Projection of North Pacific Tropical Upper-Tropospheric Trough in CMIP5 Models: Implications for Changes in Tropical Cyclone Formation Locations

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ABSTRACT

The strong westerly shear to the south flank of the tropical upper-tropospheric trough (TUTT) limits the eastward extension of tropical cyclone (TC) formation over the western North Pacific (WNP) and thus the zonal shift of the TUTT in warming scenarios has an important implication for the mean formation location of TCs. The impact of global warming on the zonal shift of the TUTT is investigated by using output from phase 5 of the Coupled Model Intercomparison Project (CMIP5) of 36 climate models in this study. It is found that considerable spread exists in the zonal position, orientation, and intensity of the simulated-climatologic TUTT in the historical runs, which is forced by observed conditions such as changes in atmospheric composition, solar forcing, and aerosols. The large spread is closely related to the diversity in the simulated SST biases over the North Pacific. Based on the 15 models with relatively high skill in their historical runs, the near-term (2016–35) projection shows no significant change of the TUTT longitude, while the TUTT experiences an eastward shift of 1.9° and 3.2° longitude in the representative concentration pathway (RCP) 4.5 and 8.5 scenarios in the long-term (2081–2100) projection with considerable intermodel variability. Further examination indicates that the projected changes in the zonal location of the TUTT are also associated with the projected relative SST anomalies over the North Pacific. A stronger (weaker) relative SST warming over the North Pacific favors an eastward (westward) shift of the TUTT, suggesting that the spatial pattern of the future SST change is an important factor for the zonal shift of the mean formation location of TCs.

1. Introduction

Tropical cyclones (TCs) can cause enormous damages to islands and coastal areas (e.g., Pielke and Landsea 1998; Pielke et al. 2008; Zhang et al. 2009) and it is pragmatically important to know how TC activity will change in a warming climate (Knutson et al. 2010; Walsh et al. 2016). Considerable efforts have been made to understand the future change of TC behaviors (Henderson-Sellers et al. 1998; Walsh 2004; Knutson

et al. 2010; Walsh et al. 2016). So far, the projected TC activity is mainly obtained through directly calculating TC statistics from climate models in different warming scenarios (e.g., Manabe et al. 1970; Bengtsson et al. 1996; Sugi et al. 2002; Chauvin et al. 2006; Zhao et al. 2009; Murakami et al. 2011, 2013; Camargo 2013) or through dynamic–statistical downscaling of specific TC features (e.g., Emanuel 1987, 2013; Knutson et al. 1998; Vecchi and Soden 2007a; Villarini and Vecchi 2012; Wang and Wu 2012, 2015). These studies suggested that the annual frequency of TC formation will either decrease or remain essentially unchanged, with an increase in intensity

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and the associated precipitation owing to global warming (Knutson et al. 2010; Walsh et al. 2016). However, relatively few studies have been conducted on possible changes in the mean formation location of TCs and impact areas, especially in individual basins (e.g., Wu and Wang 2004; Knutson et al. 2010; Seneviratne et al. 2012; Christensen et al. 2013; Kossin et al. 2014; Walsh et al. 2016).

The western North Pacific (WNP) is the most active basin for TC activity (Gray 1968), and changes in the mean formation location of TCs can affect billions of people in Pacific islands and Asian coastal regions. However, only a few studies were conducted to evaluate the impact of global climate change on the formation location in the basin. While Stowasser et al. (2007) found an increase in TC formation over the South China Sea and suggested a westward shift of the mean formation location of TCs in a global warming scenario, Yokoi et al. (2009) and Murakami et al. (2011) suggested an eastward shift of the mean formation location of TCs. Some studies argued that global warming can lead to a shift of the formation location from the western to central Pacific (Li et al. 2010; Zhao and Held 2012; Zhao et al. 2013). Despite the different trends of the mean formation location of TCs, these previous studies indicate that the mean formation location of TCs in the WNP basin may change in responses to global warming.

Considering the low skill of the state-of-the-art climate models from phase 5 of the Coupled Model Intercomparison Project (CMIP5) in simulating TCs, it is hard to examine the possible shift in the mean formation location directly (Camargo 2013). As an alternative, Wu et al. (2015) found that the tropical upper-tropospheric trough (TUTT) in the North Pacific generally inhibits the eastward extension of TC formation as a result of the related unfavorable environments. The zonal migration of the TUTT can shift the TC formation location on the interannual and interdecadal time scales by modulating the TC genesis over the eastern WNP (Wu et al. 2015; Wang and Wu 2016). These studies suggest that the shift of the TUTT in global warming scenarios is a good indicator for the future change of the mean location of TC formation. The objective of this study is to examine the zonal shift of the TUTT in global warming scenarios with the output of CMIP5 climate models and the future change in the mean formation location of TCs.

