The SST Gradient between the Southwestern Pacific and the Western Pacific Warm Pool: A New Factor Controlling the Northwestern Pacific Tropical Cyclone Genesis Frequency

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ABSTRACT

The sea surface temperature gradient (SSTG) between the southwestern Pacific Ocean (40°–20°S, 160°E–170°W) and the western Pacific warm pool (0°–16°N, 125°–165°E) in boreal spring has been identified as a new factor that controls the interannual variability of tropical cyclone (TC) frequency over the western North Pacific Ocean (WNP). This SSTG can explain 53% of the total variance of the WNP TC genesis frequency during the typhoon season for the period 1980–2011. The positive SSTG anomaly produces an anomalous cross-equatorial pressure gradient and thus anomalies in low-level southward cross-equatorial flow and tropical easterlies over the central-western Pacific. The anomalous easterlies further produce local equatorial upwelling and seasonal cooling in the central Pacific, which in turn maintains the easterly anomalies throughout the typhoon season. These dynamical/thermodynamical effects induced by the positive SSTG anomaly lead to a reduced low-level cyclonic shear, increased vertical wind shear, and weakened monsoon trough over the WNP, greatly suppressing WNP TC genesis during the typhoon season. This implies that the spring SSTG could be a good predictor for WNP TC genesis frequency.

1. Introduction

In 2004, the western North Pacific Ocean (WNP) experienced a very busy typhoon season with 29 named tropical cyclones (TCs), while in 2010 the WNP was unusually quiet with only 14 TCs forming. This indicates strong interannual variability in TC genesis frequency over the WNP (Landsea 2000; Ying et al. 2011). Over the past 2–3 decades, many efforts have been made to understand the factors controlling the interannual variability of WNP TC genesis frequency and the involved physical mechanisms. For example, El Niño–Southern Oscillation (ENSO) (Chan 2000; Wang and Chan 2002), the quasi-biennial oscillation (QBO) in the equatorial stratosphere (Chan 1995), and the Antarctic Oscillation (AAO) (Ho et al. 2005) have been identified as factors affecting the interannual variability of WNP TC genesis frequency. Recently, a causal relationship between the eastern Indian Ocean (EIO) sea surface temperature (SST) anomaly (SSTA) and WNP TC genesis frequency has also been reported (Zhan et al. 2011a,b; Tao et al. 2012).

Based on the identified relationships between TC activity and climate modes/variations, skillful seasonal forecasts for TC frequency have been issued by some major meteorological agencies around the world (Camargo et al. 2010). Unfortunately, the prediction errors for annual TC numbers over the WNP have remarkably increased in recent years (Zhan et al. 2012).
The increasing errors might be related to two facts: 1) the statistical relationships between TC activity and various large-scale climate modes are not stable with time and 2) the predictors identified could not fully explain the interannual variability of TC frequency. Take the QBO–WNP TC relationship, for instance: a recent reexamination has shown that the significant relationship found in earlier studies is no longer present in recent years (Camargo and Sobel 2010). Thus, it is necessary to discover any new factors and to understand how they contribute to the interannual variability of the WNP TC genesis frequency.

In the Atlantic Ocean, the SST gradient (SSTG) between the North and South Atlantic [Atlantic meridional mode (AMM)] is shown to modulate seasonal hurricane activity (Kossin and Vimont 2007; Vimont and Kossin 2007). Previous studies have also revealed that the SST contrast between the Northern and Southern Hemispheres exerts a significant impact on the tropical Pacific climate (Chiang et al. 2008; Chiang and Friedman 2012). A drying–wetting variation of the Northern Hemisphere monsoon and a south–north shift of the intertropical convergence zone (ITCZ) are especially pronounced (Chiang and Friedman 2012). Since WNP TC genesis is directly related to the tropical Pacific’s thermodynamical and dynamical conditions, the interhemispheric thermal gradient may also affect WNP TC genesis. In this study, we will focus on the possible effect of the cross-equatorial thermal gradient between the southwestern Pacific Ocean (SWP) and the western Pacific warm pool (WWP) on WNP TC activity. We will show that this thermal gradient in boreal spring is strongly correlated with the WNP TC genesis frequency during the typhoon season and could be a new predictor in statistical or hybrid statistical–dynamical models for seasonal prediction of WNP TC activity.

2. Data and methodology

Three best-track TC datasets over the WNP, from the Shanghai Typhoon Institute of the China Meteorological Administration (CMA), the Joint Typhoon Warning Center (JTWC), and the Regional Specialized Meteorological Center of the Japan Meteorological Agency (JMA), for the period 1980–2011 were used. TCs with at least tropical storm intensity (maximum sustained 10-m wind speed ≥17 m s$^{-1}$) over both the South China Sea (SCS) and the WNP (hereinafter referred to simply as WNP TCs) were considered in this study. Since about 80% of WNP TCs occur from June to October (JJASO), we defined JJASO as the typhoon season.

