streamline during EN and LN events in observations and the models. The MME simulation can realistically reproduce the observed difference of WNP TC genesis location between EN and LN events. The monsoon trough migrates from around 10°N during EN to near 20°N during LN. The monsoon trough is located around 170°E during EN and around 140°E during LN. As a result, the TC genesis is gathered over the southeast WNP during EN and the northwest WNP during LN along with the variation of monsoon trough. The role of ENSO can be clearly illustrated in the TC genesis anomalies (Figure 3). The observed TC genesis anomalies

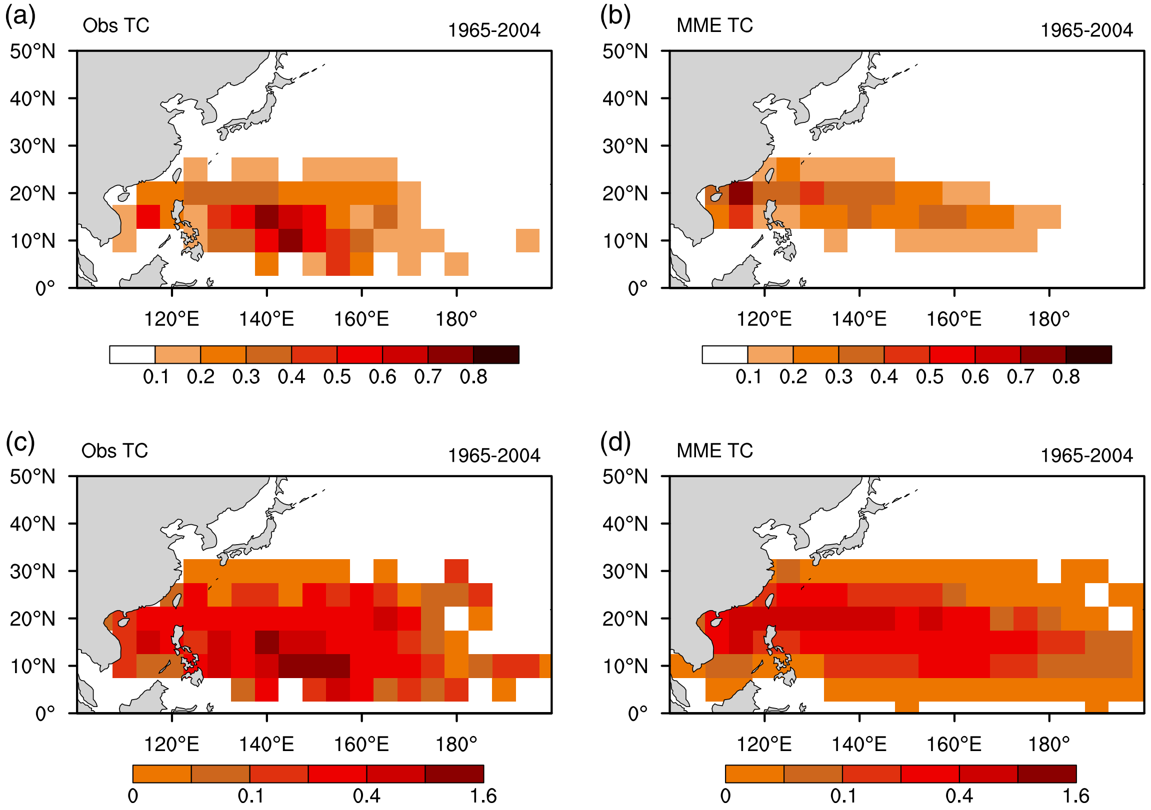

FIGURE 1 Long-term mean of WNP TC genesis frequency in JAS during 1965–2004 in (a) observations and (b) MME of the historical runs, and interannual variance of WNP TC genesis frequency in JAS during 1965–2004 in (c) observations and (d) MME of the historical runs [Colour figure can be viewed at wileyonlinelibrary.com]

