Reexamination of the Climatology and Variability of the Northwest Pacific Monsoon Trough Using a Daily Index

TAO FENG
College of Oceanography, Hohai University, Nanjing, and Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China

XIU-QUN YANG AND XUGUANG SUN
China Meteorological Administration–Nanjing University Joint Laboratory for Climate Prediction Studies, and Jiangsu Collaborative Innovation Center of Climate Change, School of Atmospheric Sciences, Nanjing University, Nanjing, China

DEJIAN YANG
College of Oceanography, Hohai University, Nanjing, China

CUIJIAO CHU
China Meteorological Administration–Nanjing University Joint Laboratory for Climate Prediction Studies, and Jiangsu Collaborative Innovation Center of Climate Change, School of Atmospheric Sciences, Nanjing University, Nanjing, China

ABSTRACT
This study developed a daily index to represent the northwest Pacific monsoon trough using westerly related cyclonic vorticity after removing tropical cyclones (TCs) from the reanalysis dataset. This index sufficiently captures the spatial and temporal variations in the monsoon trough. The use of this daily index revealed new features in the monsoon trough, including daily statistical characteristics, the active period over a year, and the main periodicity. A monsoon trough can be identified as active when the daily index is greater than $2.0 \times 10^{-4}$ s$^{-1}$. Active monsoon troughs occur during half of the summertime, and these is no monsoon trough on one-third of days, with the remaining days categorized as inactive. The most active month is August, in which approximately 20 days exhibit an active monsoon trough. Using this index, an active monsoon trough period, which is related to vigorous TC activity, was determined by identifying the establishment and decay dates for each year from 1979 to 2016. During most years, the active monsoon trough is established in mid-July and decays in late October, persisting for 3–5 months during the boreal summer. Moreover, spectral and wavelet analyses demonstrated the presence of intraseasonal, interannual, and interdecadal variabilities in the monsoon trough. The dominant periodicity for the interannual variability varied from 1.5 to 4 years in different decades. The relationship between the monsoon trough and TCs is also revealed using this index, showing that approximately 60% of TC formations were related to an active monsoon trough.

1. Introduction
The lower-tropospheric monsoon trough in the western North Pacific is a vital component of the East Asian summer monsoon system. The monsoon trough exhibits a planetary-scale cyclonic flow, which consists of southwesterlies from the Southern Hemisphere and trade easterlies from the tropical central Pacific. The monsoon trough is sometimes called a monsoon depression as it displays a region with low sea level pressure. The trough is the main region in which most of the monsoon rainfall is induced over the northwest Pacific during boreal summer due to enhanced convective activity (e.g., Wang and LinHo 2002). The trough region is also the main development region for tropical cyclones (TCs) due to its favorable dynamic and thermodynamic environments (e.g., Gray 1968; Harr and Chan 2005).
The climatology and variability of the northwest Pacific monsoon trough have been studied for decades. As revealed in previous studies (Ueda and Yasunari 1996; Wu and Wang 2001; Wu 2002), the monsoon trough is first observed over the South China Sea during mid-May. The eastward migration occurs in mid-June when the monsoon rainfall extends to the southwestern Philippine Sea. The northwest Pacific monsoon trough usually forms near mid-July, and disappears during late October and is accompanied by the eastward advance and westward withdrawal of the monsoonal southwestern erlies. Due to the complexity of the East Asian summer monsoon system, the monsoon trough varies over multiple time scales (Harr and Wu 2011). Over synoptic to intraseasonal scales, the monsoon trough interacts with equatorial waves (Takayabu and Nitta 1993; Dickinson and Molinari 2002; Molinari et al. 2007; Feng et al. 2016), cross-equatorial surges (Love 1985; Feng et al. 2017), the Madden–Julian oscillation (MJO) (Maloney and Dickinson 2003; Gao and Li 2011; Cao et al. 2013), etc. Over a longer time scale, the interannual variation in the monsoon trough is related to the El Niño–Southern Oscillation (ENSO) system (e.g., Wang and Chan 2002; Lau and Nath 2006; Wu et al. 2012; Cao et al. 2014a) or tropical tropospheric biennial oscillation of the monsoon system (Tomita and Yasunari 1996; Chang and Li 2000). An interdecadal shift in the monsoon trough affecting the interdecadal change in TC frequencies in the late 1990s was also revealed by Huangfu et al. (2017). The multiple time scale variations in the monsoon trough strongly modulated TC formations (Lander 1994, 1996; Holland 1995; Wu et al. 2012; Cao et al. 2014a; Feng et al. 2014; Zong and Wu 2015a).