The monthly mean extended reconstructed SST (ERSST) analyses with a 2.5° × 2.5° horizontal resolution from the National Oceanic and Atmospheric Administration (NOAA) (Smith and Reynolds 2003), outgoing longwave radiation (OLR) from NOAA (Liebmann and Smith 1996), and wind and sea level pressure (SLP) fields from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses (Kalnay et al. 1996) for the period 1980–2011 were also used.

According to the key regions where the SST is significantly correlated with the WNP TC genesis frequency in the correlation map (not shown), we defined the thermal gradient (SSTG) between the SWP and WWP as the difference between the SST averaged over 40°–20°S, 160°E–170°W (SWP) and that averaged over 0°–16°N, 125°–165°E (WWP) (as marked in Fig. 3a, introduced below). In the following discussion, in terms of seasons we refer to the seasons in the Northern Hemisphere.

3. Relationship between the SSTG and the WNP TC frequency

Figure 1a shows the correlations of the WNP TC genesis frequency during the typhoon season from the CMA best-track data with the SSTG indices from the preceding October–August. Before March, the correlation coefficients are low. A negative correlation becomes significant at the 99% confidence level from March and reaches the highest in April. The significant correlation is maintained until July. Since the negative correlation is the highest in spring (March–May), we will focus only on the influence of the spring SSTG in our following analyses. Figure 1b shows the time series of the normalized WNP TC genesis frequency during the typhoon season and the spring SSTG. An out-of-phase relationship is prominent with a temporal correlation coefficient of −0.73. That means that the variation of the spring SSTG can explain as much as 53% of the total variance of the variability in the WNP TC genesis frequency.

To confirm this relationship, Table 1 shows the correlations of the WNP TC frequency during the typhoon season from three best-track datasets with the spring SSTG, and the individual SSTs averaged in the SWP and the WWP in spring. All of the three original best-track datasets show significant negative correlations of the WNP TC genesis frequency with the SWP SST and the SSTG, well above the 99% confidence level. In particular, the correlation coefficients with the SSTG reach −0.73, −0.64, and −0.61 for the CMA, JMA, and JTWC datasets, respectively. The correlation between the TC genesis frequency and the WWP SST, however, is quite weak. Results with the interdecadal variability removed based on a 9-point Gaussian filter (Table 1) suggest that the SWP (WWP) SST mainly modulates the interdecadal (interannual) variability of the WNP TC genesis.
frequency. Note that the significant correlation of the TC genesis frequency with the SSTG remains regardless of whether their interdecadal variability is removed. In this sense, the spring SSTG is a better predictor for seasonal prediction of the WNP TC genesis frequency than the individual SWP and WWP SSTs. To further examine the effects of interdecadal variations, we extended our analysis back to 1951, the earliest time when the best-track data are available from all three agencies. The results show that there is a strong interdecadal modulation of this relationship, with correlations before 1975 being very weak (not shown). This indicates the unsteady nature of the statistical relationship between predictors and predictand and could explain why the errors in predicting the seasonal TC frequency over the WNP increased greatly in recent years because none of the evaluated statistical schemes has used the SSTG as a predictor for the basin (Zhan et al. 2012). The reasons for this interdecadal modulation will be examined in our future work.

4. Possible physical mechanism

Figure 2 shows the regressed seasonal mean 850-hPa wind, OLR, SLP, 850-hPa relative vorticity, vertical wind shear between 200 and 850 hPa, and 500-hPa omega during the typhoon season with respect to the spring SSTG. Over the tropical western Pacific, the positive spring SSTG anomaly raises SLP; induces low-level anomalous tropical easterlies and southward cross-equatorial flows centered at 125° and 150°E, respectively; increases local vertical wind shear; and induces anomalous midtropospheric subsidence over the WNP. The tropical easterly anomalies with anticyclonic shear reduce the low-level cyclonic vorticity over the main WNP TC genesis region. These dynamical responses to the spring SSTG anomaly would suppress WNP TC genesis.

In addition, we also calculated the correlation between the spring SSTG and the WNP summer monsoon index (Wang and Fan 1999) during 1980–2011. The correlation coefficient reaches 0.43, which is significant at the 95% confidence level, suggesting that the positive SSTG anomaly in spring can lead to the weakened WNP summer monsoon. Since the WNP summer monsoon trough contributes significantly to the WNP TC genesis (Ritchie and Holland 1999; L. Wu et al. 2012), the weakened WNP summer monsoon associated with the positive SSTG anomaly would further suppress TC genesis over the WNP.

