Tropical Cyclone Footprints in Long-Term Mean State and Multiscale Climate Variability in the Western North Pacific as Seen in the JRA-55 Reanalysis

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ABSTRACT: The monsoon trough and subtropical high have long been acknowledged to exert a substantial modulating effect on the genesis and development of tropical cyclones (TCs) in the western North Pacific (WNP). However, the potential upscaling effect of TCs on large-scale circulation remains poorly understood. This study revealed the considerable contributions of TCs to the climate mean state and variability in the WNP between 1958 and 2019, characterized by a strengthened monsoon trough and weakened subtropical anticyclonic circulation in the lower troposphere, enhanced anticyclonic circulation in the upper troposphere, and warming throughout the troposphere. TCs constituted distinct footprints in the long-term mean states of the WNP summer monsoon, and their contributions increased intraseasonal and interannual variance by 50%–70%. The interdecadal variations and long-term trends in intraseasonal variance were mainly due to the year-to-year fluctuations in TC activity. The size of TC footprints was positively correlated with the magnitude of TC activity. Our findings suggest that the full understanding of climate variability and changes cannot be achieved simply on the basis of low-frequency, large-scale circulations. Rather, TCs must be regarded as a crucial component in the climate system, and their interactions with large-scale circulations require thorough exploration. The long-term dataset created in this study provides an opportunity to study the interaction between TCs and TC-free large-scale circulations to advance our understanding of climate variability in the WNP. Our findings also indicate that realistic climate projections must involve the accurate simulations of TCs.

KEYWORDS: Potential vorticity; Tropical cyclones; Interannual variability; Interdecadal variability; Intraseasonal variability

1. Introduction

Large-scale, low-frequency circulation has long been acknowledged to exert a substantial modulating effect on the genesis and development of smaller-scale and high-frequency disturbances such as extreme weather events. In contrast to the well-studied downscaling effect, the potential upscaling feedback from these disturbances has not received much scholarly attention and thus remains unclear. Tropical cyclones (TCs) are long-lived extreme vortices generated over tropical oceans. The characteristics of large-scale environmental flow (e.g., vertical wind shear, high moisture content and cyclonic circulation related to monsoon trough, and warm ocean surfaces) are necessary conditions for TC genesis (Gray 1975; Yokoi and Takayabu 2009; Murakami et al. 2013). Several dozen TCs are born every year, causing extreme weather events over extensive areas. Characterized by intensive heating and strong disturbances, TCs are likely to trigger distinct perturbations involving upscale feedback to the background large-scale flow through thermodynamic and dynamic processes, both in situ and remotely.

Although the scale interaction involving the interplay of downscale and upscale processes is difficult to disentangle,

several studies have been conducted. Using observed TC track data and a coupled ocean–atmosphere hurricane model, Emanuel (2001) estimated the poleward heat transport triggered by global TC activity and found that the TC activity could enhance the thermohaline circulation and play an important role in terms of climate regulation. Hu and Meehl (2009) employed a coupled global model to investigate the impact of an idealized North Atlantic TC on the Atlantic meridional overturning circulation (AMOC) and northward meridional heat transport. It was revealed that strong TC wind enhanced the heat transport and thus accelerated the AMOC, while freshwater induced by strong TC rainfall decelerated the AMOC and weakened heat transport. The net effect of the North Atlantic TC on the AMOC and heat transport was determined by the magnitude of these processes. Using the reanalysis dataset and observed TC track data, Hart (2011) examined the impact of the Northern Hemispheric (NH) TC activity on the subsequent NH winter season and found a negative correlation between the NH TC activity and the stationary meridional heat transport in the NH winter season. In addition, Chang et al. (2016) revealed that the existence of TC cold wakes slowed down the warming SST trend in the western North Pacific (WNP) in the past few decades.

Hsu et al. (2008a,b) and Arakane and Hsu (2020, hereinafter AH20) have used a dynamic statistical approach to estimate the footprints of TCs in climate variability in the WNP. They indicated that TCs significantly contributed to multiscale climate features ranging from intraseasonal variance to long-term mean climatology, although specific dynamic and

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thermodynamic processes were not identified. [Hsu et al. \(2008a,b\)](#) and [AH20](#) argued that TC-related perturbations are too extreme to be removed from original data by simple temporal averaging or low-pass filtering. Thus, climate variability (e.g., variance) estimations will contain substantial TC footprints. However, climate variability research often considers only large-scale dynamics, neglecting the effects of these footprints. This means that crucial processes involving climate–TC interactions are missed, leading to the incomplete understanding of climate variability. [Hsu et al. \(2008a,b\)](#) have demonstrated the possibility of investigating the interaction between TCs and the TC-free background flow.

Using a unique dataset in which TC vortices were removed, [Hsu et al. \(2008a,b\)](#) were the first to reveal the significant contributions of TCs to climate variability in the WNP. A comparison between the original and TC-removed datasets revealed that TCs contributed to more than 50% of the intraseasonal and interannual variances. [Feng et al. \(2020\)](#) used the same procedure to isolate the TC-free monsoon trough in a 6-hourly reanalysis dataset, developing a daily index representative of spatiotemporal monsoon trough variations. This index was used to determine the onset and retreat dates of the monsoon trough and their interannual fluctuations. More than 60% of TC genesis was related to an active monsoon trough functioning as a background flow free of TC signals.

[Hsu et al. \(2008b\)](#) adopted a more dynamic approach to evaluate the contribution of TCs to the WNP circulation in 2004 through the use of a GCM. A series of hindcast experiments were conducted in two sets of simulations: one with realistic initial conditions including TC vortices and another in which TCs were not considered in the initial conditions. The seasonal mean and intraseasonal variance in both sets were calculated and compared. The second set exhibited a significant change in seasonal mean circulation and a reduction in intraseasonal variance with a ratio (40%–50%) similar to that derived directly from the empirical procedure in which TCs were removed from the reanalysis. The findings indicated the necessity of considering the contribution of TCs in GCM evaluation and the importance of their consideration in the realistic simulations of climate mean state and variability.