The remainder of this paper is organized as follows. Section 2 describes the data employed in this study, and an evaluation of the climate models is presented in section 3. Section 4 examines the future shift of the TUTT in the warming scenarios, and the uncertainty source of the projection is discussed in section 5, followed by a summary in section 6.

2. Data

The monthly wind, SST, and precipitation data of the three experiments [historical and representative concentration pathway 4.5 and 8.5 (RCP4.5 and RCP8.5) experiments] from CMIP5 models are used in this study. The historical experiment is forced by observed conditions, including changes in atmospheric composition, solar forcing, natural or anthropogenic aerosols, and so on. The radiative forcing in the RCP4.5 (RCP8.5) experiments stabilizes at 4.5 (8.5) W m^{-2} in 2100 (Taylor et al. 2012). The output of historical experiments during 1979–2005 from 43 models is used to examine the skills in simulating the climatological TUTT, and 36 of 43 models with RCP4.5 and RCP8.5 experiments are used to investigate the future changes in the TUTT. The projections are divided into near-term and long-term projections, which are expressed as the changes in 2016–35 and 2081–2100 relative to the reference period 1986–2005. The models used in this study are listed in Fig. 1.

The TC best-track dataset is from the Joint Typhoon Warning Center (JTWC). TCs are defined as those in the dataset with maximum wind speed no less than storm intensity (17.2 m s^{-1}). The TC formation location is defined as the latitude and longitude when a TC for the first time reaches tropical storm intensity. The monthly wind data are from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis dataset (ERA-I; Dee et al. 2011). The monthly SST from the National Oceanic and Atmospheric Administration (NOAA) (ERSST.v3b; Smith et al. 2008) is used in this study. To evaluate the performance of CMIP5 models against the reanalysis, all of the model and reanalysis data are interpolated into $1^\circ \times 1^\circ$ grids. We focus on the peak season [July–October (JASO)] of the TC activity in the WNP.

3. Evaluation of CMIP5 climate models

Evaluation of the biases in historical runs is helpful to understand the future projection (Whetton et al. 2007). In this section, we focus on the performances of CMIP5 models in simulating the climatological TUTT during 1979–2005.

Figure 2a displays the mean 200-hPa streamlines and the TC formation positions during July–October over 1979–2005. The climatologic mean TUTT is elongated from northeast to southwest across the North Pacific Ocean, extending to the tropical North Pacific near 160°E . The prominent westerly wind shear to the southeast of the TUTT trough line generally tends to suppress the TC formation east of 160°E . As a result,

FIG. 1. Skill scores of 200-hPa wind over 5°–25°N, 140°E–180° in historical runs of the CMIP5 models. The x axis labels show the model number. The blue text presents the models available with three experiments (historical, RCP4.5, and RCP8.5), and the black text presents the models only with historical experiment. The models with green dots denote the selected models in section 3.

Most TCs formed to west of the TUTT. As shown in Fig. 2, the north and south boundaries of the TC formation area are consistent with the subtropical westerly shear related to the midlatitude westerly jet and the tropical easterly shear associated with the South Asian high. While the vertical shear associated with the TUTT limits the eastern boundary of TC formation, it is suggested that the vertical shear is also an important factor for controlling TC activity area (e.g., Wu et al. 2015; Wang and Wu 2016).

A reasonable simulation of the climatologic TUTT is essential for using the output of a climate model to infer the change of the eastern boundary of TC formation. Figure 2b shows the multimodel ensemble (MME) mean July–October streamline at 200 hPa and vertical shear of zonal wind in the historical experiments of the 43 models during 1979–2005. It can be seen that the TUTT is reasonably well reproduced, including the northeast–southwest orientation and strong westerly shear to its southeast. However, the cyclonic curvature of streamline near the bottom of the simulated TUTT is smaller than observation, leading to a northeastward displacement of the TUTT and a weaker simulated TUTT. Figure 2c further shows the difference of 200-hPa wind between the MME mean and ERA-I. There is an anticyclonic circulation with a center in the subtropical central Pacific (Fig. 2c). Since the TUTT is a cyclonic

circulation located in this region (e.g., Sadler 1967, 1976), the anticyclonic bias makes the simulated TUTT in the CMIP5 models weaker than the observation. In fact, such an anticyclonic bias is closely associated with the southward displacement of subtropical westerly jet over the North Pacific, which is a common feature in the simulation of the CMIP5 models (e.g., Ma et al. 2015). The above evaluation shows that the northeastward displacement and weaker intensity of the TUTT are the major biases in the MME mean wind field.