The positive spring SSTG anomaly also induces anomalous diabatic cooling in the central equatorial Pacific as inferred from the regressed OLR field in Fig. 2a. The simple model from Gill (1980) suggests that an equatorial cooling source in the midtroposphere can produce anomalous low-level easterlies to its west with anticyclonic circulations on its northwestern and southwestern flanks as a result of the equatorial Rossby wave response. Therefore, the anomalous diabatic cooling in the central equatorial Pacific may enhance the anomalous tropical easterlies induced by the positive SSTG.
anomaly and the anomalous anticyclone over the main WNP TC genesis region, which is unfavorable for TC genesis. That means that the combined dynamical and thermodynamical effect associated with the positive spring SSTG anomaly greatly suppresses WNP TC genesis.

To address how the spring SSTG affects the dynamical and thermodynamical conditions over the main WNP TC genesis region during the typhoon season, we show in Figs. 3c and 3e the regressed seasonal mean 850-hPa winds and SLP in spring with respect to the spring SSTG. In spring, the positive SSTG anomaly gives rise to a cross-equatorial pressure gradient west of about 170°E with low pressure over the warmed southern subtropics and high pressure over the cooled northern subtropics. Previous studies have suggested that the cross-equatorial pressure gradient is important for driving the cross-equatorial flow (Mahrt 1972; Hoskins and Wang 2006). Thus, such an anomalous pressure distribution in response to the spring SSTG anomaly drives the anomalous southward cross-equatorial flow and equatorial easterlies in the lower troposphere (Fig. 3c). This suggests that the dynamical environment during the typhoon season shown in Fig. 2 has been preconditioned in spring.

To confirm the above result, several numerical experiments were conducted using the University of Hawaii International Pacific Research Center (IPRC) Regional Atmospheric Model (iRAM). The details of the model can be found in Wang et al. (2007). The model has been

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**Fig. 2.** Regression patterns of (a) the seasonal mean 850-hPa winds (m s\(^{-1}\); vectors), OLR (W m\(^{-2}\); shaded), and SLP (hPa; black contour) and (b) 850-hPa vorticity (Vor; 10\(^{-5}\) s\(^{-1}\); green dashed contour), vertical wind shear between 200 and 850 hPa (VWS; m s\(^{-1}\); shaded), and 500-hPa omega (10\(^{-2}\) Pa s\(^{-1}\); black contour) during the typhoon season with respect to the spring SSTG. Only areas where the difference is statistically significant at the 95% confidence level based on the F test are shown. In the OLR field, the shaded values are significantly positive. In the VWS field, the significantly positive (negative) values are shaded in red (blue).
used in the studies of dynamically downscaled WNP TC activity and has shown good skill (Zhan et al. 2011b; C.-C. Wu et al. 2012). The model settings are the same as those in Zhan et al. (2011b), except that the model domain is 50°S–57.5°N, 100°E–160°W with a grid spacing of 0.5° in this study. We conducted a control simulation (CTRL) and two sensitivity experiments (CS_2004 and WS_2004) for 2004, a year in which both the TC frequency during the typhoon season and the spring SSTG are nearly normal. In the CS_2004 run, a negative SSTG anomaly of 1°C was imposed by adding +0.3°C to the SSTs over the WWP and −0.7°C to the SSTs over the SWP onto the observed SSTs in the CTRL run, while in the WS_2004 run a positive SSTG anomaly of 1°C was imposed by adding −0.3°C to the SSTs over the WWP and +0.7°C to the SSTs over the SWP. The above negative and positive SSTG anomalies were chosen based on observations, which shows a greater anomaly in the SWP than in the WWP. The model was initialized at 0000 UTC 21 February 2004 and integrated through the end of May 2004.

FIG. 3. The seasonal mean 850-hPa winds (m s⁻¹) in the spring of 2004 from (a) the NCEP reanalysis and (b) the CTRL experiment; the regressed seasonal mean (c) 850-hPa winds (m s⁻¹) and (e) SLP (hPa) during 1980–2011 with respect to the spring SSTG; and differences in the seasonal mean (d) 850-hPa winds (m s⁻¹) and (f) SLP (hPa) between the WS_2004 and the CS_2004 runs for the spring of 2004. In (a), the solid box indicates the domain of the SWP, and the dashed one indicates that of the WWP.
Figures 3a and 3b show the seasonal mean 850-hPa winds in the spring of 2004 from the NCEP reanalysis and the CTRL experiment, respectively. The low-level circulation in the reanalysis is characterized by the Australian high and the WNP subtropical high. These main features are well captured by the model, although the WNP subtropical high is slightly weaker and the equatorial westerlies west of 170°E are stronger in the CTRL simulation than in the reanalysis. Nevertheless, overall, the iRAM forced by the reanalysis captures reasonably well the large-scale features in the region.

