Intensified impact of the central Pacific warming on the monsoon trough over the western North Pacific since 1984

Hongjie Zhang1,2 | Liang Wu1 | Ronghui Huang1 | Jau-Ming Chen3

1Center for Monsoon System Research, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
2College of Earth Sciences, University of Chinese Academy of Science, Beijing, China
3Department of Maritime Information and Technology, National Kaohsiung Marine University, Kaohsiung, Taiwan

Correspondence
Liang Wu, Center for Monsoon System Research, Institute of Atmospheric Physics, Chinese Academy of Sciences, P.O. Box 2718, Beijing 100190, China.
Email: wul@mail.iap.ac.cn

Funding information
the National Natural Science Foundation of China, Grant/Award Number: 41475077, 41461164005, and 41230527; the National Basic Research Program of China, Grant/Award Number: 2014CB953902; the Youth Innovation Promotion Association CAS, Grant/Award Number: 2017106

The present study investigates the impact of the central Pacific warming (CPW) on the monsoon trough (MT) over the western North Pacific (WNP) during July–November of 1948–2015. It is shown that the relationship of the CPW with the MT experienced a remarkable change around 1984. Compared with 1948–1983, the MT was significantly stronger and extended eastward during the CPW events from 1984 to 2015. This relationship can be explained by the increase in the sea surface temperature (SST) in the tropical Pacific around 1984, especially over the central Pacific. Before 1984, the significantly cool ocean in the tropical western Pacific with the weakly warm ocean in the tropical central Pacific reduced the MT development and the eastward shift over the WNP during the CPW events. However, the enhanced low-level westerlies and cyclonic vorticity induced by the warmer ocean surface in the tropical central Pacific led to the strengthening and further eastward extension of the MT during the CPW events after 1984. Following the eastward extension of the MT, the enhanced 850-hPa positive vorticity, intensified 200-hPa divergence, increased relative humidity, and reduced vertical wind shear tend to shift eastward during the CPW events after 1984, which favor tropical cyclone (TC) genesis. The results show more TCs after 1984 over the WNP during the CPW events than before 1984.

KEYWORDS
central Pacific warming, eastern Pacific warming, monsoon trough, tropical cyclone, western North Pacific

1 | INTRODUCTION

The El Niño–Southern Oscillation (ENSO) event is a dominant mode of climate variability on the inter-annual timescale, which influences worldwide weather systems, including rainfall and tropical cyclones (TCs). Previous studies have found that during El Niño years, there is a significant change in the inter-annual variations in TC activity over the western North Pacific (WNP), including genesis location, population, lifetime, and intensity (Chen, 2000; Wu et al., 2012). The effect of ENSO on TC activity is closely linked to the change in tropical atmospheric circulation. As an important part of the tropical circulation over the WNP, the monsoon trough (MT) is the convergence region between the cross-equatorial westerly flow and the easterly trade flow. The changes in the MT location associated with ENSO have a high impact on the spatial distribution of TCs (Chen and Ropelewski, 2002), and over 70% of all TC genesis over the WNP are closely tied to the MT (Molinari and Volland, 2013). In other words, an anomalous MT is a key factor that bridges ENSO and TC over the WNP (Wu et al., 2012; 2014). Thus, the relationship of ENSO with the MT plays an important role in the modulation of TC genesis over the WNP.
Recently, the El Niño phenomenon not only showed an anomalously warming over the eastern Pacific (EP), referred to as EP warming (EPW), but also showed a warmer sea surface temperature anomaly (SSTA) over the tropical central Pacific, which is known variously as El Niño Modoki (Ashok et al., 2007) or CP warming (CPW) (Kim et al., 2009). Several previous studies have focused on the CPW affecting TC activity. Chen and Tam (2010) found that the TC frequency over the WNP has a significant positive correlation with the CPW index. Hong et al. (2011) notes that the CPW events have shown different impacts on the TC tracks over the WNP compared with the EPW events. Wu et al. (2018) found that the different Pacific warming has different impact on the location and intensity of the MT and the variability of the MT can further affect TC activity.

Several studies have noted that the frequency of the CPW events increases after the 1980s under global warming (Ashok et al., 2007; Yeh et al., 2009), and the intensity of the CPW events has also increased since the 1990s (Lee and McPhaden, 2010). Following the increases in intensity and frequency in recent years, the impact of the CPW has become increasingly important. However, it is not clear whether the relationship between the CPW and the MT would be changed or not during climate change.