Here we use a skill score defined by Taylor (2001) to quantify the model performance in the TUTT simulation. The skill score S is defined as

$$S \equiv \frac{(1 + R)^4}{4 \left(\text{SDR} + \frac{1}{\text{SDR}} \right)^2},$$

where R is the pattern correlation between a model and the ERA-I, and SDR is the ratio of spatial standard deviations of a model to that of ERA-I. The score S measures the similarity of a spatial pattern to the observation. Figure 1 shows the skill scores of 200-hPa winds over 5°–25°N, 140°E–180° in 43 models. Because the TUTT bottom in observation is usually located over 5°–25°N, 140°E–180°, we use the zonal wind over this

FIG. 2. (a) The 200-hPa winds (streamlines) and vertical shear of zonal wind (shading; m s^{-1}) averaged over 1979–2005 in ERA-I. (b) As in (a), but for the MME mean of historical runs over 1979–2005. (c) Difference of 200-hPa wind (vectors; m s^{-1}) and vertical shear of zonal wind (shading; m s^{-1}) between (a) and (b). The blue dots in (a) indicate TC formation locations and the thick black lines in (a) and (b) schematically indicate the trough lines of the TUTT. Green lines show the zero contours of zonal wind speed in ERA-I in (a) and (c) and MME in (b).

region to evaluate the simulated TUTT climatology in CMIP5 models. The mean skill score is 0.55. In addition, there is considerable intermodel variations in the skill scores. In particular, the skill scores range from 0.22 in the MIROC-ESM model to 0.86 in the CESM1(CAM5) model with a standard deviation of 0.18 (hereinafter, please see <http://www.ametsoc.org/PubsAcronymList> for model acronym expansions). It is found that the large intermodel spread of skill scores results mainly from the different zonal locations of the simulated TUTT in the climate models. To confirm this, we further examine the longitudinal positions of the simulated TUTT. The TUTT longitude is determined by the dividing boundary (the zero contour of zonal wind speed over 5° – 20° N) between the easterly and westerly wind in the trough (Wu et al. 2015). Figure 3 shows the

FIG. 3. Scatterplots of skill scores and the absolute TUTT longitude biases in CMIP5 models. The red line denotes linear fitting by the least squares method, and the correlation R is shown in red at the bottom left.

relationship between the TUTT skill score and the absolute bias in the TUTT longitude. A significant correlation of -0.74 is found between these two measures of the simulated TUTT. That is, the model with higher skill score also shows a smaller longitude bias. This allows us to use this skill for evaluating the simulated TUTT in the climate models.

Such a large intermodel spread of skill scores and the corresponding zonal locations of the TUTT may lead to remarkable differences in their large-scale circulations and distinct eastern boundaries of the TC formation in the individual models. As a proxy, the genesis potential index (GPI) defined by Emanuel and Nolan (2004) has been widely used to demonstrate effects of large-scale environmental conditions on TC formation in climate models (e.g., Camargo et al. 2007, Yokoi et al. 2009; Murakami et al. 2011; Emanuel 2013). Figure 4 shows the GPI in the historical runs of the MIROC-ESM, GFDL CM3, and CESM1(CAM5) models during 1979–2005, and the corresponding spatial distribution of TC formation in the JTWC dataset. As presented in Fig. 1, the MIROC-ESM and GFDL CM3 models have a poor skill, while the TUTT is reasonably well reproduced in the CESM1(CAM5) model. The simulated TUTT experiences a westward bias in the MIROC-ESM model but an eastward displacement in the GFDL CM3 model (figure not shown). Because of the opposite bias in the zonal location of the TUTT, the corresponding spatial distribution of GPI shows a striking contrast (Figs. 4a,b)

FIG. 4. The GPI (shading) in the historical runs of (a) MIROC-ESM, (b) GFDL CM3, and (c) CESM1(CAM5) models over 1979–2005. Contours show the annual frequency of the observed TC formation in the JTWC best-track dataset.

in the two models. The maximum zone of GPI is confined to the South China Sea and the TUTT shows a farther westward displacement in the MIROC-ESM model (Fig. 4a). On the other hand, the maximum center of GPI in the GFDL CM3 model is located to the east of 140°E owing to the eastward bias of the simulated TUTT. It is clear that a reasonable simulation of the TUTT is crucial to a good estimation of the mean area of

TC formation. As shown in Fig. 4c, the GPI in the CESM1(CAM5) model reasonably well indicates the observed spatial distribution of TC formation, with a maximum zone between 10°–30°N and a maximum center from the South China Sea to east of Philippines.