As shown in [Hsu et al. \(2008a,b\)](#) and [Feng et al. \(2020\)](#), the TC removal approach was effective in assessing the footprints of TCs in large-scale, low-frequency circulations. However, the TC removal scheme used by [Hsu et al. \(2008a,b\)](#), a spatial filtering scheme in a TC domain, was applied only to the low-level wind field, limiting the scope of the analysis to presenting a holistic picture of TC footprints. Moreover, the dynamic balance was not considered; therefore, more complex types of analyses of scale interactions between TCs and the background flow, such as energetics, could not be performed.

To examine TC footprints in climate variability in other variables in the troposphere, [AH20](#) used a sophisticated TC removal scheme to construct a TC-removed dataset for the WNP in which TC components were removed from all variables at all levels through PV inversion in which the dynamic balance was maintained. TC structures were efficiently removed not only from the wind field, as in previous studies, but

also from other fields (e.g., geopotential height and temperature). The contribution of TCs to the climate variance in the low-level wind field during the WNP typhoon season in 2004 was slightly larger than that estimated by [Hsu et al. \(2008a,b\)](#). [AH20](#) also identified the intensification of the western flank of subtropical high (accompanied by a considerably weakened monsoon trough) and upper-level cooling in the WNP after the removal of TC signals. Notably, the removal scheme was applied only to TCs in 2004; the contribution of TCs to long-term means and variability was not explored.

The present study revisited the TC contribution issue by using the PV inversion technique employed by [AH20](#) to remove TC structures in winds, geopotential height, and temperature in the troposphere in the WNP. TC footprints in the long-term climate means and variability between 1958 and 2019 were examined. This paper is organized as follows. [Section 2](#) describes the data and methodology for TC removal. TC contributions to seasonal and long-term means, interannual variability, and intraseasonal variability are reported in [sections 3, 4, and 5](#), respectively. We summarize the key findings and discuss the usefulness of the TC-removed dataset in climate variability studies in [section 6](#).

2. Data and methodology

In this study, we used the JRA-55 reanalysis ([Kobayashi et al. 2015](#); [Harada et al. 2016](#)) provided by the JMA and the best track data provided by the Regional Specialized Meteorological Center (RSMC) Tokyo to detect TCs and their center locations. All TC information over the WNP is recorded in the RSMC Tokyo best track data from 1951 to the present. The JRA-55 reanalysis data are available in a 1.25° horizontal resolution in latitude and longitude and at 37 pressure levels for every 6 h. Although the 1.25° horizontal resolution cannot resolve a realistic TC structure, the TC intensity and location are relatively better represented in the JRA-55 reanalysis than those in other reanalysis data because TC surrounding winds are included in the data assimilation system ([Murakami 2014](#)). As a result of the analysis, the agreement¹ between the WNP TC positions recorded in the RSMC best track data and the positions in the JRA-55 reanalysis in 1958–2019 TC season is 99.40%; especially, for TCs after 1980, when satellite data are assimilated, the agreement is 99.76% (not shown).

In the present study, we evaluated the contributions of TCs to interannual and intraseasonal variabilities over the WNP between 1958 and 2019 by comparing the variance between the original and TC-removed data. The interannual variance was calculated as the variance of the June–October seasonal mean in each year over this range. The intraseasonal components were extracted from the datasets through the application of a 20–80-day Butterworth bandpass filter.

¹ The agreement is defined when the low-level circulation center represented in the JRA-55 reanalysis exists within a two-grid distance (280 km) from the observed TC position recorded in the RSMC best track data.

PV composite (1958–2019)

FIG. 1. Composites of a radial–height cross section of a tangentially averaged PV anomaly related to TCs (defined as a deviation from the averaged PV at 1500 km from the TC center), June–October 1958–2019 (in PV units: 1 PVU = $10^{-6} \text{ m}^2 \text{ kg}^{-1} \text{ s}^{-1} \text{ K}$). (a) TCs with minimum sea level pressure (MSLP) < 980 hPa, (b) TCs for which 960 hPa < MSLP ≤ 980 hPa, (c) TCs for which 930 hPa < MSLP ≤ 960 hPa, and (d) TCs with MSLP ≤ 930 hPa. The horizontal and vertical axes represent the distance from the TC center and the pressure level (in km and hPa, respectively).

TCs over the WNP that were recorded as tropical storm, severe tropical storm, and typhoon in the RSMC Tokyo best track data were removed from the JRA-55 reanalysis. However, TC-related disturbances in the early and late stages of a TC (categorized as tropical depression or extratropical cyclone) were not removed. The TC removal was performed on the basis of the PV inversion technique originally proposed by Davis and Emanuel (1991). The PV inversion domain for the TC removal was from 0° to 60°N and from 90°E to 150°W . All target TCs for the removal were captured in the domain. To ensure stable calculation, the inhomogeneous vertical grid in pressure coordinates was reconstructed into the π [$= C_p(p/p_0)^\kappa$] coordinate whose vertical grid interval is constant ($\Delta\pi = 0.02C_p$), where $\kappa = R_d/C_p$ is the ratio of the gas constant for dry air R_d to specific heat at a constant pressure C_p , p is the pressure, and p_0 is the reference pressure (1000 hPa). The reconstructed data had 26 layers, satisfying $\pi = C_p$ at the bottom and $\pi = C_p/2$ at the top of the removal domain.

The removal procedure was performed as described previously (AH20) except for the PV anomaly decomposition for TCs. To decompose the PV anomaly related to the TC, a TC domain must be determined. AH20 determined the TC domain at each level by using a somewhat complicated and time-consuming process. In the present study, we simply defined the TC domain as a cylinder of a specified radius

from the TC center from 1000 to 88 hPa in the PV inversion domain. All positive and negative PV anomalies in the TC domain are referred to as the PV anomalies of the TC throughout this study. Using the PV anomalies, the TC components in other variables, such as geopotential height and temperature, were derived through the piecewise PV inversion technique as described previously (Shapiro 1996; Wu and Emanuel 1995; Wang and Zhang 2003; Wu et al. 2003, 2004). To obtain the TC-removed fields, the TC components were then subtracted from the original fields. Thus, the relationships among variables X in the original field (X_{total}), the TC-removed field (X_{noTC}), and the TC component (X_{TC}) can be expressed as $\Delta X_{\text{total}} = X_{\text{noTC}} + X_{\text{TC}}$. For more details regarding the removal procedure, see AH20.