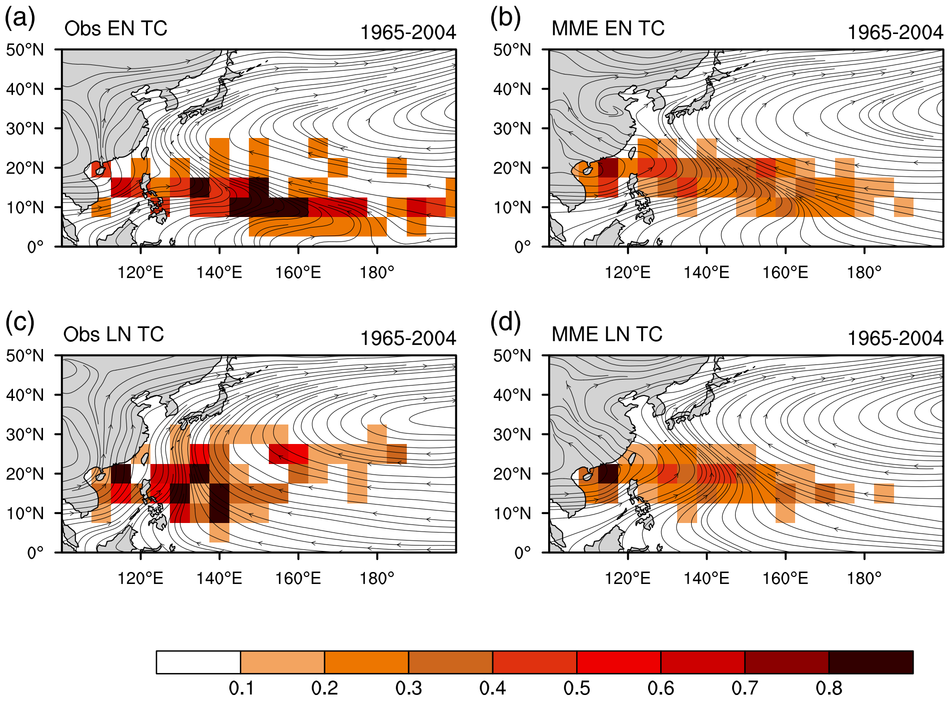

FIGURE 2 Composited 850-hPa streamline and WNP TC genesis frequency during the (a, b) EN and (c, d) LN events in (a, c) observations and the MME (b, d) of the historical runs [Colour figure can be viewed at wileyonlinelibrary.com]

during ENSO show a southeast–northwest dipole pattern (Figure 3a,c), and it can be well reproduced in the MME of the models (Figure 3b,d).

The shift role of ENSO's positive and negative phases on the location of WNP TC genesis is more apparent in the different TC genesis frequency anomalies between EN and

