Simulations of development of tropical disturbances associated with the monsoon trough over the western North Pacific

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The genesis of tropical disturbances in strong and weak monsoon trough (MT) patterns is examined in an idealized model. The initial MT patterns in the model simulations are obtained from a global reanalysis dataset that encompasses a 29-year period. The simulations show that a tropical disturbance tends to develop over the eastern part of western North Pacific (WNP) near 150°–160°E when the MT extends eastward, whereas a tropical disturbance tends to occur over the western part of the WNP near 120°–130°E when the MT retreats westward. In addition, there is a faster development of tropical disturbance with a greater intensity in the strong MT pattern than that in the weak MT pattern. The tropical disturbances are triggered in the most convectively unstable region through the local dynamic and thermodynamic processes in the strong and weak MT patterns.

KEYWORDS
idealized simulation, tropical disturbance, monsoon trough

INTRODUCTION

The western North Pacific (WNP) is the basin of the most active tropical cyclone (TC) genesis around the globe. This is related to the lower-level monsoon trough (MT) over the WNP, which features a convergence and a meridional shear line (Li, 2012), where approximately 70–80% of TCs develop in association with MT (Molinari and Vollaro, 2013). Synoptic-scale tropical disturbances are usually embedded in the MT over the WNP and are often associated with synoptic-scale wave trains that have alternating cyclonic and anticyclonic circulations and that propagate northwestward (Takayabu and Nitta, 1993; Li, 2006; Fu et al., 2007; Cao et al., 2013). The MT is a favorable region for the growth of synoptic-scale disturbances. Westward-propagating synoptic-scale disturbances were found to be a possible forcing mechanism of tropical cyclogenesis through a local increase in lower-level convergence and relative vorticity (Shapiro, 1977; Zehnder, 1991). In this study, we mainly discuss the development of tropical disturbances in the background of different season mean flows over the WNP.

It has been recognized that the TC genesis over the WNP shows a pronounced interannual variation (Wang and Chan, 2002). Previous observational studies indicate that the interannual variation of TC genesis is closely associated with the El Niño–Southern Oscillation (ENSO) phenomenon (Chen et al., 1998, Wang and Chan, 2002; Camargo et al., 2007). During El Niño summers, TCs appear more frequently over the southeast quadrant and less frequently over the northwest quadrant of the WNP; during La Niña summers, opposite features are observed (Wang and Chan, 2002). However, these previous studies were limited to observational composite analyses. Whether the tropical disturbance could be triggered through the composited large-scale circulation systems has not been established.

Cao et al. (2014) indicated that the interannual MT anomalies strongly affect TC genesis, through both dynamic and thermodynamic factors, using an idealized numerical
model. In their study, the initial large-scale fields in the simulations only include the large-scale anomalies associated with the MT interannual variation in a resting environment. A recent study of Cao et al. (2016) investigated how the large-scale fields, including both the MT interannual variation and the climatological mean fields, affect the TC genesis. The present study extends the work of Cao et al. (2016) by including the composite sea surface temperature (SST) data in the background of the climatological mean fields. The purpose is to compare, in detail, the contribution of the large-scale environmental factors to tropical disturbance genesis in the strong and weak MT patterns using an idealized model.

This paper is arranged as follows. In section 2, we describe the large-scale MT patterns and SST conditions during the strong and weak MT years and the design of numerical experiments. In section 3, we examine the evolution of large-scale circulation and the related physical processes affecting the genesis of tropical disturbance in the model simulations. Finally, we conclude the paper with a summary and discussion in section 4.

### 2. THE PATTERNS OF MT AND EXPERIMENTAL DESIGN

#### 2.1 Large-scale fields of MT

The large-scale fields of MT are the same as those in Cao et al. (2016). Therefore, a relatively simple description is presented here. The large-scale fields associated with the MT interannual variation are first obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) reanalysis data (Kalnay et al., 1996) according to the zonal variation of the MT intensity, which is defined by seasonal mean relative vorticity averaged from 5° to 20°N during July–November from 1979 to 2007 (Wu et al., 2012). The composite is then applied to obtain the large-scale fields during the strong and weak MT years. Figure 1 shows the composite 850-hPa wind fields and SST during the strong and weak MT years. A remarkable difference is that the MT expands southeastward to near 170°E during the strong years, whereas the MT is confined to the west of 140°E during the weak years (see the dashed lines). Correspondingly, the highest SST maximum is observed east of 160°E and west of 150°E during the strong and weak MT years, respectively.