As reported by AH20, considering the negative PV anomalies in the upper level that are related to TCs is vital when applying PV inversion to TCs. In particular, accounting for the contribution of negative PV anomalies leads to a better estimation of the warm core. As shown in Fig. 1, a radius of approximately 800 km from the TC center was sufficient to define the TC domain when considering only the positive PV anomaly in the troposphere. By contrast, the negative PV anomaly in the upper level was more widespread, and its distribution was highly asymmetric (AH20). A larger domain was therefore needed. Notably, an excessively large TC domain would result

FIG. 2. (a) Relative vorticity at 850 hPa (10^{-5} s^{-1}), (b) geopotential height at 850 hPa (gpm), and (c) temperature at 250 hPa (K) at 1200 UTC 6 August 2019. (d)–(f) As in (a)–(c), but for the TC-removed fields. (g)–(i) As in (a)–(c), but for the TC components.

in the removal of other convective systems near but not part of the TC. We tested the results with radius settings at 600, 800, and 1000 km, and then the radius of the TC domain was set to 1000 km.²

3. TC footprints in climatological seasonal mean circulations

The TC and non-TC components were well separated using the present procedure. An example is shown in Fig. 2. At 1200 UTC 6 August 2019, three TCs had formed over the WNP: Tropical Storm Francisco at 35.1°N, 129.5°E; Typhoon Lekima at 19.5°N, 128.7°E; and Tropical Storm Krosa at 18.9°N, 142.4°E. The three TCs appeared as isolated vortices in the low-level relative vorticity and geopotential height fields, and Typhoon Lekima and Tropical Storm Krosa were embedded in the monsoon trough (Figs. 2a,b). The corresponding warm cores were observable in the upper-level temperature field (Fig. 2c). Through piecewise PV inversion, the TC

components were derived (Figs. 2g–i). Next, the TC-removed fields were obtained by subtracting the TC components from the total fields (Figs. 2d–f). The three vortices were cleanly removed from the original fields. Other (nontargeted) disturbances were not removed. For example, a weak vortex over the South China Sea (SCS) remained after the removal. The TC component of vorticity was localized, whereas the TC component of geopotential height was widespread. This is known as the far-field effect of PV anomalies (Bishop and Thorpe 1994; Thorpe and Bishop 1995). Owing to both the in situ and far-field effects, the subtropical high became stronger and expanded westward to cover most of the WNP. By contrast, the monsoon trough became considerably weaker and retreated westward to the SCS (Fig. 2e). The warm cores in the upper level were also thoroughly removed (Fig. 2f). The features observed in the TC-removed fields, such as the intensified subtropical high, weakened monsoon trough, and absence of warm cores, were consistent with those noted by AH20.

Figure 3 presents the climatological means of low-level vorticity, low-level geopotential height, and upper-level temperature during the typhoon season (June–October) from 1958 to 2019. After TC removal, the positive vorticity related to the monsoon trough elongated at 15°N was weakened, and the negative vorticity related to the subtropical high south of Japan was strengthened (Figs. 3a,d). A weaker monsoon trough after TC removal was therefore observable in the low-level geopotential height field. After TC removal, the elongated

² Note that PV anomalies in the domain are not completely removed. We employed a removal rate function introduced in Kwon and Cheong (2010): the removal rate of the PV anomaly decreases with distance moving away from the domain center, and it becomes zero at the maximum radius. Thus, the effects of disturbances in the vicinity of TC on the results are minimal.

FIG. 3. As in Fig. 2, but for the climatological means, June–October 1958–2019. Geopotential height (contour) and wind (vector) are indicated in the column on the right. The geopotential height contour (wind vector) in (c) and (f) is omitted where the geopotential height is less than 10 940 gpm (where the wind speed is greater than 10 m s^{-1}).

monsoon trough originally extending eastward over the SCS and the west Philippine Sea retreated westward (Figs. 3b,e). The enhanced negative vorticity area in Fig. 3d corresponded to the westward expansion and intensification of the subtropical high seen in Figs. 3b,e. The reduction in the mean temperature in the upper troposphere was due to the removal of the TC warm core (Figs. 3c,f). The differences before and after TC removal (Figs. 3g–i) demonstrate the size of TC footprints with regard to both the amplitude and affected area. As manifested by a bull’s-eye shape, the differences in vorticity spanned the SCS and the northwestern Philippine Sea, whereas those in geopotential height and temperature covered almost the entire WNP. The affected area in geopotential height and temperature was larger because of the far-field effect of PV inversion. TCs often follow the background steering flow between the subtropical high and monsoon trough. Therefore, the areas of the largest TC footprints appeared between the subtropical high and monsoon trough, exerting substantial effects on both.

The effect of TCs extended throughout the troposphere and into the lower stratosphere. Figure 4 presents the vertical structure of the WNP monsoon system and the corresponding TC contribution along 130°E . The contribution to the mean geopotential height was characterized by a deep negative anomaly, the maximum of which was near the surface, that

decayed upward to the upper troposphere. The lower stratosphere was characterized by a positive anomaly. The corresponding contribution to temperature was distinguished by a positive anomaly, the maximum of which was in the upper troposphere, that decayed downward to the surface. The lower stratosphere was distinguished by a negative anomaly. The negative geopotential height and positive temperature contributions in the deep troposphere were mainly related to the positive PV anomaly in the troposphere, and the positive geopotential height and negative temperature contributions in the lower stratosphere were mainly related to the negative PV anomaly in the upper troposphere and lower stratosphere. In sum, TCs contributed crucially to the observed mean 3D circulation (e.g., the monsoon trough and subtropical high in the lower troposphere and the upper-level anticyclone and mid-Pacific trough) and the corresponding warm core structure of the WNP summer monsoon system. The effect of TC on long-term mean circulation was notable.