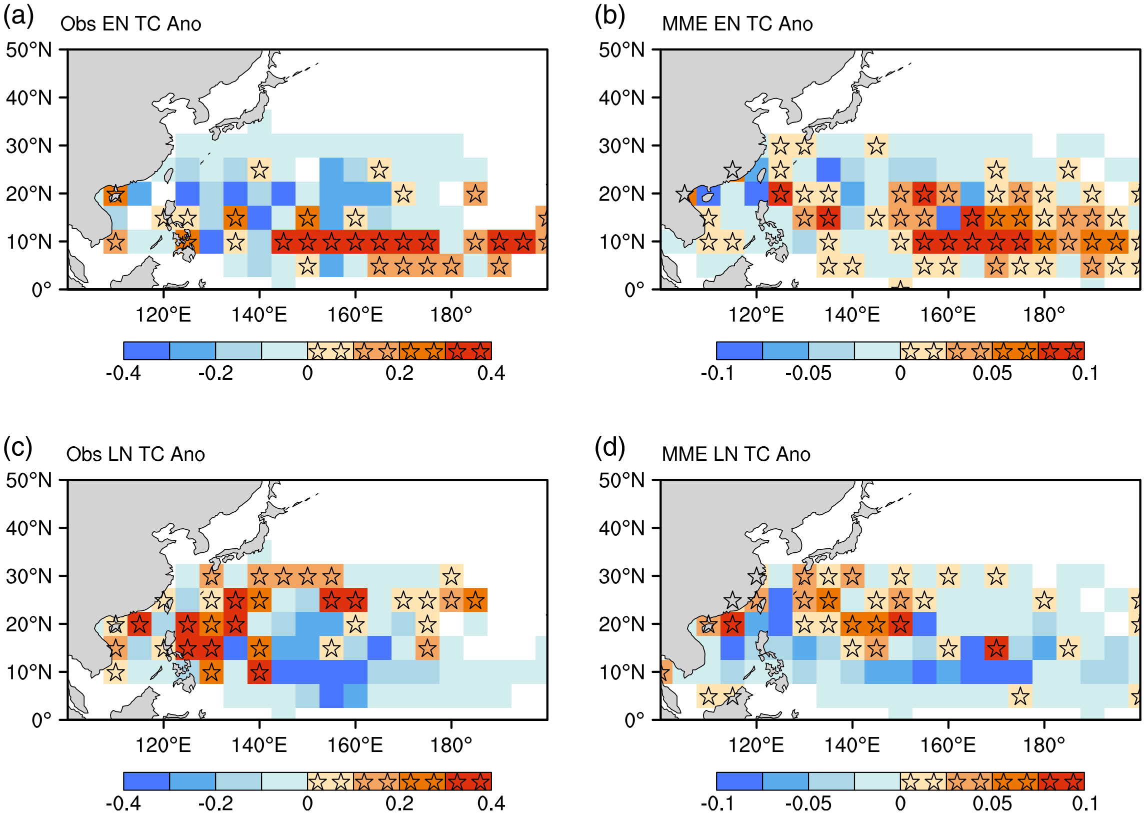

FIGURE 3 Composited WNP TC genesis frequency anomalies in JAS during the (a, b) EN and (c, c) LN events in (a, c) observations and the MME (b, d) of the historical runs [Colour figure can be viewed at wileyonlinelibrary.com]

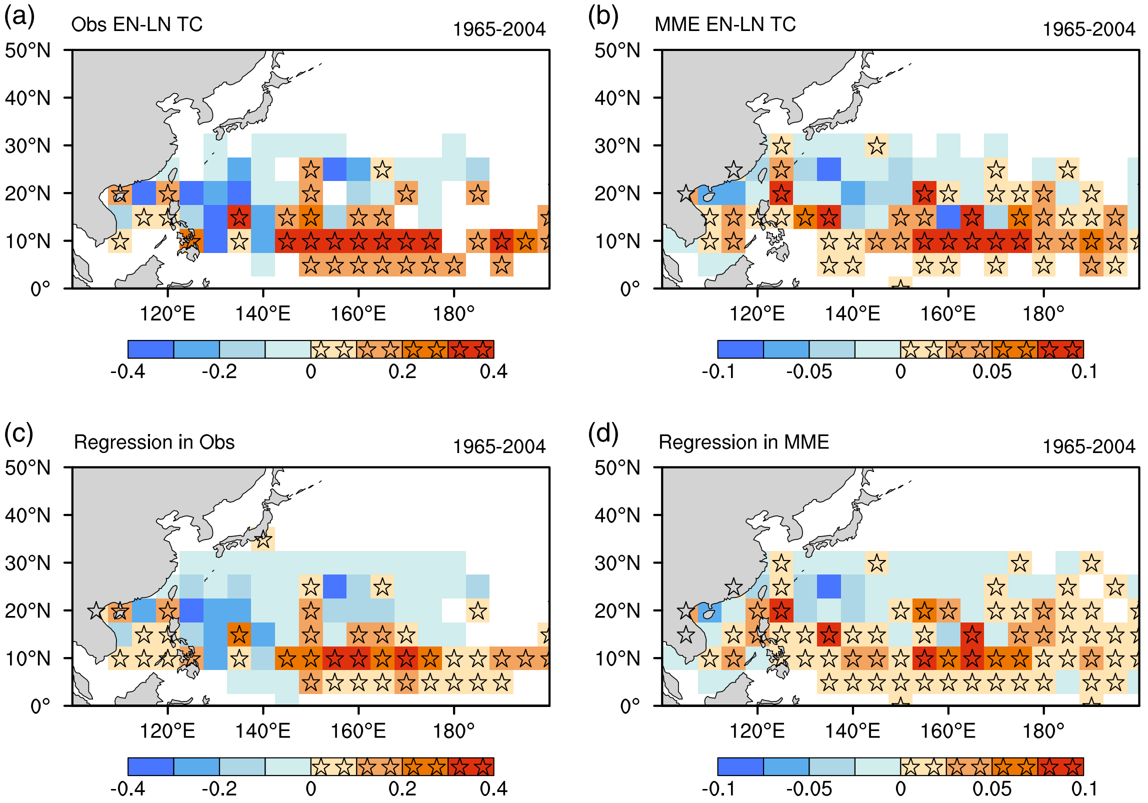

FIGURE 4 The difference of WNP TC genesis frequency between EN and LN in (a) observations and (b) the MME in the historical runs, and the regression of WNP TC genesis frequency onto the Niño3.4 index in (c) observations and (d) the MME in the historical runs [Colour figure can be viewed at wileyonlinelibrary.com]