The present study focuses on investigating the change in the impact of the CPW on the MT and the relationships with TCs over the WNP. This article is divided into five sections. Section 2 describes the data and methods. In section 3, we study the abrupt changes in the relationships between the WNP MT and CPW, as well as possible causes. In section 4, the relationship with TC genesis is expounded. Finally, a summary is presented in section 5.

2 | DATA AND METHODS

The monthly sea surface temperature (SST) with a $1 \times 1^\circ$ horizontal resolution are obtained from the Hadley Centre (HadISST) (Rayner et al., 2003). The monthly subsurface ocean temperature (SOT) data set used is the ocean reanalysis system 4 (ORAS4) implemented at the European Centre for Medium-Range Weather Forecasts (ECMWF) and compiled on a $1 \times 1^\circ$ latitude-longitude grid (Balmaseda et al., 2013). The TC data sets over the WNP are extracted from the International Best Tracks Archive for Climate Stewardship (IBTrACS) (Knapp et al., 2010). Other atmospheric variables are derived from the National Center for Environment Prediction/National Center for Atmospheric Research (NCAR/NCAR) reanalysis products with a horizontal resolution of $2.5 \times 2.5^\circ$ (Kalnay et al., 1996). Besides, we use the ERA-55 and ERA-40 data sets to validate our results. All data sets extend from the period 1948–2015, except for the ORAS4 data, which are used for the period 1958–2014 because of data limitations. Considering only the TC active season (July–November) for the WNP MT (Wu et al., 2012), the data from this season are used in this study.

The El Niño Modoki index (EMI) (Ashok et al., 2007), used to define the CPW events, can be computed by the following formula: $EMI = 1.0 \times [SSTA]_C - 0.5 \times [SSTA]_E - 0.5 \times [SSTA]_W$, where $[SSTA]_C$, $[SSTA]_E$, and $[SSTA]_W$ represent the area-averaged SSTA of region C ($10^\circ S$–$10^\circ N$, $165^\circ E$–$140^\circ W$), E ($15^\circ S$–$5^\circ N$, $110^\circ$–$70^\circ W$), and W ($10^\circ S$–$20^\circ N$, $125^\circ$–$145^\circ E$), respectively. To study the contemporaneous influence of CPW events on TC, the July–November-averaged EMI have a standard deviation of larger than 0.7, identified as CPW events (1966, 1967, 1977, 1986, 1990, 1991, 1992, 1993, 1994, 2002, and 2004). Comparing the pattern correlation method (PTN) defined by Yu and Kim (2013), the chosen events have some differences because of they calculate the SSTA during December–January. The Niño3 index is defined as the area-averaged SSTA in the Niño3 region ($5^\circ S$–$5^\circ N, 150^\circ$–$90^\circ W$). The Niño3 index for the same seasons has a standard deviation of larger than 0.7 and is identified as EPW events (1951, 1957, 1963, 1965, 1969, 1972, 1976, 1982, 1987, 1997, 2009, and 2015). The correlation between the EMI and the Niño3 index is 0.27, which is not a statistically significant correlation. This indicates that these two indices can be used well to clearly distinguish the two types of El Niño events.

On the basis of the previous study, the intensity of the MT over the WNP can be represented by the positive vorticity over the tropical WNP (Wu et al., 2012). Thus, we define the regional average of the 850-hPa positive vorticity in the area ($5^\circ$–$20^\circ N$, $135^\circ$–$175^\circ E$) as the MT index (MTI) to quantify its intensity. Increased (decreased) MTI means a strengthened (weakened) MT with an eastward extension (westward retreat), which is the same as the findings of Wu et al. (2012).

3 | ABRUPT CHANGES IN THE RELATIONSHIP BETWEEN THE WNP MT AND CPW AND POSSIBLE CAUSES

To identify the relationship between ENSO and the MT, we first calculate the correlation of the MTI with the Niño3 index and the EMI during the entire period of 1948–2015. The results show that the correlation of the Niño3 index (EMI) with the MTI is 0.72 (0.52), both of which pass the 95% significance test, but the EMI has a relatively weaker relationship with the MTI than the Niño3 index. Furthermore, the 15-year running correlations of the Niño3 index and the EMI with MTI are calculated (Figure 1a). The relationship between the Niño3 index and the MTI always maintains a significant positive correlation for all epochs. The moving correlation for the EMI and the MTI has been above the 95% confidence level since 1984, which is remarkably different from the Niño3 index and the MTI.
This change in the correlation around 1984 indicates that the MT is less affected by the CPW events before 1984 but is significantly enhanced after 1984.