There is a considerable intermodel spread in the zonal location of the simulated TUTT (Fig. 3). For instance, the TUTT longitude in MIROC-ESM model is about

110°E, while it shifts to 150°W in the GFDL CM3 model. Since the zonal location of the TUTT is sensitive to variations in SST in the central-eastern Pacific on interannual time scale (e.g., Wang and Chan 2002; Wang and Wu 2016), we first examine the possible difference of SST anomalies in the climate models. It is found that the biases in zonal location of the TUTT are related to the SST biases over the region underlying the TUTT. Figure 5, top, shows the scatterplot of the TUTT longitude biases and SST biases over the central North Pacific (10°–30°N, 150°E–150°W). It can be seen that the TUTT longitude biases are closely related to the SST biases in this region, with a correlation of 0.76. Fitzpatrick et al. (1995) suggested that the TUTT is maintained by the radiational cooling and subsidence feedback. The significant correlation between the SST and TUTT longitudes bias indicates the crucial role of vertical motions in the zonal TUTT location. The positive (negative) SST biases stimulate the anomalous ascending (descending) motion, leading to an eastward (westward) bias of the TUTT (Fig. 5, top).

The distinct features of large-scale environments in the climate models with various skills and zonal location of the TUTT confirm the importance of the validation. It is found that some of the models failed to simulate the climatological TUTT in their historical runs. Therefore, we should exclude the models with poor performance and select models with relatively higher skill in simulating the TUTT for further projection. Among the 43 total simulations, 16 models exhibit relatively higher skill in simulating the climatological TUTT, with skill scores exceeding 0.5 and longitude biases of the TUTT less than 10°. Because the RCP4.5 and RCP8.5 projections are not available in the CNRM-CM5.2 model, only 15 models are selected for further analysis (Fig. 1).

4. Zonal shift of the TUTT in the warming scenarios

This section focuses on the zonal location of the TUTT in the RCP4.5 and RCP8.5 scenarios. Following the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC), the projections are divided into near-term and long-term projections, which are expressed as the changes in 2016–35 and 2081–2100 relative to the reference period 1986–2005, respectively.

a. Near-term projection

Figure 6a shows selected 15-model MME mean change in 200-hPa wind over 2016–35 in the RCP4.5 scenario. It is featured with anomalous westerlies in zonal band of 10°–25°N and easterlies anomalies north of 30°N, constructing an anomalous cyclonic circulation over the

FIG. 5. Scatterplot of (top) the TUTT longitude biases and SST biases and (bottom) the TUTT longitude biases (° lon) and vertical motion biases ($10^{-2} \text{ Pa s}^{-1}$) over 10°–30°N, 150°E–150°W in CMIP5 models. The red lines denote linear fitting by the least squares method and the correlation R is shown in red at the bottom left in each panel.

subtropical North Pacific. Accordingly, the zonal wind shear increases between 10° and 25°N. The westerly anomalies between 10° and 25°N enhance the westerly near the western end of the TUTT, and the anomalous cyclonic circulation also intensifies the cyclonic curve associated with the TUTT. As shown in Fig. 6b, most of the selected models show a westward shift with variable magnitudes, and the MME mean indicates a slight westward shift of 0.7° longitude during this

FIG. 6. (a) Changes of the 15-model MME mean 200-hPa wind (vectors; m s^{-1}) and the vertical shear of zonal wind (shading; m s^{-1}), and (b) changes of the TUTT longitude ($^{\circ}$ lon) in each model and the corresponding MME mean (the rightmost bar) between 2016–35 and 1986–2005 in RCP4.5 scenario. (c),(d) As in (a),(b), but for the RCP8.5 scenario.

period. As the radiative forcing increases in the RCP8.5 scenario, the westerly anomalies in the RCP4.5 scenario weakens and the easterly anomalies in the tropical eastern-central Pacific extend westward (Fig. 6c). Figure 6d shows the changes of zonal location of the

TUTT in the individual models. There is a large inter-model spread in the migration of the TUTT, and the MME mean shows a slightly eastward shift of 0.3° longitude. It is found that the zonal location of the TUTT experiences little shift in both scenarios during 2016–35.