#### 2.2 Experimental design

The experimental design is the same as that in Cao et al. (2016), except for SST. In this study, we used the non-hydrostatic Advanced Research Weather Research and Forecasting (WRF-ARW) model (version 3.3.1) (Skamarock et al., 2008). To reduce the potential mesh interference on the structure of MT, we used a single mesh with a uniform grid spacing of 30 km on a beta plane centered at 15°N (Li et al., 2006). The SST data at the initial time are obtained using the same composite method as for the other large-scale fields and derived from the NCEP reanalysis, which are fixed during the model integration, as shown in Figure 1. The model is integrated for 20 days.

Two idealized experiments are carried out in this study. In the first experiment, the composite strong MT pattern and associated SST are specified as the initial condition in the model, as shown in Figure 1a. In a similar way, the composite weak MT pattern and corresponding SST, as shown in Figure 1b, are specified in the second experiment. The two experiments are called as STRSST and WEASST, respectively. Additional sensitivity experiments are performed to examine the robustness of simulation results in relation to the initial conditions. Eight 2-dimensional random disturbances are added to the zonal wind fields at the initial time in the STRSST and WEASST experiments, respectively, which have no influence on the initial pattern of MT. Those ensemble experiments show that the
simulation results are not very sensitive to the initial conditions, particularly in the STRSST experiment (figure not shown).

3 | MECHANISM OF TROPICAL DISTURBANCE GENESIS

Figures 2 and 3 show the simulated 850-hPa wind fields in STRSST from $t = 24$ to 216 hr and in WEASST from $t = 168$ to 360 hr, respectively. A weak tropical disturbance occurs at approximately 160°E in a region east of MT at $t = 48$ hr (Figure 2b). In the following 72 hr, the tropical disturbance gradually intensifies along with the enhancement of westerly winds induced by the cross-equatorial flows (Figure 2c–e). At $t = 144$ hr, the tropical disturbance obviously intensifies along with the enhancement of easterly winds near 10°N (Figure 2f). At $t = 168$ hr, the tropical disturbance develops into a tropical depression, with the maximum wind of 12 m/s (Figure 2g). Eventually, the tropical depression develops into a strong TC, with the minimum sea level pressure (MSLP) of 986.7 hPa and a maximum wind of 30 m/s at $t = 216$ hr (Figure 2i).

In WEASST, the easterly winds dominate over the WNP before $t = 168$ hr (figure not shown). At approximately $t = 216$ hr, a weak tropical disturbance starts to develop near 130°E, even though the easterly winds are still dominant, which indicates that the development of a tropical disturbance occurs much more slowly compared with the STRSST run (Figures 3c and 2b). Under the influence of easterly winds, the cyclonic shear to the south of the easterly winds is enhanced near 15°N (Figure 3d–e). At $t = 288$ hr, an obvious tropical disturbance develops over the Philippine Islands (Figure 3f). In the following 24 hr, the vortex gradually intensifies and moves westward into the South China Sea under the steering easterly flows (Figure 3g) and then moves northwestward to the southern China coast (Figure 3h–i). At $t = 360$ hr, it develops into a weak tropical storm with the MSLP of 997.9 hPa (Figure 3i); the storm quickly weakens after landfall (figure not shown). If the time of TC genesis is defined as the maximum wind at 10-m height exceeding 15 m/s, TC genesis occurs at $t = 186$ hr in STRSST and at $t = 303$ hr in WEASST.

The modeling results show that the most favorable positions for tropical disturbance genesis are located over the eastern and western parts of the WNP in STRSST and WEASST, respectively. There is a greater intensity of the vortex in STRSST than in WEASST. The results are consistent with previous observational analyses, which shows that the large-scale circulations in the strong MT years provide a more favorable environment for TC genesis and intensification than in the weak MT years (Chia and Ropelewski, 2002; Li, 2012; Wu et al., 2012; Cao et al., 2014). The ensemble experiments show that the simulation results are more robust and reliable in STRSST.