LN (Figure 4a,b). The different TC genesis shows positive anomalies over the southeast WNP and negative over the northwest WNP. The observed dipole pattern of TC genesis anomalies between EN and LN are quite well reproduced in the MME of the models. With the well-reproduced pattern, the magnitude of the observed difference is underestimated in the models from the comparison of Figure 4a,b. However, when we consider the generally underestimated climatological TC genesis frequency in the models (Figure 1a,b), the ENSO's impact in the models is not as underestimated as the direct comparison in Figure 3a,b. The role of ENSO in WNP TC genesis location is also evaluated using the linear regression of TC genesis frequency onto the Niño3.4 index (Figure 4c,d). Consistent to the composite results, the regressions show a similar pattern but an underestimated magnitude to observations.

The simulated TC genesis frequency during EN and LN in each model is shown in Figures S1 and S2, Supporting Information, the TC genesis frequency anomalies during EN and LN in Figures S3 and S4 and the different TC genesis frequency between EN and LN in Figure 5. Generally, all the 10 models can reproduce the observed difference of TC genesis location during EN and LN associated with the different monsoon trough. However, there are great discrepancies among the models. For example, the modulation of ENSO on TC is pronounced in CMCC-CM (Figure 5b), CNRM-CM5 (Figure 5c), MIROC5 (Figure 5g), MPI-ESM-LR (Figure 5h) and MRI-CGCM3 (Figure 5j), whereas the ENSO's modulation is weak in the other models. This result is hard to compare with the assessment in Chand *et al.* (2016), because the conclusion of the assessment in Chand *et al.* (2016) was drawn for the global TC.

Although the zonal shift of genesis location as the main impact of ENSO on the WNP TC genesis in the observations can be well reproduced in the models, some other important impacts of ENSO on the WNP TC genesis, for example, the TCs over the South China Sea (Wang *et al.*, 2007; Goh and Chan, 2009; Li and Zhou, 2014; Wang *et al.*, 2014b), are not apparent in the models (Figure 4). This result indicates that the ability of CMIP5 models needs further improvement