However, the definition of a monsoon trough differs between these studies, resulting in difficulties in understanding the climatology and variability of the northwest Pacific monsoon trough. Some studies identified a monsoon trough as a zonally elongated sheared region with northwesterlies in its southern part and easterlies in its northern part (e.g., Lander 1994, 1996; Holland 1995). Ritchie and Holland (1999) counted monsoon gyres, which are characterized by a near-circular cyclonic circulation, as a part of a monsoon trough. In other studies (e.g., Chen and Chang 1980), the mei-yu front during the presummer and early summer periods from mid-May to mid-June is also counted as an early monsoon trough. Molinari and Vollaro (2013) discussed several definitions and defined a monsoon trough as follows: regions with a positive relative vorticity averaged over at least several months. However, Molinari and Vollaro (2013) identified those positive relative vorticity regions on the equator induced by trade northeasterlies as a monsoon trough when the boreal winter monsoon prevails.

In most of these studies, identification of a monsoon trough relied on subjective analysis of the lower-tropospheric circulation pattern on a synoptic map. Some studies have attempted to produce an objective index to represent the intensity and location of a monsoon trough. Gao et al. (2011) defined intensity and location indices to investigate multi-TC formation events in association with a monsoon trough. Wu et al. (2012) used the June–November mean positive relative vorticity averaged from 5° to 20°N to represent the strength of a monsoon trough. This index was subsequently used in several studies (Wu et al. 2015; Huangfu et al. 2017; C. Li et al. 2017). Cao et al. (2014a) used a region-averaged OLR instead of relative vorticity to reveal the interannual variation in the monsoon trough. In addition, some East Asian summer monsoon indices, which are often expressed by a north–south gradient of zonal winds, actually measure the strength of the northwest Pacific monsoon trough (e.g., Wang and Fan 1999; Wang et al. 2008). Most of these indices are applicable when the average period is longer than one month. If these indices are applied to define the monsoon trough on a daily basis, several critical drawbacks are encountered. Molinari and Vollaro (2013) summarized these drawbacks as follows: 1) too much influence from TCs in the vorticity fields, 2) noncontiguous vorticity regions related to higher-frequency perturbations, and 3) a lack of separability from tropical low-frequency oscillations because the variability in the monsoon trough overlaps with various oscillation phenomena at similar frequencies in the tropics (e.g., the MJO). To avoid these drawbacks, they suggested that the monsoon trough is a climatology phenomenon and should be defined using multimonth mean vorticity.

Although the climatology and variability of the monsoon trough are described in the literature, some of their basic features remain vague without a reliable definition of the monsoon trough on a daily basis. For instance, daily weather maps show that the monsoon trough does not always exist over the northwest Pacific during boreal summer (not shown). What is the percentage of days when an active monsoon trough exists over the western North Pacific? Sometimes we assess the establishment of the monsoon trough by analyzing the monsoon trough line from a weather map. What are the criteria for identifying the establishment of the monsoon trough? Moreover, what are the criteria for determining the TC genesis capacity in a monsoon trough? Previous studies mentioned that monsoon trough possesses intraseasonal, interannual, or interdecadal variabilities. Are these periods statistically significant? Can the monsoon trough have other significant periods? At the interannual time scale, the monsoon trough can be
categorized as active or inactive using the annual averaged index (Wu et al. 2012). How can we define activity or inactivity on a daily basis? A daily index, which represents daily variations in a monsoon trough, is of great help in addressing these issues.