It has long been implicitly accepted that long-term averaging removes perturbations such as TCs, which fluctuate over a much shorter period than the averaging period. However, Hsu et al. (2008a) reported that the large perturbations of TCs could not be removed through averaging and left substantial footprints in the averaged field. Their findings were confirmed in the present study, even though averaging over 62 years was

FIG. 4. Vertical cross section of the climatological mean (June–October 1958–2019) of (left) geopotential height (gpm) and (right) temperature (K) at 130°E. (a),(d) Total field, (b),(e) TC-removed field, and (c),(f) TC component. The deviations from the 90°E–150°W zonal mean are shown to represent the spatial structure.

performed. TC appeared to be a crucial component in the WNP monsoon system. Its existence clearly influenced the scales and locations of the subtropical high and monsoon trough conventionally regarded as the background state of high-frequency disturbances, such as TCs and tropical-wave-like perturbations.

4. TC footprints in the interannual variability

According to the RSMC best track data, the number of TCs over the WNP varied each year between 1958 and 2019, ranging from 14 to 39 overall. To examine the impact of differences in TC number on the seasonal mean field, we compared the June–October mean fields in the 3 years in which TCs were the most active (1994, 1967, and 1966; total 91) and inactive (1998, 1969, and 2010; total 37). The distributions of seasonal mean monsoon troughs and subtropical highs differed considerably in the active and inactive years (Fig. 5). Specifically, in the active years, the subtropical high was

weaker and confined to the east (e.g., the 1510-gpm contour was located east of 150°E) and the monsoon trough extended eastward to 140°E (Fig. 5a), indicating a strong monsoon trough and a weak subtropical high that favored TC genesis and development. In the inactive years, a strong western flank of subtropical high extended westward to eastern China. The monsoon trough was confined to the west of 110°E and was not observable over the Philippine Sea (Fig. 5d), reflecting an unfavorable environment for TC genesis and development. This interpretation was based on the concept that an environment dominated by large-scale background circulation determines TC genesis and development. This was correct in general. On the other hand, the results mentioned in the figures discussed thus far and in the study by Hsu et al. (2008a) suggest the following: the analysis of seasonal mean circulation (Figs. 5a,d) likely ignored the large TC footprints in the mean flow statistics because of the inability of time-averaging and low-pass filtering to cleanly remove the strong vortices and precipitation embedded in TCs.

FIG. 5. Seasonal mean of the geopotential height at 850 hPa (gpm) from June to October in the 3 years in which the most TCs occurred (1994, 1967, and 1966): (a) total field, (b) TC-removed field, and (c) TC component. (d)–(f) As in (a)–(c), but for the 3 years in which the fewest TCs occurred (1998, 1969, and 2010). The thick solid line in the top and middle rows marks the 1510-gpm contour. The white lines in (a) and (b) denote the tracks of TCs that occurred in the active and inactive years, respectively.

The strength of the TC footprint was dependent on TC activity and the degree of clustering: the stronger the activity and clustering, the larger the footprint. The contrast of the TC component of geopotential height is observable in Figs. 5c,f. The bull's-eye-like negative anomaly coinciding with the TC-prevailing region was stronger in the active years and covered a larger region; by contrast, it was weaker and spanned a smaller region in the inactive years. The maximum anomaly in the active years exceeded 28 gpm, more than twice as large as that in the inactive years (13 gpm). The large differences between the TC footprints reflected the fact of the substantially stronger (weaker) monsoon trough and weaker (stronger) subtropical high in the active (inactive) years (Figs. 5a,d). The seasonal mean monsoon trough and subtropical high remained almost unchanged after the removal of TCs in the inactive years; by contrast, in the active years, the monsoon trough in the Philippine Sea disappeared completely and the subtropical high expanded

considerably westward. The geopotential height contrast between the active and inactive years became almost indistinguishable after the TC removal (Figs. 5b,e), indicating that the interannual variation between the active and inactive years was strongly affected by TC footprints. A similar contrast before and after the TC removal was noted in all other variables, including winds, vorticity, and temperature.

The interannual variance of the June–October seasonal mean of relative vorticity at 850 hPa from 1958 to 2019 is shown in Fig. 6. A region exhibiting large vorticity variance was observed over the ocean east of Taiwan and the Philippines (Fig. 6a) but disappeared in the TC-removed field (Fig. 6b). The TC contribution to the interannual variance (Fig. 6e) is defined as the difference between variances in the total and TC-removed fields, or $\text{Var}(X_{\text{total}}) - \text{Var}(X_{\text{noTC}})$, where $\text{Var}(X)$ represents the variance of variable X . As reported by Hsu et al. (2008a), the distribution of the TC contribution shown in Fig. 6e corresponded with TC tracks in which the

FIG. 6. Interannual variance of 850-hPa relative vorticity (10^{-10} s^{-2}), June–October 1958–2019. (a) Variance of total field [corresponding to $\text{Var}(X_{\text{total}})$ in Eq. (1)], (b) variance of TC-removed field [corresponding to $\text{Var}(X_{\text{noTC}})$ in Eq. (1)], (c) variance of TC component [corresponding to $\text{Var}(X_{\text{TC}})$ in Eq. (1)], (d) twice the covariance of TC-removed field and TC component [corresponding to $2\text{Cov}(X_{\text{noTC}}, X_{\text{TC}})$; contour interval is $0.02 \times 10^{-10} \text{ s}^{-2}$], (e) TC contribution [corresponding to $\text{Var}(X_{\text{total}}) - \text{Var}(X_{\text{noTC}})$; contour interval is $0.02 \times 10^{-10} \text{ s}^{-2}$], and (f) TC contribution ratio [corresponding to $1 - \text{Var}(X_{\text{noTC}})/\text{Var}(X_{\text{total}})$; the contour interval is 0.1].

maximum occurred near the TC recurvature point (tracks not shown). Figure 6f presents the TC contribution ratio, defined as the ratio of the TC contribution to the total variance, or $1 - \text{Var}(X_{\text{noTC}})/\text{Var}(X_{\text{total}})$. The ratio generally exceeded 40% along the TC tracks that covered almost the entire subtropical WNP from 120° to 160°E . Overall, apart from a slightly larger contribution ratio, the TC footprint in the interannual variance of the low-level vorticity is consistent with that in Hsu et al. (2008a).