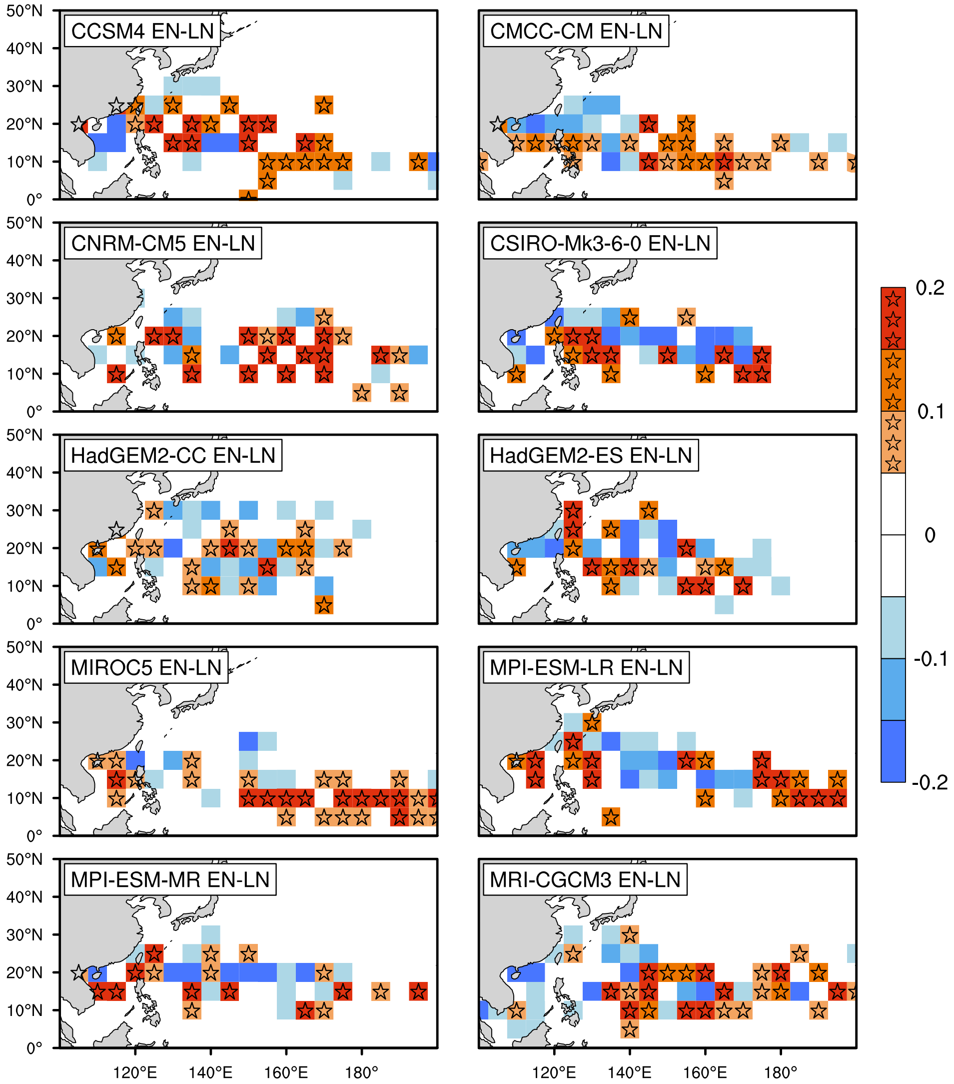

FIGURE 5 The difference of WNP TC genesis frequency between EN and LN in the 10 CMIP5 models [Colour figure can be viewed at wileyonlinelibrary.com]