The CMIP5 models initialized by randomly selected preindustrial states, so the inherent variability in projections is not synchronized with observations, and thus the MME mean is only an estimate of responses of external forcing (e.g., Meehl et al. 2014; Dai et al. 2015). Note that the internal variability plays a dominant role since the effects of external forcing are still small in the near-term projection (e.g., Hawkins and Sutton 2009; Meehl et al. 2009, 2014). The results suggested that the zonal shift in the TUTT may generally determine by the internal variability of the climate system in the near-term projection.

b. Long-term projection

Previous studies found that the climate response becomes prominent and the contribution from internal variability falls very rapidly with the increase of the projection time as the signal of climate change strengthens, while the amplitude of internal variability remains constant (Cox and Stephenson 2007; Hawkins and Sutton 2009). Changes in the late-twenty-first century can be viewed as the responses to external forcing of the climate system. Figure 7a shows the changes of the selected 15-model MME 200-hPa wind over 2081–2100 in RCP4.5 scenario. As the forcing increases with time, the changes generally have a greater magnitude than that of 2016–35. The most prominent feature is the easterly anomalies and the associated anomalous easterly shear to the south of 25°N. Such wind anomalies will weaken the westerly associated with the TUTT, decreasing the westerly shear and shifting the TUTT eastward. The corresponding changes in the RCP8.5 scenario also show a similar result but with a greater magnitude under the stronger radiative forcing (Fig. 7c). For instance, changes in vertical zonal shear over 5°–20°N, 150°E–180° is -2.1 m s^{-1} in the RCP8.5 scenario, while that in RCP4.5 scenario is only -0.9 m s^{-1} . Previous studies have shown that vertical shear in this region exerts great impacts on TC formation over the WNP (e.g., Chan 2008; Liu and Chan 2013; Wu et al. 2015); such a weakening in the vertical shear indicates an eastward shift of TC formation during the late twenty-first century. In addition, there is an anomalous cyclonic circulation east of 140°E. Wang and Wu (2015) suggested that this anomalous cyclonic circulation would steer more TCs landing over eastern China. Figures 7b–d further demonstrate changes in the TUTT longitudes in individual selected models. In accordance with the anomalous easterly over the eastern WNP, two-thirds of the selected models show an eastward shift of the TUTT in both scenarios. The MME mean changes of the TUTT longitude are 1.9° and 3.2° in the RCP4.5 and RCP8.5 scenarios, respectively, suggesting an eastward

migration of the TUTT over 2081–2100. It should be noted that the projected eastward projection is different from that of Wu et al. (2015), which suggested a westward shift of the TUTT during 1979–2012. Some studies found that the Pacific SST experienced a La Niña-like change during this period (e.g., Burgman et al. 2008; Wang et al. 2013), and such a change increased the east–west SST gradient over the North Pacific. It favors the westward shift of the TUTT as well as the TC formation location (Wu et al. 2015). However, the SST warming anomaly in the long-term projection shows a greater amplitude over the eastern North Pacific than that of the western North Pacific (see Fig. 9a), decreasing the east–west SST gradient, and thus favoring the eastward shift of the TUTT. These results, in fact, indicate the potential important role of anomalous SST patterns on the TUTT migration.

5. Influence of SST over the North Pacific on the zonal shift of the TUTT in the warming scenarios

To understand the intermodel spread in the projection of the TUTT shift, we examine all of the 36 models available with three experiments (historical, RCP4.5, and RCP8.5 experiments) in this section. Given poor skills in simulating the climatological TUTT in some models (Fig. 3), we define an index for the zonal shift of the TUTT in the warming scenarios, which is the negative change of the 200-hPa zonal wind averaged over 5°–20°N, 150°E–180°. The zonal wind in this region is a good indicator of the TUTT longitudes in historical runs and global warming experiments in the selected climate models, with a correlation exceeding 0.9 in the three types of the experiments (figure not shown). The reason for using the negative changes in zonal wind is to make the index the same sign with the TUTT shift direction (i.e., the positive index anomaly corresponds to the eastward shift of the TUTT).