However, based on the moving t-test and Mann–Kendall test (not shown), we do not find that the EMI has a sudden decadal change around 1984. As seen in Figure 1b, the EPW events tend to have a clear increase in their intensity (Niño3 index) after 1984 compared with before 1984 but decrease in intensity during the CPW events (EMI). The numbers of the CPW (EPW) events are obviously increased (decreased) since 1984 (Figure 1c). The relationship of the CPW events to the MT shows an abrupt increase since 1984, while the amplitude of the CPW events is reduced. Besides, we calculate the regime-shift index (Rodionov, 2004) that is positive, which proves the abrupt change around 1984. So why the relationship between the CPW event with EMI is increased when the EMI is decreased since 1984? In order to solve this question, we do some further studies.

Furthermore, we composite the SSTA and subsurface ocean temperature anomaly (SOTA) during the CPW events around 1984 (Figure 2). Before 1984, the SSTA distribution shows a zonal triple pattern during the CPW events (Figure 2a). During these events, the warm SSTA in the central Pacific is not remarkable, and the colder SSTA over the western tropical Pacific is significant. The anomalously warmer SSTA over the western tropical Pacific warms slightly. The changed zonal distribution of the SSTA around 1984 is consistent with the change in the SOTA. As shown in Figure 2a, the warm water at the deep level is not significant, and the ocean surface water shows a weak warming over the central tropical Pacific. Consequently, the warm SSTA in this region is not remarkable. However, the cold anomalous water, which can extend to 150 m over the western tropical Pacific and the surface water, shows significantly abnormal cold. The SOTA over the tropical western Pacific transits from the negative to the positive. The warm SOTA is highly significant and extends eastward with more intensity over the central tropical Pacific than the events before 1984 (Figure 2b). Hence, the SSTA over the western tropical Pacific warms up, and the intensity of the SSTA over the tropical central Pacific is significantly increased. Thus, it can be clearly explained by the distribution of the SSTA and SOTA over the tropical Pacific that the CPW has obviously changed since 1984. We also composite the SSTA and SOTA of the EPW events around 1984, and the result shows a consistent dipole pattern of the SSTA and SOTA around 1984 (not shown).

The inter-decadal variations in the area-averaged SSTA over the western Pacific (W; 10°S–20°N, 125°–145°E), the central Pacific (C; 10°S–10°N, 165°E–140°W), and the Niño3 region are shown in Figure 3a. This further illustrates that under global warming, the SSTA over the central and West Pacific since 1984 has increased remarkably (0.007 and 0.011, significant at 95% confidence level), more than that of the Niño3 region (0.005, significant at 95% confidence level). Furthermore, the area-averaged SST over the western and central Pacific during the CPW events around
1984 as well as their differences are displayed in Figure 3b. There is a similar SST warming in the western and central region during the events around 1984. Thus, the difference in the SST between the two regions after 1984 is slight and not obviously increasing, indicating that the EMI has little difference and that the SST warming in the central Pacific has an obvious increase around 1984. As a consistency check for the increasing amplitude of the CPW, during the CPW events, the trend of the SSTA over the central Pacific (Figure 3c) shows a significant upward trend, similar to the trend for the western Pacific (0.015 and 0.011, significant at 95% confidence level). These trends occur more quickly during the CPW events than in the others (0.007 and 0.011, significant at 95% confidence level). Therefore, the amplitude of the CPW (EMI) did not have a significant change, but the SST of the central and western Pacific have become more intense. Wu et al. (2018) found that the different location and intensity Pacific warming have different
impact on the low-level westerlies. So comparing with the CPW events before 1984, the SST warming trend during CPW events since 1984 may have different impact on the atmospheric circulation.

Two anomalous Walker circulation cells occurred during the CPW events, which can cause the westerly (easterly) wind anomalies over the western (eastern) tropical Pacific (Weng et al., 2007). These anomalies enhance the westerly monsoonal wind over the WNP and the tropical easterly flow, which further affect the change in the MT location over the WNP. To study the change in the MT that corresponds to the change in the SSTA during the events around 1984, we composite the mean low-level flow field, the 850-hPa relative vorticity anomalies, and the zonal anomalous circulation (Figure 4). The less dramatic warming over the tropical central Pacific and the cool SSTA over the tropical western Pacific might reduce the development of the MT and restrain its eastward shift during the events before 1984 (Figure 4a). The warming in the tropical central Pacific can lead to the low-level positive vorticity anomalies, which increased in the vicinity of the MT. Thus, this change promotes the further development and the more eastward extension of the MT during the CPW events after 1984 (Figure 4b). As displayed in Figure 4d, the downdraft from 120° to 140°E, related to the cooler SSTA, and the remarkably low-level westerly anomalies are not conducive to the enhancement of the low-level cyclonic vorticity and the eastward extension of the MT during the CPW events before 1984. However, during the CPW events after 1984 (Figure 4e), the westerly flow to the east of 120°E enhances significantly below 500 hPa, which is conducive to the development of the low-level positive vorticity and the eastward extension of the MT. The difference in the zonal circulation shown in Figure 4f also indicates that the MT is expanded eastward during the CPW events after 1984. The changes in the position and intensity of the MT have a further significant impact on the location of the TC genesis over the WNP, which will be discussed in the next section.