As shown in Figs. 7 and 8, the features of the TC contributions of interannual variances in low-level geopotential height

and upper-level temperature differed from those of interannual variances in low-level relative vorticity. Positive TC contributions were noted in a large region over the subtropical WNP, with the center near 20°N , 155°E , and negative contributions were observed over the Korean Peninsula, Japan, and the East China Sea (Figs. 7e and 8e). The reason behind the negative contribution is discussed as follows. Under the assumption of the linear relationship for variable X ($X_{\text{total}} = X_{\text{noTC}} + X_{\text{TC}}$), the variance of X_{total} can be decomposed as follows:

$$\begin{aligned}
 \text{Var}(X_{\text{total}}) &= \overline{X_{\text{total}}^2} - \overline{X_{\text{total}}}^2 = \overline{(X_{\text{noTC}} + X_{\text{TC}})^2} - \overline{X_{\text{noTC}} + X_{\text{TC}}}^2, \\
 &= \left(\overline{X_{\text{noTC}}^2} - \overline{X_{\text{noTC}}}^2 \right) + \left(\overline{X_{\text{TC}}^2} - \overline{X_{\text{TC}}}^2 \right) + 2(\overline{X_{\text{noTC}}X_{\text{TC}}} - \overline{X_{\text{noTC}}}\overline{X_{\text{TC}}}), \\
 &= \text{Var}(X_{\text{noTC}}) + \text{Var}(X_{\text{TC}}) + 2\text{Cov}(X_{\text{noTC}}, X_{\text{TC}}),
 \end{aligned} \tag{1}$$

where $\overline{[]}$ denotes the time average for a specified period and $\text{Cov}(X_{\text{noTC}}, X_{\text{TC}})$ is the covariance of X_{noTC} and X_{TC} . Thus, the TC contribution can be expressed as $\text{Var}(X_{\text{total}}) - \text{Var}(X_{\text{noTC}}) = \text{Var}(X_{\text{TC}}) + 2\text{Cov}(X_{\text{noTC}}, X_{\text{TC}})$. Although $\text{Var}(X_{\text{TC}})$ is always nonnegative, the sign of $\text{Cov}(X_{\text{noTC}}, X_{\text{TC}})$ is dependent on the relationship between the distributions of X_{noTC} and X_{TC} . In the low-level vorticity, the covariance term of the TC-removed field and the TC component in the TC-active region was negative but its magnitude was smaller than the variance of the TC component (Figs. 6c,d), explaining the positive TC contribution spread across the region. However, for the low-level geopotential height and upper-level temperature, the magnitudes of negative covariance in the TC-active region exceeded those of the variances of the TC component in the area surrounding the East China Sea (Figs. 7c,d and 8c,d). As a result, the dipole structures of the TC contributions were observed. This contrast can be understood physically in terms of the prevailing circulation regimes: the western flank of subtropical high in the north and the monsoon trough in the south.³ As shown in Fig. 3, TCs amplified the monsoon trough and weakened the subtropical high. This was related to the fact that TCs mainly translated along the western flank of the subtropical high, causing a decrease in geopotential along the western flank, and thus, an apparent retreat of the flank to the east. Therefore, the year-to-year fluctuation in TC activity amplified the interannual fluctuation of the monsoon trough and diminished the interannual fluctuation of the western flank of subtropical high in the WNP.

The TC contribution ratio of the low-level geopotential height exceeded 50% at 20°N, 155°E, and the positive contribution area expanded eastward from 130°E (Fig. 7f). The distribution of the TC contribution ratio in the upper-level temperature was similar to that in the low-level vorticity, but the maximum ratio was approximately 20% (Fig. 8f). By contrast, the negative TC contributions around the East China Sea in the low-level geopotential height and upper-level temperature exceeded 70% and 10%, respectively. This indicates that in a world without TCs, the monsoon trough and the western flank of subtropical high would experience less and more vigorous fluctuations, respectively. The negative contributions in the low-level geopotential height and the upper-level temperature appeared to be larger than those in the low-level vorticity. This can be attributed to the far-field effect of PV inversion that expanded the affected region.

5. TC footprints in the intraseasonal variability

Hsu et al. (2008a,b) reported that TC footprints in the intraseasonal variance of the low-level vorticity in the major

regions of the clustered TC tracks exceeded 50%. In the present study, we evaluated the contribution of TCs to the intraseasonal variance to answer the following questions: Could a similar contribution be identified in our dataset constructed using the new TC removal technique? Would such a large contribution also be observable in other variables at other levels?

Figure 9 shows the intraseasonal variance in vorticity at 850 hPa between 1958 and 2019. The intraseasonal component was extracted by applying a 20–80-day Butterworth band-pass filter to unfiltered data. In the original field with TCs, a large vorticity variance was observed over the northern SCS and the northwestern Philippine Sea between Taiwan and Japan (Fig. 9a). This variance vanished after the TC removal (Fig. 9b). The largest reduction, which means the TC footprint, was noted over almost the entire region in which major variance was observed (Fig. 9e), with the TC contribution ranging from 30% to greater than 70% (Fig. 9f). This region was near the clustered TC tracks and the recurvature area of the TCs, where they tended to reach the maximum intensity.

The intraseasonal variances of low-level geopotential height and upper-level temperature are shown in Figs. 10a and 11a, respectively. Similar to the results of the low-level vorticity, the largest TC contribution in both the variables was observed near the TC recurvature area (Figs. 10e and 11e). The TC contribution ratio in the low-level geopotential height and the upper-level temperature was more than 60% and 50%, respectively, with the major contribution region covering the northern SCS and the Philippine Sea (Figs. 10f and 11f). As in the interannual variance, the negative TC contribution in the low-level geopotential height was observed around 35°N, 115°E, and 10°N, 155°E. Unlike the TC contribution to the interannual variance over the Philippine Sea where the subtropical high and monsoon trough prevailed, the distribution of the positive TC contributions to the intraseasonal variance was widespread, centered near the TC recurvature area.⁴