Figure 8 shows the TUTT index of the 36 models over 2081–2100 in the RCP8.5 scenario. The MME mean shows an increase of easterly wind in this region, indicating an eastward shift of the TUTT (Fig. 7). Such an MME mean eastward shift results mainly from the greater magnitude of eastward migration than that of westward migration. As shown in Fig. 8, there is a considerable intermodel spread in the projected zonal shift of the TUTT. Of the 36 models, 19 project an eastward shift, while the TUTTs in the other 17 models show a westward shift. Of the 15 selected models, 11 are from the group with the eastward shift, resulting in the projected eastward migration of the TUTT (Fig. 7).

What determine the projected zonal shift of the TUTT in the MME mean and individual models? The

FIG. 7. As in Fig. 6, but for the change between 2081–2100 and 1986–2005.

zonal location of the TUTT is closely associated with the SST and related vertical motion over the North Pacific. Figure 9a shows the MME mean changes in SST and 850-hPa wind over 2081–2100 in the RCP8.5 scenario. The SST anomalies feature a strong warming in the equatorial central-eastern Pacific and subtropical North Pacific, whereas relatively weak warming occurs in the

subtropical South Pacific (Xie et al. 2010; Zhang and Li 2014; Ying and Huang 2016). Xie et al. (2010) suggested that the warming pattern is closely associated with the ocean dynamic effects and wind anomalies according to the wind–evaporation–SST feedback (Xie and Philander 1994). Specifically, the westerly wind anomalies in the equatorial Pacific weaken the trade wind,

FIG. 8. TUTT index of 36 models over 2081–2100 in RCP8.5 scenario relative to 1986–2005. The x axis labels show the model number from Fig. 1. The red (blue) bars denote the changes greater (less) than zero. Hatched bars denote the 15 selected models and the green dashed line denotes the mean change.

suppressing the sea surface evaporation and further leading to the SST warming in this region. In fact, the westerly wind anomalies in the tropical WNP indicate the eastward extension of the monsoon trough, which is in accordance with the eastward shift of the TUTT in the MME mean (Fig. 8).

To further understand the spread source in the projected zonal shift of the TUTT, we regressed the normalized TUTT index onto the relative SST and 200-hPa wind changes in the 36 models over 2081–2100 in the RCP8.5 scenario. Previous studies suggested that the relative SST warming pattern, not the magnitude of SST warming, can influence large-scale circulations in warming scenarios (e.g., Vecchi and Soden 2007b, hereafter VS07; Johnson and Xie 2010). Following VS07, the relative SST is defined as the anomalous SST relative to the global tropics 20°S–20°N. Our purpose of using the relative SST is to remove the different warming magnitudes in various projection periods and scenarios, and emphasize the influences of the relative SST warming on large-scale circulations. In fact, the relative SST can indicate the impacts of SST change on large scale circulations in different climate scenarios because it including the effects of SST gradient (e.g., Lindzen and Nigam 1987) as well as changing SST threshold for convection (e.g., Johnson and Xie 2010), while the local absolute SST can only work in a single climate scenario. Therefore, when we consider different scenarios and periods, the relative SST is more reasonable than the absolute local SST because of the different warming magnitudes in various projection periods and scenarios. As shown in Fig. 9b, the anomalous SST pattern associated with eastward shift of the TUTT is characterized by stronger SST warming over the central and eastern North Pacific, and relatively weaker warming over the WNP. At the upper levels, there is an anomalous

FIG. 9. (a) Changes of the 36-model MME mean SST (shading; K) and 850-hPa wind (vectors; m s^{-1}) over 2081–2100 in RCP8.5 scenario. (b) Intermodel regression of relative SST anomalies (shading; K), precipitation (contours; mm day^{-1}), and 200-hPa wind anomalies (vectors; m s^{-1}) with respect to the normalized TUTT index over 2081–2100 in RCP8.5 scenario relative to 1986–2005. (c) Simulated difference in precipitation (shading; mm day^{-1}) and 200-hPa wind (vectors; m s^{-1}) between the sensitivity and control experiments.

anticyclonic circulation located at the central and eastern North Pacific, which is consistent with the projected eastward shift of the TUTT. We also examined the capacity of the CMIP5 models in reproducing the observed TUTT–SST relationship. It is found that the anomalous SST pattern associated with the eastward shift of the TUTT in observation is reasonably reproduced by the CMIP5 models, which resembles that in Fig. 9b.