4 RELATIONSHIP WITH TC GENESIS

TC genesis is closely associated with some large-scale environmental factors, such as the low-level relative vorticity, the upper-level divergence, the relative humidity (RH) in the low and middle troposphere, and the vertical wind shear (VWS) (Feng et al., 2014). Corresponding to the changes in the MT, these factors that are necessary for TC genesis have a homologous change. Figure 5a displays the difference in 850-hPa relative vorticity during the CPW events around 1984. The positive vorticity anomalies predominating along the MT with increased values to the east of 140°E mean that the MT extends eastward and is further enhanced after 1984. The distribution of the 200-hPa divergence is consistent with the low-level vorticity, which is favorable for the development of the deep convection that can greatly enhance the MT (Figure 5b). As shown in Figure 5c, the difference in the RH that extends along the MT is positive with a significant maximum value of up to 4%, and this means more latent heat could be provided for TC genesis during the CPW events after 1984. The small VWS is one of the key factors for TC genesis in the MT and the negative area to the north of 10°N, which is more conducive to TC genesis during the events after 1984, although the difference is relatively small (Figure 5d).

The WNP MT is greatly strengthened and extends eastward under the impact of the CPW events after 1984. Accordingly, the intensified positive vorticity, the enhanced divergence, the increased RH, and the reduced VWS are
consistent with the movement of the MT. Hence, these changes are more favorable for TC genesis in the region of the MT during the events after 1984. Statistics show that, on average, 19 TCs form per year in the MT during the CPW events after 1984, which is far more than the 13 TCs before 1984. The spatial distribution of TC genesis is shown in Figure 4 (top). This illustrates that during the CPW events before 1984, when the MT leans toward the west, less TCs form within it, implicating that the weaker MT has a limited effect on TC genesis. However, after 1984, when the MT extends eastward, more TCs form within it, and therefore, the stronger MT has a more marked impact on TC genesis. This change in the MT’s influence on TC genesis can be explained by some changed environmental factors. The variation in the frequency and the location of TC genesis over the WNP are associated with a shift in the MT.

5 | CONCLUSIONS

This study focuses on analyzing the intensified impact of the CPW events on the WNP MT after 1984. Based on the method of composite analysis, we find a remarkable difference in the spatial distribution of the SSTA over the tropical Pacific during the CPW events around 1984, which is consistent with the SOTA. The MT has been impacted by anomalous atmospheric circulation, which is associated with SST warming over the tropical central Pacific. Under the colder SSTA impact, inducing the downdraft from 120°E–140°E and the low-level westerly anomalies, the MT is restrained and leaned toward the west during the CPW events before 1984. The warmer SSTA over the tropical central Pacific induces the enhanced westerly wind to the east of 120°E as well as the anomalous relative vorticity, which can lead to the further development and an eastern extension of the MT during the CPW events after 1984.

TC genesis is greatly influenced by the large-scale environmental factors associated with the longitudinal shift of the MT. The intensified 850-hPa positive vorticity, the enhanced 200-hPa divergence, the increased RH and the reduced VWS are all consistent with the movement of the MT. Hence, these changes lead to more TCs genesis (19/year) during the CPW events since 1984 than before 1984 (13/year). In addition, more TCs form at the axis of the WNP MT during the CPW events after 1984.

ACKNOWLEDGEMENTS

This work was jointly supported by the National Natural Science Foundation of China (Grant Nos. 41475077, 41461164005, and 41230527) and the National Basic Research Program of China under Grant No. 2014CB953902; the Youth Innovation Promotion Association CAS, Grant No. 2017106.