As mentioned, TCs had a substantial impact on the intraseasonal variance in the TC-active area (15°–30°N, 120°–140°E). It can be inferred that the interannual variation of this variance was likely closely associated with the interannual variation in TC activity. Shown in Fig. 12 is the interannual variation of the intraseasonal variance averaged over 15°–30°N, 120°–140°E. The intraseasonal variance in the total field fluctuated considerably every year, with the maximum and minimum values of 2.02×10^{-10} and $0.59 \times 10^{-10} \text{ s}^{-2}$ in 1968 and 2010, respectively (Fig. 12a). Moreover, as seen in the 9-yr running mean, the intraseasonal variance between 1958 and 2019 fluctuated on the interdecadal scale and decreased with time. The Mann–Kendall nonparametric test (Kendall 1948) revealed that this decreasing trend was significant at the 5%

³ An additional analysis was executed in order to understand the meaning of the covariance terms (i.e., the relationship between the TC and non-TC components). We found a weak correlation ($|r| > 0.5$) for the low-level geopotential height around 30°N, 130°E, but no clear relationship was observed for the others (not shown). Thus, the insignificant correlations in most areas suggest the weak relationship between the TC-free large-scale circulation and TCs in most of the WNP.

⁴ As with the interannual variances of the low-level vorticity and upper-level temperature in most of the WNP, correlations between the non-TC and TC components for the intraseasonal variances in the whole WNP were low. Therefore, a weak relationship between the TC-free large-scale circulation and TCs is indicated.

FIG. 7. As in Fig. 6, but for the interannual variance of 850-hPa geopotential height (gpm^2). The contour interval in (d) and (e) is 10 gpm^2 .

level. After the TC removal, the magnitude of the intra-seasonal variance fluctuations decreased to a range between 0.32×10^{-10} and $0.73 \times 10^{-10} \text{ s}^{-2}$ (a more than threefold reduction), and the interdecadal variation and decreasing trend disappeared (Fig. 12b). The time series of the TC component exhibited almost the same fluctuation pattern with an equivalent amplitude in the total field (Fig. 12c). The correlation coefficient between the time series of the total field and the TC component was 0.95, whereas the correlation with the TC-removed time series was close to zero (0.03), indicating that the interannual and interdecadal variations in intraseasonal variance in the TC-active area were dominated by TC activity. By contrast, the contribution of large-scale circulation systems on the variation was minimal. As same as in the low-level relative vorticity, the correlation coefficients between the time series of the total field and TC component in the low-level geopotential height and upper-level temperature were also high (0.83 and 0.84, respectively; not shown). However, the correlations with the time series of the total and TC-removed fields were 0.53 (low-level geopotential height) and 0.78 (upper-level temperature), indicating that the fluctuations of the TC-removed

fields averaged over 15° – 30°N , 120° – 140°E might not be negligible. The contrast may be explained as follows. First, vorticity is a variable that better reflects TC dynamics than inverted geopotential height and temperature fields, which exhibit a smoother and larger-scale pattern as shown in Figs. 2h,i. Second, the TC contribution to the fluctuations in vorticity occurs mainly along TC tracks and is much larger than the negative values within the averaged area (Figs. 13e,f) because of the strong vortices associated with TCs. This contrast between positive and negative perturbations is less significant in the inverted geopotential height and temperature fields and therefore TC footprint is weaker in the area-averaged quantity.

The time series of intraseasonal variance also indicated regime shifts in the region. Shifts in 1972/73 and 1997/98 (marked in Fig. 12) were detected on the basis of the approach used by Rodionov (2004). This finding is consistent with the regime shifts in TC activity reported in other studies, such as the event in the early 1970s (Matsuura et al. 2003; Liu and Chan 2013) and in the late 1990s (Liu and Chan 2013; He et al. 2015; Hong et al. 2016; Zhao et al. 2018). To investigate the relationship between the changes in the intraseasonal variance of the total

FIG. 8. As in Fig. 6, but for the interannual variance of 250-hPa temperature (K^2). The contour interval in (d) and (e) is $0.01 K^2$.

field and the TC contribution, we constructed the spatial distributions of the intraseasonal variance of low-level vorticity in different decades. From 1973 to 1997, the large variance region in the total field was widespread over the northwestern Philippine Sea and the northern SCS. From 1998 to 2019, the large variance was confined to a smaller area centered near $27^\circ N$, $127^\circ E$ (Figs. 13a,c). The TC contribution domain was larger in 1973–97 than in 1998–2019, and the center of the large TC contribution region shifted from 23° to $27^\circ N$ (Figs. 13b,d). The northward shift was consistent with the differences between the two periods (Figs. 13e,f). Notably, the differences in the total field and the TC component were comparable between the two periods, indicating that the interdecadal shift in the intraseasonal variance of low-level vorticity was dominated by the changes in TC activity in the WNP. This was also true for the low-level geopotential height and upper-level temperature (not shown). In other words, the interdecadal variation of intraseasonal variance in the WNP was spatiotemporally correlated with TC activity. In addition, the decreasing trend in intraseasonal variance corresponded to a significant decreasing trend in TC number in the WNP (-0.057 yr^{-1} ; Fig. 12d).

The range at which to detect the TC perturbations during the TC removal was set as 1000 km. This radial length was somewhat arbitrary; therefore, we tested the sensitivity of our results to the TC radius. The vertical profiles of the TC contribution in the TC-active region (15° – $30^\circ N$, 120° – $140^\circ E$) for different radii are shown in Fig. 14. In the analysis over a 1000-km radius, a maximum TC contribution to the relative vorticity variance of more than 58% was observed at approximately 850 hPa and decreased with height. By contrast, the TC contribution to the temperature variance, which accounted for more than 50% of the total variance, increased with height, reaching its maximum at approximately 200 hPa. The heights of these maximum TC contributions corresponded approximately to the heights of the maximum relative vorticity and warm cores in the basic TC structure, respectively. A comparison revealed that the smaller the detecting radius, the smaller the TC contribution. However, the sensitivity to the detection range was much smaller than the TC contribution itself. The TC contributions to the vorticity and temperature variances at the maximum contribution height were 56% and 46% when the radius was 800 km and 54% and 40% when it

FIG. 9. As in Fig. 6, but for the intraseasonal (20–80 day) variance of 850-hPa relative vorticity (10^{-10} s^{-2}). The contour interval in (d) and (e) is $0.1 \times 10^{-10} \text{ s}^{-2}$.

was 600 km, respectively. Although the contributions at all altitudes differed slightly with the detection radius, the profiles were consistent, and the degree of contribution was sufficiently large to confirm the substantial footprint of TCs in climate variability. Notably, the uncertainty of the TC contribution increased from 5% to 10% with the altitude, indicating that the detection domain must be carefully tested, particularly in the upper troposphere, where the relationship between negative PV anomaly and TC is not as obvious as that in the lower troposphere.