To investigate the associated mechanism of the TUTT migration, we designed idealized numerical experiments

by using the ECHAM version 5.3 atmospheric global climate model (hereafter ECHAM5), which was developed by the Max Planck Institute for Meteorology (MPI; Roeckner et al. 2003). The model was run at a horizontal resolution of spectral triangular 42 (T42), with 31 vertical levels in a hybrid sigma–pressure coordinate system. The control run is forced by the Hadley Centre Sea Ice and Sea Surface Temperature data, which are averaged from 1970 to 1999. The sensitivity run is identical to control run except that the regressed SST anomaly over the North Pacific (10° – 30° N, 150° E– 150° W) in Fig. 9b was added to the climatological SST. For each experiment, a 32-yr integration was conducted and the last 30 years of results are used to construct the 30 ensemble members. The ensemble mean of July–October is analyzed. Figure 9c shows the simulated difference in 200-hPa wind and precipitation between control run and sensitivity run. As shown in Fig. 9, the warm SST anomalies in the central and eastern Pacific enhance the precipitation in this region, and the associated convective heating further stimulates westerly anomalies at low levels to its west (Matsuno 1966; Gill 1980), extending the monsoon trough eastward (Fig. 9a). In the upper troposphere, the TUTT shifts eastward as a result of the stimulated anticyclonic wind anomalies by increased convective heating in central and eastern Pacific (Figs. 9b,c). Additionally, the enhanced vertical motion over the central and eastern Pacific is unfavorable for the maintaining of radiational cooling and subsidence feedback in the TUTT (Fitzpatrick et al. 1995). To confirm this relationship, Fig. 10 further shows the scatterplot of the TUTT index and the anomalous relative SST over 10° – 30° N, 150° E– 150° W in the near-term and long-term projections in the RCP4.5 and RCP8.5 scenarios. The changes in zonal wind associated with the TUTT migration are closely related to the relative SST over the North Pacific, with a correlation of 0.69. That is, a stronger (weaker) relative SST warming over the North Pacific favors an eastward (westward) shift of the TUTT. The diverse future changes in the zonal location of the TUTT are related to projected relative SST anomalies in the Pacific. It is suggested that the spatial pattern of the future SST change is an important factor in the change of TC formation location.

6. Summary

The strong westerly shear to the south flank of the TUTT limits the east boundary of tropical cyclone (TC) formation over the WNP and thus the zonal shift of the TUTT in warming scenarios has an important implication for the mean formation location of TCs. Using the output of the CMIP5 models, it is found that

FIG. 10. Scatterplot of the TUTT index and the relative SST anomaly (K) over the North Pacific (10° – 30° N, 150° E– 150° W) in near-term (blue dots) and long-term (red dots) projections in RCP4.5 and RCP8.5 scenarios. The green line denotes linear fitting by the least squares method and the correlation R is shown in green at the bottom left.

considerable spreads exist in the zonal position, orientation, and intensity of the simulated-climatologic TUTTs in the historical runs. The large spread results mainly from the diversity in the simulated SST patterns over the North Pacific. Since some of the models failed to simulate the climatological TUTT, 15 of them with relatively higher skill in their historical runs are used for the future projection. Based on the 15 selected models, it is found that the zonal location of the TUTT experiences little shift in both the RCP4.5 and RCP8.5 scenarios during 2016–35. As the external forcing increases over time, the TUTT shifts eastward by 1.9° and 3.2° longitude in RCP4.5 and RCP 8.5 scenarios during 2081–2100, respectively. Such an eastward migration of the TUTT and the associated large-scale conditions may favor the TC formation over the eastern WNP, shifting the TC formation locations eastward. The eastward shift of the formation location makes TCs have longer time over the tropical warm ocean and get stronger intensity (e.g., Wang and Chan 2002; Camargo and Sobel 2005; Zhan et al. 2011; Zhao et al. 2011).

Although the MME mean of selected models shows an eastward shift, considerable intermodel variability is found in the projected migration of the TUTT in all available 36 models. About half of the models project an eastward shift and other half of the models project a westward shift. The projected changes in the zonal

location of the TUTT are dominated by the future changes in relative SST anomalies over the North Pacific. A stronger (weaker) relative SST warming over the North Pacific favors an eastward (westward) shift of the TUTT. It is suggested that the spatial pattern of future SST change is an important factor for the change of the mean formation of TCs.

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