ORCID

Hongjie Zhang http://orcid.org/0000-0002-8602-0971
Liang Wu http://orcid.org/0000-0001-9410-0050
Jau-Ming Chen http://orcid.org/0000-0002-5072-7545

REFERENCES

Ashok, K., Behera, S.K., Rao, S.A., Weng, H.Y. and Yamagata, T. (2007) El Niño Modoki and its possible teleconnection. Journal of Geophysical Research: Oceans, 112, C110070.
Balmaseda, M.A., Mogensen, K. and Weaver, A.T. (2013) Evaluation of the ECMWF ocean reanalysis system ORAS4. Quarterly Journal of the Royal Meteorological Society, 139, 1132–1161.
Chan, J.C.L. (2000) Tropical cyclone activity over the western North Pacific associated with El Niño and La Niña events. Journal of Climate, 13, 2960–2972.
Chen, G.H. and Tam, C.Y. (2010) Different impacts of two kinds of Pacific Ocean warming on tropical cyclone frequency over the western North Pacific. Geophysical Research Letters, 37, L01803.
Chia, H.H. and Ropelewski, C.F. (2002) The interannual variability in the genesis location of tropical cyclones in the northwest Pacific. *Journal of Climate*, 15, 2934–2944.

Feng, T., Chen, G.H., Huang, R.H. and Shen, X.Y. (2014) Large-scale circulation patterns favorable to tropical cyclogenesis over the western North Pacific and associated barotropic energy conversions. *International Journal of Climatology*, 34, 216–227.

Hong, C.C., Li, Y.H., Li, T. and Lee, M.Y. (2011) Impacts of central Pacific and eastern Pacific El Niños on tropical cyclone tracks over the western North Pacific. *Geophysical Research Letters*, 38, L16712.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Lredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuaki, W., Higgin, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R. and Joseph, D. (1996) The NCEP/NCAR 40-year reanalysis project. *Bulletin of American Meteorological Society*, 77, 437–471.

Kim, H.M., Webster, P.J. and Curry, J.A. (2009) Impact of shifting patterns of Pacific Ocean warming on North Atlantic tropical cyclones. *Science*, 325, 77–80.

Knapp, K.R., Kruk, M.C., Levinson, D.H., Diamond, H.J. and Neumann, C.J. (2010) The International Best Track Archive for Climate Stewardship (IBTrACS) unifying tropical cyclone data. *Bulletin American of Meteorological Society*, 91, 363–376.

Lee, T. and McPhaden, M.J. (2010) Increasing intensity of El Niño in the central-equatorial Pacific. *Geophysical Research Letters*, 37, L14603.

Molinari, J. and Vollaro, D. (2013) What percentage of western North Pacific tropical cyclones form within the monsoon trough? *Monthly Weather Review*, 141, 499–505.

Rayner, N.A., Parker, D.E., Horton, E.B., Folland, C.K., Alexander, L.V., Rowell, D.P., Ken, E.C. and Kaplan, A. (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research: Atmospheres*, 108, 4407.

Rodionov, S.N. (2004) A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters*, 31(9), L09204.

Weng, H.Y., Ashok, K., Behera, S.K., Rao, S.A. and Yamagata, T. (2007) Impacts of recent El Niño Modoki on dry/wet conditions in the Pacific rim during boreal summer. *Climate Dynamics*, 29, 113–129.

Wu, L., Wen, Z.P., Huang, R.H. and Wu, R.G. (2012) Possible linkage between the monsoon trough variability and the tropical cyclone activity over the western North Pacific. *Monthly Weather Review*, 140, 140–150.

Wu, L., Chou, C., Chen, C.T., Huang, R.H., Knutson, T.R., Sirutis, J.J., Graner, S.T., Kerr, C. and Feng, Y.C. (2014) Simulations of the present and late-twenty-first-century western North Pacific tropical cyclone activity using a regional model. *Journal of Climate*, 27, 3405–3424.

Wu, L., Zhang, H.J., Chen, J.M. and Feng, T. (2018) Impact of two types of El Niño on tropical cyclones over the western North Pacific: sensitivity to location and intensity of Pacific warming. *Journal of Climate*, 31(5), 1725–1742.

Yeh, S.W., Kug, J.S., Dewitte, B., Kwon, M.H., Kirtman, B.P. and Jin, F.F. (2009) El Niño in a changing climate. *Nature*, 461, 511–514.

Yu, J.Y. and Kim, S.T. (2013) Identifying the types of major El Niño events since 1870. *International Journal of Climatology*, 33, 2105–2112.

---

**How to cite this article:** Zhang H, Wu L, Huang R, Chen J-M. Intensified impact of the central Pacific warming on the monsoon trough over the western North Pacific since 1984. *Atmos Sci Lett*. 2018;19: e828. [https://doi.org/10.1002/asl.828](https://doi.org/10.1002/asl.828)