6. Conclusions and discussion

This study estimated the TC footprints in the climate mean state and multiscale variability in the WNP by comparing original reanalysis data (1958–2019) with those over the same period after removal of the TC signals. The removal was performed by subtracting the TC components, which were derived from the piecewise PV inversion, from the reanalysis data. In this framework, the TC-removed data were dynamically balanced. The present approach and methodology, which allowed

the bulk assessment of the effect of TCs on climate variability, can be used as a powerful tool in climate studies involving scale interactions. As mentioned, this study was a revisit of the TC contribution issue raised in the studies by Hsu et al. (2008a,b), in which only winds related to TCs at a single level were removed and dynamic balance was not maintained. By contrast, the present study retained this dynamic balance and removed multiple variables at all levels in the troposphere and lower stratosphere, an approach that provided a more holistic view of TC footprints in climate mean state and variability.

We compared long-term mean fields in the WNP during the TC season between 1958 and 2019. Although the TCs were present for a much shorter period than the 62-yr averaging period, TC footprints could not be removed. This suggests that even if TCs may appear in clusters because of the modulating effect of background flows favorable to their genesis, the TC circulation of an extremely large amplitude can leave a distinct footprint in low-frequency, large-scale circulation, which is typically identified in the post analysis through long-term averaging or low-pass filtering. As explained in Hsu et al. (2008a), this inseparability between

FIG. 10. As in Fig. 6, but for the intraseasonal (20–80 day) variance of 850-hPa geopotential height (gpm^2). The contour interval in (d) and (e) is 50 gpm^2 .

the extremely strong TC perturbations and the low-frequency large-scale background flow was because the widely adopted statistical procedure could not properly separate the signals of different time scales that actively interacted. A pure background flow for TC genesis and development could be maintained in a carefully designed numerical experiment or theoretical study but cannot be identified in the real world. This limited the studies to determine the modulating effect of large-scale circulation on TCs through an empirical approach that has been applied in TC and climate research for several decades. For example, the likelihood of TC formation has often been estimated on the basis of the genesis potential index (GPI; Emanuel and Nolan 2004; Camargo et al. 2007), defined by the time averages of vorticity, relative humidity, potential intensity (Emanuel 1986; Bister and Emanuel 2002), and vertical wind shear. As mentioned, these averages likely include distinct TC footprints that enhance the background flow favorable to TC formation. The GPI and background flow approaches are therefore likely to overestimate the likelihood of TC genesis and development. Examining how the TC contributions to these averages (according to the

TC-removed data) are reflected in the GPI may aid in the understanding of the relationship between TCs and background circulation as well as TC–climate interactions.

The present study demonstrated that although TCs tended to be more active when background flow was cyclonic, they left a large cyclonic footprint in the background, enhanced the mean monsoon trough, and weakened the mean subtropical high. In other words, a larger footprint was left in the active years, which were characterized by the clusters of high numbers of strong TCs. This resulted in much weaker subtropical high and a stronger monsoon trough than in the inactive years. This contrast enhanced their interannual variances. According to our estimation, the TC contribution to the interannual variance exceeded 50% in the lower troposphere and decreased to 20% in the upper troposphere. That is, TCs increased the interannual variance of the monsoon trough and weakened that of the western flank of subtropical high. Note that although the TC clusters enhanced the monsoon trough and thus created a better condition for TC genesis, this does not necessarily imply a positive feedback between the TC genesis and the favorable

FIG. 11. As in Fig. 6, but for the intraseasonal (20–80 day) variance of 250-hPa temperature (K^2). The contour interval in (d) and (e) is $0.05 K^2$.

condition. Further study is needed to reveal whether or not the feedback process exists.

The TC contribution to the intraseasonal variances of low-level vorticity, low-level geopotential height, and upper-level temperatures exceeded 50%, with a widespread positive TC contribution along prevailing TC tracks and the maximum located around the recurvature point. Notably, the intraseasonal variance also exhibited strong interannual fluctuations that were in turn embedded in an interdecadal fluctuation and a decreasing long-term trend and distinguished by regime shifts around 1972/73 and in 1997/98. After the TC removal, the interannual and interdecadal variations, regime shifts, and long-term trends of the intraseasonal variance became much weaker than before. This indicates the dominance of TC footprints across multiple time scales—intraseasonal, seasonal, interannual, and interdecadal—and also in long-term trends.

Because of the substantial TC footprints in the long-term climate, TCs distinctly modified mean circulation patterns in the WNP from conditions with a strong subtropical high and a weak monsoon trough to those with a weaker subtropical high and a stronger monsoon trough. In addition, these variabilities

were considerably greater than they would be in a world with no TCs. Our results indicate that, in terms of the characteristics of the monsoon trough in the long-term mean state, TCs should be regarded as a crucial element in the WNP monsoon system rather than just as extreme weather events modulated by large-scale environmental flows. The long-term dataset created in this study provides an opportunity to study the interaction between TCs and TC-free large-scale circulations to advance our understanding of climate variability in the WNP.

