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• **Original Paper** •

Impact of the Spring SST Gradient between the Tropical Indian Ocean and Western Pacific on Landfalling Tropical Cyclone Frequency in China

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ABSTRACT

The present study identifies a significant influence of the sea surface temperature gradient (SSTG) between the tropical Indian Ocean (TIO; 15°S–15°N, 40°–90°E) and the western Pacific warm pool (WWP; 0°–15°N, 125°–155°E) in boreal spring on tropical cyclone (TC) landfall frequency in mainland China in boreal summer. During the period 1979–2015, a positive spring SSTG induces a zonal inter-basin circulation anomaly with lower-level convergence, mid-tropospheric ascendance and upper-level divergence over the west-central TIO, and the opposite situation over the WWP, which produces lower-level anomalous easterlies and upper-level anomalous westerlies between the TIO and WWP. This zonal circulation anomaly further warms the west-central TIO by driving warm water westward and cools the WWP by inducing local upwelling, which facilitates the persistence of the anomaly until the summer. Consequently, lower-level negative vorticity, strong vertical wind shear and lower-level anticyclonic anomalies prevail over most of the western North Pacific (WNP), which decreases the TC genesis frequency. Meanwhile, there is an anomalous mid-tropospheric anticyclone over the main WNP TC genesis region, meaning a westerly anomaly dominates over coastal regions of mainland China, which is unfavorable for steering TCs to make landfall in mainland China during summer. This implies that the spring SSTG may act as a potential indicator for TC landfall frequency in mainland China.

Key words: tropical cyclone, landfall, sea surface temperature gradient, air–sea interaction

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1. Introduction

Tropical cyclone (TC) landfall activity is very frequent over the west coasts of the western North Pacific (WNP), especially in mainland China. During the period 1979–2015, the annual mean number of landfalling TCs (LTCs) in mainland China was greater than seven, among which five occurred in summer on average. In this peak season, LTCs cause serious disasters in Chinese coastal regions. Seasonal forecasting factors modulating TC landfall frequency in South China, such as El Niño–Southern Oscillation (ENSO), have been investigated (e.g., Liu and Chan, 2003; Goh and Chan, 2010). Moreover, previous studies have pointed out that TC landfall activity is closely related to TC genesis location and steering flow (Liu and Chan, 2003; Wu et al., 2004; Goh and Chan, 2010; Mei et al., 2015). Generally, TC genesis depends largely on favorable environmental fields, such as low-level relative vorticity, vertical wind shear, and sea surface temperature (SST) (Gray, 1979; Emanuel, 2003; Li and Zhou, 2012). The TC steering flow can be measured by large-scale mid-tropospheric flow (Chan and Gray, 1982) and is largely responsible for TC tracks (Ho et al., 2004). In seasonal TC forecasts, TC landfall in a targeted area is of more concern, but numerous errors still sometimes appear due to our limited understating (Zhan et al., 2012). Therefore, it is imperative to explore reliable factors and shed light on the key mechanisms involved in the interannual variation of LTCs in mainland China.

The dynamic and thermodynamic conditions mentioned above can be significantly modulated by atmospheric teleconnection and air–sea interaction associated with SST gradients (SSTGs) during the TC season. In the Atlantic, the seasonal hurricane activity can be directly impacted by the SSTG between the North and South Atlantic (Kossin and Vimont, 2007; Vimont and Kossin, 2007). In the Pacific, the spring SSTG between the southwestern Pacific and the western Pacific warm pool (WWP) has been identified as a new factor controlling TC genesis frequency in the typhoon season (June–October) (Zhan et al., 2013). A follow-up study (Zhao et al., 2016) indicated that the connection between them intensified after the mid-1970s, as compared to the period 1951–74. The SSTG anomaly in the Atlantic can persist through the hurricane season and directly modulate hur-

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ricane activity, whereas the Pacific SSTG weakens rapidly after spring and influences TC genesis via the persistence of the preconditioned atmospheric circulation based on the air–sea interaction. In these individual basins, both the Atlantic and Pacific SSTG anomalies show a meridional distribution.