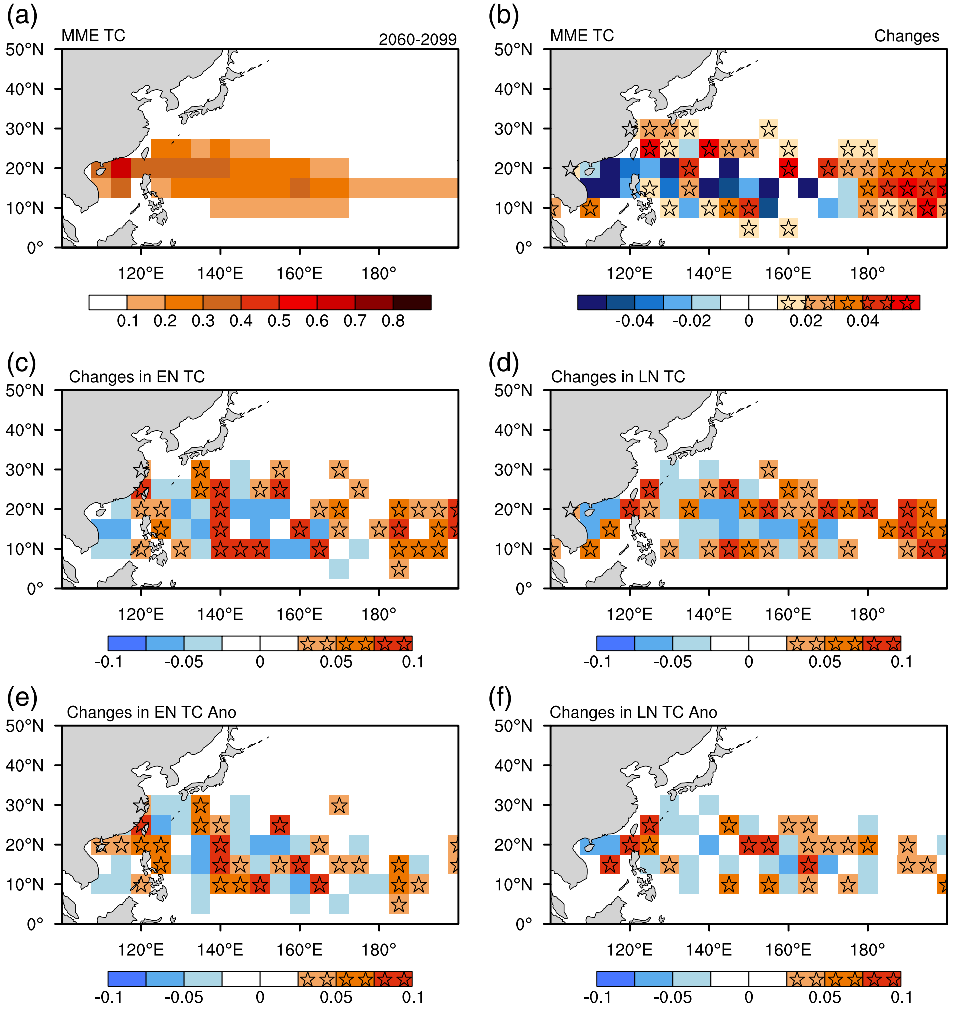

FIGURE 6 (a) The MME long-term mean of WNP TC genesis frequency in JAS during 2060–2099 in RCP8.5 runs, and (b) the changes in TC genesis frequency in RCP8.5 runs. The changes in the WNP TC genesis frequency during (c) EN and (d) LN events in the MME of RCP8.5 runs. The (e, f) are the same as (c, d) but for the changes in EN/LN TC anomalies [Colour figure can be viewed at wileyonlinelibrary.com]

to simulate ENSO's impact on regional TC with smaller spatial scales to be able to study future changes under global warming.

4 | CHANGES IN THE ENSO'S IMPACT ON WNP TC GENESIS

The well-simulated ENSO–TC relationship in the models indicates that the detected TC data sets are practicable to study the changes in the ENSO's impact on WNP TC genesis under global warming. The changes were analysed based on the difference between the RCP8.5 and historical simulations of the 10 CMIP5 models. Figure 6a,b shows the future WNP TC genesis frequency in MME for 2060–2099 in the RCP8.5 runs and the changes, respectively. There is a robust decrease in TC frequency over west of WNP and an increase over the central Pacific under global warming. The eastwards shift of climatology WNP TC genesis is consistent with the result in previous studies (Li *et al*., 2010; Murakami *et al*., 2011; Yokoi *et al*., 2012; Yokoi *et al*., 2013; Colbert *et al*., 2015; Chand *et al*., 2016). It was suggested in previous studies that the eastwards shift of TC genesis location is induced by the changes in the activity of synoptic-scale perturbation and the associated with the lower-level relative vorticity and vertical shear of horizontal wind, which could further be contributed by the El Niño-like background SST changes (Li *et al*., 2010; Murakami *et al*., 2011; Yokoi *et al*., 2012; Yokoi *et al*., 2013; Colbert *et al*., 2015).

The regular way to calculate changes in anomalies is that the EN/LN-induced anomalies of TC genesis frequency in the present-day and future climate is first calculated relative to their respective long-term mean TC genesis frequency, and then the difference of the EN/LN-induced TC genesis anomalies between the present-day and future climate is calculated as the changes in EN/LN-induced TC anomalies (hereafter referred to as changes in EN/LN TC anomalies). Here we also calculated the changes in TC frequency during ENSO in another way following the calculation in Chand *et al*. (2016) for comparison, in which the different TC genesis frequency during EN/LN between the present-day and future climate (hereafter referred to as changes in EN/LN

TC). The difference between the two calculations is that the changes in EN/LN TC (Figure 6c,d) include the changes in climatological TC genesis (Figure 6b), whereas the climatological TC changes are removed in the changes in EN/LN TC anomalies (Figure 6e,f).

As shown in Figure 6c,d, both the EN and LN TC changes show an apparent east–west dipole with increased (decreased) TC genesis over east (west) of 170°E. The result of the changes in EN TC (Figure 6c) is consistent with Chand *et al*. (2016), whereas the dipole pattern of LN TC changes (Figure 6d) is not apparent in Chand *et al*. (2016). However, when the apparent dipole changes in climatological TC genesis (Figure 6b) are removed to obtain the changes in EN/LN TC anomalies, the changes in ENSO's impact do not show any regular pattern (Figure 6e,f). This result suggests the climatological TC changes are very important in considering the changes in ENSO's impact on TC. The changes in EN/LN TC in each model are shown in Figures S5 and S6, and the changes in EN/LN TC anomalies in Figures S7 and S8. Both the two changes show very large inter-model spread. Basically, no model project the changes with a similar pattern to the MME results.