The present findings have implications for GCM performance evaluations. Considering the considerable TC contributions to climate means and variability, GCMs that cannot properly simulate TCs (e.g., low-resolution GCMs) would exhibit a much weaker monsoon trough and a much stronger western flank of subtropical high, as well as substantially less climate variability, in the WNP. If such models show means and variability with amplitudes that are not equivalent to those observed in the real world, other climate processes would likely behave unrealistically to compensate for the would-be underestimation. Most state-of-the-art GCMs used in climate projections, such as CMIP5 and CMIP6, are in lower resolutions

FIG. 12. Time series of the intraseasonal variance of 850-hPa relative vorticity averaged over the 15° – 30° N, 120° – 140° E area from June to October (thin black line; 10^{-10} s^{-2}) and its 9-yr running mean (thick black line): (a) total field, (b) TC-removed field, and (c) TC contribution. The filled bar and thick gray line in (a) represent the regime shift index (y axis at the right) and the time mean in each regime, respectively. (d) Time series of the number of TCs from June to October over the WNP (thin line) and the linear regression line derived through the least squares method (thick line). The linear decreasing trend ($-0.57 \text{ decade}^{-1}$) was statistically significant at the 10% level.

and are therefore not capable of properly simulating TC circulation and activity. Hypothetically, such models would tend to undersimulate the mean summer circulation and variability in the WNP both in the present and the future, leading to likely improper estimations of changes caused by global warming. Studies to check on the validity of this hypothesis are needed. In view of the substantial contributions of TCs, high-resolution models that realistically simulate TC activity would be better able to reliably project future climate changes in circulation and precipitation over the WNP and would have a higher chance to narrow down the projection uncertainty. Moreover, Knutson et al. (2020) reported that, in the comparison of TC activity projections responding to global warming in climate models, some of the projections were robust in the models (e.g., increases of global TC intensity and precipitation), while some were in lower confidence levels (e.g., a decrease of global TC frequency, an increase of global very intense TC frequency). It was also reported that some GCMs are better than others at producing realistic TCs (Camargo and Wing 2016). Analyzing the models that adequately simulate TCs may help reduce the uncertainty of the projections with large intermodel differences.

Studies have suggested that under global warming conditions, TCs decrease in number but the number of strong TCs increase (Sugi et al. 2002; Camargo 2013; Yamada et al. 2017). In regions where TCs are active, the reduction in TC number

would result in smaller multiscale variability, whereas the increase in strong TCs would enhance variability. Moreover, TC genesis locations shift to the east due to the eastward monsoon trough extension (Yokoi et al. 2012; Wang and Wu 2018), TC tracks migrate poleward (Knutson et al. 2019, 2020; Kossin et al. 2014, 2016), and TC translation speed slows down (Kossin 2018) under future climate. This implies that the distance between the TC genesis location and the TC recurvature location will be longer. Coupled with the deceleration of TC transition speed, these changes would enhance TC contributions and shift the distributions of TC contribution on the climate means and variabilities to the northeast. Additional detailed diagnostics on the relative contribution from the various changes related to TCs are required to yield more reliable estimations of TC contributions under such conditions.

TCs likely also contribute crucially to climate variability in other regions in which TCs are active, such as the tropical North Atlantic, the northern Indian Ocean, and the tropical western South Pacific. The extent of these contributions is possibly dependent on the mean state. For example, they are presumably smaller in the tropical North Atlantic because of the dominance of the subtropical high and the absence of a monsoon trough in that region. Future studies focusing on other basins are warranted to extend the understanding of the relative effects of TCs on the mean state and variability of the climate.

FIG. 13. Intraseasonal (20–80 day) variance of 850-hPa relative vorticity (10^{-10} s^{-2}). (a) Total field and (b) TC component, June–October 1973–97. (c) Total field and (d) TC component, June–October 1998–2019. Difference between the intraseasonal variance from 1998 to 2019 and from 1973 to 1997 in the (e) total field and (f) TC contribution.

Horizontal resolution could be an important issue for this type of study. Although TCs in the JRA-55 reanalysis show better representation compared with TCs in other reanalysis data (see section 2), the 1.25° horizontal resolution is not high enough to represent the real TC intensity and structure, especially for strong TCs. The resolution dependence of TC footprint was explored in Hsu et al. (2008a) by comparing reanalysis data with different resolutions. Their conclusion was that the higher-resolution data revealed the TC contribution pattern in greater details (in both distribution pattern and amplitude) but yielded essentially the same results as in the lower-resolution data. It follows that the higher-resolution data are expected to reveal an even higher contribution from TCs than the 50%–70% identified in our study. While this resolution issue deserves a following study, the large contribution from TCs identified in this study, although likely underestimated, is of major concern for the climate variability study.

Another issue is the influence of satellite observation after the late 1970s. We conducted the same analysis to the data in 1980–2019 and compared the results with those presented here. The estimated TC footprints in 1980–2019 were essentially the same as those in 1958–2019 except an about 10% difference in the interannual variance of low-level geopotential and upper-level temperature. The relative minimum differences suggest the reliability of our results.

The observed TC location and intensity are not perfectly represented in reanalyses. However, it is unavoidable to use reanalyses because they are the major data sources that have been widely used to understand climate variability and change. It is therefore important to understand how the resolved TCs in reanalyses might affect our understanding of climate variability and change. Exact TC location and strength likely vary between reanalyses, and it is important to resolve TC more accurately in case studies. But climatic footprints of TCs estimated from different reanalyses are likely similar in a

Intraseasonal variance, TC contribution ratio (JJASO 1958–2019, 120–140E 15–30N)

FIG. 14. Relationship between the TC contribution and height. The solid (dotted) line represents the TC contribution to relative vorticity (temperature). The blue, red, and black lines represent the estimated contribution with 600, 800, and 1000 km as the TC removal radius, respectively. The horizontal and vertical axes represent the contribution ratio and the pressure level (hPa), respectively.

statistical sense considering the large amplitude and spatial scale. The consistency between the current study and the finding in Hsu et al. (2008a,b), which used ECMWF reanalysis of different resolutions, supports this point. An intercomparison project using different reanalyses is warranted to resolve this uncertainty issue, although we expect to see similar results because of the relatively small impacts of shifted location on the long-term ensemble effect. The current TC removal scheme applies PV inversion to a limited domain covering only the western North Pacific. Ideally, the TC removal by PV inversion should be done in a global domain. Such an approach will be conducted in a following study.

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Data availability statement. The JRA-55 reanalysis and RSMC best track data are available at https://jra.kishou.go.jp/JRA-55/index_en.html and https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/RSMC_HP.htm, respectively.

The TC removal data used in this study are available from the first author upon request.

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