Figures 3d and 3f show the differences in the simulated seasonal mean 850-hPa winds and SLP between the WS_2004 and the CS_2004 runs. When the SSTG is increased, a cross-equatorial pressure gradient occurs in the region west of 150°E, with low pressure over the warmed southern subtropics and high pressure over the cooled northern subtropics, and southward cross-equatorial flow and the equatorial easterlies are triggered in the lower troposphere. The simulated dynamical response to the SSTG anomaly is very similar to the regressed pattern based on the reanalysis as shown in Figs. 3c and 3e, although the cross-equatorial pressure gradient and equatorial easterlies are located more westward in the former than in the latter. This suggests that it is in spring that the SSTG anomaly produces the dynamical environments similar to those during the typhoon season.

Since the response of the dynamical environments to the SSTG anomaly is established in spring while the SSTG anomaly weakens significantly toward the typhoon season, a question arises as to how the preconditioned dynamical environments are maintained and intensified throughout the upcoming typhoon season. This is discussed by examining the lagged correlations between the spring SSTG and several key dynamical and thermodynamical variables in the following months as shown in Fig. 4. The key factors are selected based on the regressed patterns in spring and during the typhoon season as shown in Figs. 2 and 3, including the SLP gradient measured as the difference between SLP averaged over 10°–25°N, 105°–165°E and that averaged over 25°–10°S, 105°–165°E; cross-equatorial flow averaged over 5°S–5°N, 140°E–180°; and OLR averaged over 5°S–5°N, 160°E–180° from April to October during 1980–2011. The solid (dashed) transverse line indicates correlations significant at the 95% (99%) confidence level.

In April, significant correlations exist between the spring SSTG and the SLP gradient and the cross-equatorial flow, which can persist throughout the typhoon season with some changes in magnitude only. From May, the negative correlation between the spring SSTG and the equatorial westerlies becomes significant. The correlation coefficient between the spring SSTG and the OLR over the equatorial central Pacific increases from April, reaches the 95% confidence level in July, and then remains above this level until October. These correlations indicate a pathway for the spring SSTG to control the WNP TC genesis frequency during the upcoming typhoon season. In spring, the positive SSTG anomaly
produces the cross-equatorial pressure gradient, which forces both the anomalous southward cross-equatorial flow and equatorial easterly anomalies. The equatorial easterlies then act to cool the central equatorial Pacific by inducing local upwelling and raising the thermocline to the east, which, in turn, maintains and intensifies the equatorial easterly anomalies and hence the cross-equatorial pressure gradient in the following months during the typhoon season.

5. Conclusions

We have discovered a new factor: namely, the spring SST gradient between the SWP and the WWP, which is significantly negatively correlated with the WNP TC genesis frequency during the typhoon season. The correlations of the spring SSTG with frequencies of different intensity categories (weak TCs, intense TCs, and typhoons) and the power dissipation index (PDI) are also statistically significant (not shown). This suggests that the statistical model uncovered in this study might be valid not only for TC genesis but also for TC intensity.

This SSTG–WNP TC relationship has been physically explained by the atmospheric response to the SSTG anomaly in spring and the air–sea interaction during the typhoon season triggered by the spring SSTG anomaly, as shown schematically in Fig. 5. In spring, the positive SSTG anomaly leads to a cross-equatorial pressure gradient, which forces anomalous southward cross-equatorial flow and tropical easterlies over the WNP. This observed response was further demonstrated by several sensitivity experiments using a regional climate model. After being triggered, the equatorial easterlies act to cool the equatorial central Pacific by inducing local upwelling and raising the thermocline in the east, which, in turn, maintains and intensifies the equatorial easterlies and hence the cross-equatorial pressure gradient during the upcoming typhoon season. As a result, the combined dynamical and thermodynamical effect triggered by the spring SSTG anomaly produces the low-level negative vorticity anomaly, the strong vertical wind shear, and the weak WNP summer monsoon throughout the typhoon season, greatly suppressing the WNP TC genesis. Conversely, the negative SSTG anomaly would play a role opposite to the positive spring SSTG anomaly and will produce dynamical and thermodynamical conditions favorable for TC genesis over the WNP in summer.

As indicated in section 1, a similar relationship between the interhemispheric SSTG and TC activity has also been documented for the Atlantic. Both the SSTG in the Pacific revealed here and the AMM in the Atlantic are associated with climatic variations in the individual basins via both the teleconnection and the air–sea interaction that all coherently control TC activity. However, the evolution of the effect is somewhat different. The AMM variance can persist through the hurricane season and contribute directly to Atlantic hurricane activity, while the SSTG anomaly in the Pacific peaks in spring and weakens rapidly afterward and thus modulates WNP TC activity via the persistence of the preconditioned atmospheric circulation and the subsequent air–sea interaction in summer.
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