The irregular pattern of the changes in EN/LN TC anomalies is not consistent with the previous conclusion that the ENSO's impact on tropical rainfall and circulation will robustly shift eastwards under global warming (Kug *et al*., 2010; Power *et al*., 2013; Cai *et al*., 2014; Zhou *et al*., 2014; Huang and Xie, 2015; Huang and Chen, 2017). This result might be associated with the different climatological SST changes in the 10 models from the large member results in previous studies, in which more than 30 CMIP5 models were often used. Figure 7a shows the tropical Pacific relative SST changes—the SST changes with its regional mean removed—of the 10-model MME, suggested to be the key factor modifying the ENSO's impact on the tropical Pacific precipitation and circulation (Power *et al*., 2013; Cai *et al*., 2014; Huang and Xie, 2015; Huang, 2016; Huang and Chen, 2017). Roughly, the 10-member MME relative SST changes consistent with the result based on large member ensemble of CMIP5 models (e.g., Huang and Ying, 2015; Ying *et al*., 2016), appearing as an El Niño-like pattern with larger warming in the equatorial central and eastern Pacific than other oceans. However, the central Pacific Ocean with relatively large warming in the 10-model MME is quite smaller than the previous large member ensemble results. Especially, the climatological SST changes in the 10-model ensemble over the WNP are also very irregular. The irregular climatological SST changes in these models could not induce robust changes in ENSO's impact on large-scale atmospheric environment and then on the WNP TC genesis (Figure 6e,f). The inter-model spread of the relative SST changes measured by the inter-model standard deviation (Figure 7b) is very large compared with the MME result (Figure 7a). The large inter-model spread in the climatological SST changes contributes to the uncertain changes in EN/LN TC genesis shown in Figures S5–S8.

We also selected the projection of the top-five models, which simulate ENSO–TC relationship relatively realistically (Figure 5). They are CMCC-CM, CNRM-CM5, MIROC5, MPI-ESM-LR and MRI-CGCM3. The results of the analysis same as Figures 6 and 7 are shown in Figures S9 and S10. Basically, the MME results of the five selected models are very similar to the MME of all 10 models.

5 | CONCLUSIONS AND DISCUSSIONS

This study evaluated the ENSO's impact on the WNP TC genesis simulated in 10 CMIP5 models based on the TCs detected by the algorithm in Murakami and Sugi (2010) and Murakami *et al*. (2014). Furthermore, we analysed the changes in ENSO's impact on WNP TC genesis under global warming using the historical and RCP8.5 simulations.

Basically, the models can realistically reproduce the observed pattern of the climatology of WNP TC genesis, although there are some discrepancies with the observations. For example, the underestimated frequency over around 140 °E and 10°N and the overestimated frequency over the South China Sea. The simulation of inter-annual variance of WNP TC genesis is similar to the performance of the models simulating the climatological WNP TC genesis. The observed zonal shift of WNP TC genesis location between

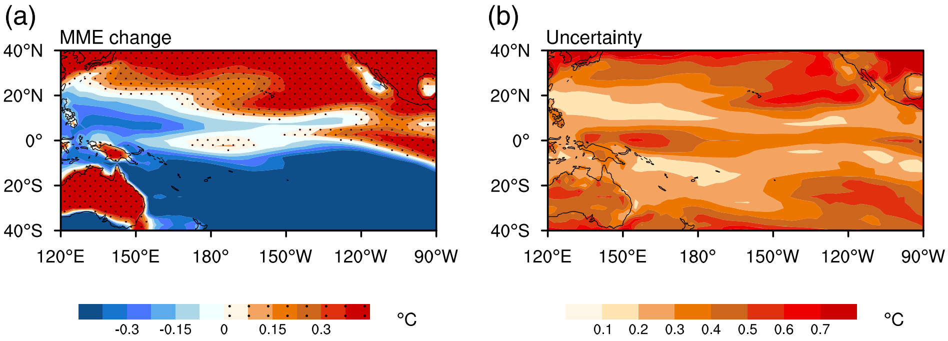

FIGURE 7 (a) The MME tropical Pacific relative SST changes between the difference of historical runs and RCP8.5 scenario, and (b) the inter-model standard deviation of the relative SST changes [Colour figure can be viewed at wileyonlinelibrary.com]