Wang and Chan (2002) showed that the frequency of TC genesis is above normal over the southeastern WNP when the MT extends eastward during the El Niño summers, while more TCs form over the northwestern WNP when the MT retreats westward, using the observational data. The results of present numerical simulations are similar to those of previous observational analyses, but they have different physical meanings. In the observational composite analysis, tropical disturbances have occurred over the WNP. The development of a tropical disturbance prior to TC genesis is associated with the TC energy dispersion, synoptic wave train, and easterly wave over the WNP (Fu et al., 2007; Li, 2012) associated with the large-scale environmental conditions (Harr and Chan, 2005). Previous studies were mainly concerned with the effects of large-scale flows on the transformation of the preexisting tropical disturbances into TCs (Wang and Chan, 2002; Wu et al., 2012). When the MT extends eastward, the large-scale flows are favorable for the transition from the preexisting tropical disturbances to TCs over the southeastern part of the WNP, and vice versa. On the other hand, in an idealized numerical simulation, an artificial bogus vortex is inserted into the experiments to investigate the genesis and intensification of TC (Braun and Sippel 2012; Ge et al. 2013; Cao et al., 2014). In the present study, the composite climatological mean fields during the strong and weak MT years are specified, and there are no preexisting synoptic-scale or higher-frequency tropical disturbances at the initial time. The process of tropical disturbance genesis can be called as spontaneous genesis. This is a unique feature in our simulation results. As a result, the tropical disturbances need to be triggered through local dynamic and thermodynamic processes in STRSST and WEASST. Next, we investigate why the tropical disturbances occur over the eastern and western quadrants of the WNP in STRSST and WEASST, respectively.

To understand the primary processes responsible for the spin-up of tropical disturbances in STRSST and WEASST, Figure 4 displays 850-hPa relative vorticity, divergence averaged between 1,000 and 900 hPa, and the 10-m wind fields, the specific humidity and equivalent potential temperatures averaged between 1,000 and 700 hPa, and the vertical-zonal cross sections of vertical motion, which are averaged at $t = 72, 96$, and 120 hr in STRSST and $t = 216, 240$, and 264 hr in WEASST. In STRSST, the maximum specific humidity center is located in the eastern WNP near 155°–160°E, which is collocated with the divergence, vorticity, and equivalent potential temperature centers (Figure 4a,b). Due to the convective instability defined by the difference of equivalent potential temperature between 1,000 and 500 hPa (figure not shown) and lower-level convergence, strong convection first appears over the eastern WNP in STRSST, as shown by the vertical–zonal cross sections of vertical motion (Figure 5e). Moisture and vertical motion processes may contribute to a strong diabatic
heating, and thus promote a positive convection–circulation–moisture feedback. As a result, the tropical disturbances start to develop over the eastern WNP in STRSST.

In WEASST, the two specific humidity maxima are located over the western WNP near 120°–135°E, collocated with the divergence, vorticity, and equivalent potential temperature centers (Figure 4c,d). Particularly, greater vorticity and divergence center are located near 125°E, which leads to stronger convection west of 130°E (Figure 4f). The comparison of Figure 4a–d shows that the dynamic and thermodynamic factors do not match as well in WEASST as in STRSST. The magnitudes of divergence and vorticity are smaller in WEASST than in STRSST. In addition, other small disturbances are scattered near 5° and 20°N in WEASST (Figure 4d).

To further compare the difference of the processes contributing to TC genesis and intensification, Figure 5 shows the vertical-time evolution of area-averaged relative vorticity in the core region, and the vertical profiles of the tangential wind and radial wind of the vortex after TC genesis in STRSST and WEASST. Before the TC genesis, the maximum relative vorticity appears first in the lower level in STRSST (Figure 5a). The gradual enhancement of lower-level relative vorticity is mainly associated with the obvious lower-level convergence (figure not shown). While in WEASST, there is a decrease of relative vorticity from $t = 264$ to 276 hr before the TC genesis (Figure 5b). This may be associated with the effect of the topography, because the vortex is located near the Philippine Islands during these periods (Figure 3e,f). Therefore, the TC formation is much slower in WEASST than in STRSST. In addition to TC genesis, the vertical structures of TCs after the TC genesis are also compared in both experiments. Note that the time is chosen when the TCs in STRSST and WEASST have the same MSLP of 998 hPa. Thus, the TCs have the similar magnitude of tangential wind in STRSST and WEASST (Figure 5c,d). An obvious feature is that the outer flows in the upper level are much stronger in STRSST than in WEASST (Figure 5e,f). Another feature is that the inflow is
obviously deeper in STRSST than in WEASST (Figure 5e,f). Both features can result in the faster intensification of TC in STRSST than in WEASST.