Recently, the zonal response of atmospheric circulation over the WNP to Indian Ocean (IO) SST change has become an area of interest. In summer, northwestern IO cooling leads to an anomalous cyclone over the subtropical WNP (Wang and Wu, 2012). Via a baroclinic Kelvin wave, tropical IO (TIO) warming can induce an anomalous anticyclone and suppressed convection over the WNP throughout summer after El Niño, followed by dissipation in spring (Yang et al., 2007; Xie et al., 2009), which decreases the summer TC frequency over the WNP (Du et al., 2011). Besides, the effect of eastern IO SST anomalies on TC genesis over the WNP has been confirmed in numerical experiments with specified SST forcing in the eastern IO (Zhan et al., 2011b). The eastern IO SST in spring can be regarded as a seasonal predictor for WNP TC activity (Zhan et al., 2011a). Compared with ENSO, the TIO SST has a more direct and significant effect on WNP TC activity during El Niño and La Niña decaying years (Tao et al., 2012). Through air–sea interaction, the summertime TC genesis over the South China Sea can be modulated by the zonal SSTG between the northern IO and the WNP (Li and Zhou, 2014). Furthermore, inter-basin air–sea interaction can create positive feedback between the northern IO warming and the anomalous anticyclone spanning the tropical WNP and the northern IO (Xie et al., 2016).

Few studies on the relationship between LTC activity and SSTGs, especially zonal SSTGs, have been conducted. In view of the significant seasonal relationship between WNP TC activity and the zonal inter-basin atmospheric circulation induced by SST, we focus on the possible influence of the spring SSTG between the TIO and WWP on the LTC frequency in mainland China in summer. We begin by identifying the LTCs in mainland China and the regions of the zonal SSTG. The relationship between the LTC frequency and the SSTG is then explained by investigating the air–sea interaction that impacts the genesis frequency and location of WNP TCs and the large-scale steering flows.

2. Data and methodology

Monthly mean ERA-Interim data from the European Centre for Medium-Range Weather Forecasts (Dee et al., 2011) and SST data from the Met Office Hadley Centre (Rayner et al., 2003) are used to identify the relationship between the SSTG and large-scale circulation anomalies over the WNP from 1979 to 2015. In the same period, the TC best-track data (including LTC position and time) from the International Best Tracks Archive for Climate Stewardship (IBTrACS) project (Knapp et al., 2010) are used to investigate the LTC information. A current time record is regarded as a TC landfall record if the minimum distance from a TC to land between the current time and the next reporting time is zero in the IBTrACS data. These data undergo quality control and combine information from numerous TC datasets, such as the Joint Typhoon Warning Center, China Meteorological Administration, and Hong Kong Observatory.

The IBTrACS data provide an LTC record without isolating the LTCs in mainland China. As shown in Fig. 1, if any of the TC landfall location lies within the region enclosed by the blue line, it is regarded as an LTC in mainland China and its first landfall record in the region can be identified as the landfall location and time. According to this criterion, 185 TCs made landfall in mainland China in summer during the period 1979–2015. Manual examination verifies that LTCs in mainland China can be identified effectively using this key region. The LTC frequency is defined as the annual number of LTCs in mainland China in summer. In addition, correlation analysis is used to reveal the relationship between the SSTG and LTC frequency in mainland China. Regression and composite analyses are applied to investigate the response of the atmospheric circulation to the SSTG.

3. Relationship between the SSTG and LTC frequency

To investigate whether the spring zonal SSTG plays a role in the interannual variation of summertime LTC frequency in mainland China, the correlation coefficients between the LTC frequency in mainland China and the SST are shown in Fig. 2. There are significant negative correlations in the TIO and positive correlations in the WWP. In this study, the zonal SSTG is defined as the difference between the SST averaged over the TIO (15°S–15°N, 40°–90°E) and that averaged over the WWP (0°–15°N, 125°–155°E). A positive (negative) SSTG is thus related to warmer (cooler) SST over the TIO and cooler (warmer) SST in the WWP.

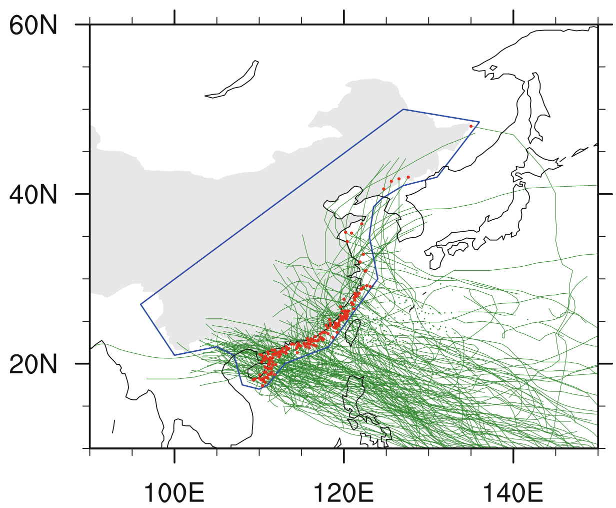

Fig. 1. Tracks (green lines) and landfall locations (red dots indicate LTC center positions) of LTCs in mainland China identified by the region enclosed within the blue line in summer (June–August) during 1979–2015. Green dots denote disconnected LTC tracks due to missing values in the IBTrACS data.