EN and LN events are well reproduced in CMCC-CM, CNRM-CM5, MIROC5, MPI-ESM-LR and MRI-CGCM3, which dominates the performance of the MME of the 10 models. The well-reproduced zonal shift of WNP TC genesis anomalies associated with ENSO agree with the monsoon trough anomalies in the models, which migrates from around 10°N and 170°E during EN events to near 20°N and 140°E during LN events. With the well-reproduced spatial pattern, the magnitude of the observed ENSO's impact is underestimated in models, since the WNP TC genesis frequency is generally underestimated in the models. Although the TC detection method used here differs from that in Chand *et al*. (2016), both studies conclude that most of CMIP5 models can basically reproduce the location shift role of ENSO in WNP TC genesis.

We further investigated the changes in the ENSO's impact on WNP TC genesis under global warming. When the changes were calculated in a regular way as the different EN/LN-induced TC genesis anomalies between the RCP8.5 and historical simulations, the changes in EN/LN TC anomalies do not show any regular pattern. However, when the changes were calculated as the different TC genesis during EN/LN between the RCP8.5 and historical simulations, as the calculation in Chand *et al*. (2016), both the EN and LN TC changes show an apparent increased (decreased) TC genesis over east (west) of 170°E. The difference between the two calculations is that the climatological changes in TC genesis were removed in the regular method but not in the calculation of Chand *et al*. (2016). This result suggests that the climatological TC changes are much more robust than the changes in ENSO's impact on WNP TC, and the robust changes in ENSO's impact suggested in Chand *et al*. (2016) could be a result of the calculation in which the changes in TC climatology were not removed.

The irregular changes in EN/LN TC anomalies might be associated with the irregular pattern of the changes in the climatological SST in the 10 models, which differ from the robust El Niño-like pattern in the large-member MME in previous studies (e.g., Huang and Ying, 2015; Ying *et al*., 2016). The previous conclusion of the robust changes in ENSO-induced large-scale environment was drawn based on the robust El Niño-like pattern of the climatology SST changes in much larger model members (Power *et al*., 2013; Cai *et al*., 2014; Huang and Xie, 2015). The current studies on TC genesis change from CMIP5 models are strongly limited by the number of available models, because the 6-hourly outputs are required by the current TC detection method but only provided in a minority of CMIP5 models. This result implies more models with 6-hourly outputs are needed to detect TC genesis and study model biases and their inter-model agreement in future studies.

The large-scale atmospheric environment anomalies are the bridge through which the SST anomalies associated with ENSO play roles in TC genesis, for example the anomalies of vortex, relative humidity, moisture instability and vertical wind shear (e.g., Lander, 1994a; Chen *et al*., 1998; Chia and Ropelewski, 2002; Wang and Chan, 2002; Camargo *et al*., 2007a; Hsu *et al*., 2009; Li and Zhou, 2012; Chen *et al*., 2018). The possible changes in ENSO-induced large-scale environment anomalies over the WNP were not studied here, which could differ from the robust changes in ENSO-induced tropical rainfall. Moreover, the influence of environment anomalies on TC genesis is an integrated process with different roles of these variables, which could also be changed under global warming. The comprehensive processes of the changes in ENSO's impact on WNP TC genesis must be a valuable issue to be studied in future.

In this study, all results are based on the TC detection method of Murakami and Sugi (2010) and Murakami *et al*. (2014)). Although our analyses obtain some consistent results of the changes in TC climatology with previous studies using different detection methods, there are some discrepancies with previous conclusions in some models. For instance, Camargo (2013) shows a slight increase of global TC genesis frequency in MPI-ESM-LR and MRI-CGCM3, while the present study does not show increase in these models. This discrepancy implies that the conclusion on the changes in ENSO's impact on WNP TC genesis drawn here should be further verified using other TC detection methods, which could be another important uncertainty source of the present projection.

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