**4 SUMMARY AND DISCUSSION**

Previous studies have indicated that the variability of TC genesis over the WNP is associated with the interannual MT variations. The frequency of TC genesis is above normal over the southeastern part of the WNP when the MT expands eastward, while more TCs form in the northwestern part of the WNP when the MT retreats westward. However, most of the studies were limited to the composite analysis by using the observational data. Specific processes through which the MT variability affects the tropical disturbance or the TC genesis are not clear. Therefore, we design two idealized numerical experiments that include the climatological mean states of MT interannual variation to investigate the most favorable position for the tropical disturbance formation during the strong and weak MT years using a mesoscale model.

Our simulations show that during the early stage, tropical disturbances tend to favorably form over the eastern (near 150°–160°E) and western parts (near 120°–130°E) of the WNP in STRSST and WEASST, respectively. The large-scale circulations in the STRSST simulation can result in a faster development of the tropical disturbance and a greater intensity than that in WEASST. The results are consistent with observational analysis. In STRSST, the high SST and strong convergence circulations over the eastern WNP help the moisture increase in the lower level. The maximum equivalent potential temperature and moist static energy are also collocated with the convergence center, which implies the greatest convective instability. The moisture and convection processes may both contribute to a strong diabatic heating and thus promote a positive convection–circulation–moisture feedback. Through this positive feedback, the tropical disturbance quickly develops in STRSST over the eastern WNP. While in WEASST, the weaker divergence, vorticity, and vertical motion, along with the mismatch among the centers of divergence, vorticity, specific humidity and vertical motion, inhibit the fast
FIGURE 4  The wind fields at 10-m height (vector), divergence (contoured at the interval of 0.5 × 10^-5 per second) averaged between 1,000 and 900 hPa, and specific humidity (shaded, g/kg) averaged between 1,000 and 700 hPa, (a) in the STRSST run, which are averages at t = 72, 96, and 120 hr and (c) in the WEASST run, which are averages at t = 216, 240, and 264 hr. The divergences in (a) and (c) are shown as negative values and blue dashed lines, beginning from −0.5 × 10^-5/s at the intervals of 1 × 10^-5/s. (b, d) are the same as (a, c), but for the equivalent potential temperature (shaded, K) averaged between 1,000 and 700 hPa and 850-hPa relative vorticity (contoured 10^-5/s). The vorticities in (b) and (d) are shown as positive values and black solid lines, beginning from 1.0 × 10^-5/s at the intervals of 2 × 10^-5/s. The vertical–zonal cross section of vertical motion (10^-2 m/s) (e) in the STRSST run averaged between 3.5° and 8.5°N and averaged at t = 72, 96, and 120 hr and (f) in the WEASST run averaged between 12.5° and 17.5°N and averaged at t = 216, 240, and 264 hr.
FIGURE 5  The vertical–time evolution of area-averaged (420 km × 420 km) relative vorticity ($10^{-5}$ s$^{-1}$) in (a) STRSST from $t = 120$ to 264 hr and (b) WEASST from $t = 216$ to 360 hr. The blue solid lines in (a and b) denote the TC genesis time. The vertical-longitude cross section of meridional wind (contour, m/s) and temperature anomaly (shaded, K) across the center of the simulated TC (c) at $t = 192$ hr in STRSST and (d) at $t = 360$ hr in WEASST; (e and f) is the same as (c and d) but for the vertical-radial cross section of azimuthal-mean radial wind (m/s)
development of a tropical disturbance. In addition, the effect of the topography results in the temporary weakening of the development of relative vorticity. The vortex in WEASST has a shallower radial inflow in the lower-middle level and weaker outflow in the upper level. As a result, relatively weak tropical disturbance appears over the western WNP in WEASST.

In this study, we mainly focus on the processes for the tropical disturbance genesis using a single domain, given the respective composite SST distribution under the strong and weak MT patterns. However, the sensitivity of modeling results to model physics is unknown. In the future, a series of sensitivity experiments will be performed to examine the robustness of the simulation results. Additional experiments with climatological mean SST distribution and constant SST of 29°C will be performed to investigate the sensitivity of TC genesis to SST patterns. The simulation results show that the TC genesis is significantly affected by different SST patterns, particularly the constant SST distribution. The details about the impacts of the SST pattern will be investigated in another work. In addition, we will investigate where the weak bogus vortex can develop the fastest when the artificial vortex is inserted into the different positions of strong MT.

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