In this study, a feasible index that represents the daily variation in the northwest Pacific monsoon trough was developed. The climatology and variability of the monsoon trough are investigated using this daily index to address the above-mentioned remaining issues. The rest of this paper is organized as follows: In section 2, the dataset and methodology are described. In section 3, the definition of a daily monsoon trough index is provided. In section 4, the climatology and variability of the monsoon trough is examined using this index to address some statistical results. Finally, in section 5, the conclusions and discussion of this study are presented.

2. Datasets and methodology

The daily atmospheric fields on a global grid are obtained from the National Centers for Environmental Prediction–Department of Energy (NCEP–DOE) AMIP-II Reanalysis (Kanamitsu et al. 2002; NCEP et al. 2000) from 1979 to 2016. The data have a resolution of 2.5° × 2.5° and 17 pressure levels. Extended reconstructed sea surface temperature (ERSST) v5 data (Huang et al. 2017a,b) are used to provide the surface thermal state of the Pacific Ocean. The El Niño index is calculated from the SST anomalies averaged during the preceding December–February (DJF) in the Niño-3.4 region (5°N–5°S, 120°–170°W). The DJF mean SST is used because El Niño exerts a delayed impact on the western North Pacific summer monsoon (Zhang et al. 1996; Wang et al. 2000; T. Li et al. 2017). The velocity potential MJO (VPM) index produced by Ventrice et al. (2013), which is available at https://www.esrl.noaa.gov/psd/mjo/mjoindext/, is used to track MJO activity. Thus, the relationship between the establishment of the monsoon trough and the MJO can be discussed. The VPM index is derived from the widely used real-time multivariate MJO (RMM) index (Wheeler and Hendon 2004) by replacing the input from the OLR with the 200-hPa velocity potential. Compared to the RMM, the VPM index better discriminates MJO-associated signals during boreal summer (Ventrice et al. 2013; Kiladis et al. 2014).

The genesis and intensity information of TCs are adopted from the International Best Track Archival For Climate Stewardship (IBTrACS) version 10 (Knapp et al. 2010; NOAA/NCDC 2017). The first occurrence of the maximum near-surface wind speed reaching 35 kt (1 kt = 0.51 m s⁻¹) is defined as the genesis time. Following previous studies (Hall et al. 2001; Kim et al. 2008; Li et al. 2014), a daily genesis rate (DGR) of TCs is defined as the number of TC genesis divided by the number of total days. A statistical test is then employed to examine whether the DGR significantly differs from the climatology following the definition by Li and Zhou (2013). The daily accumulated cyclone energy (ACE) is also calculated as the sum of the squares of the 6-hourly maximum sustained wind for all TCs in the northwest Pacific basin for each day (Bell et al. 2000). The DGR and ACE are applied to show how this index can represent the possible interactions between the monsoon trough and TCs.

3. Development of a daily monsoon trough index

a. How to define a monsoon trough conceptually

As defined in the Glossary of Meteorology (Glickman 2000; AMS 2019a), a monsoon trough is “the line in a weather map showing the locations of relatively minimum sea level pressure in a monsoon region.” We agree with Molinari and Vollaro (2013) that this definition is problematic. We think we can refer to the definition of the term trough to develop a more appropriate definition of monsoon trough. The Glossary of Meteorology (Glickman 2000; AMS 2019b) defines a trough as “an elongated area of relatively low atmospheric pressure; the opposite of a ridge.” We noticed the explanation under the term trough saying “the axis of a trough is the trough line.” Apparently, the original term monsoon trough in the Glossary of Meteorology is the definition of a monsoon trough line. Amending the “line” issue, the definition of monsoon trough should be revised to “an elongated area in a weather map showing relatively low atmospheric pressure in a monsoon region.” However, this definition would recognize an equatorial trough, which is induced by southward cross-equatorial flows in boreal winter, as a monsoon trough. Following previous studies, the northwest Pacific monsoon trough should consist of low-level easterly trade winds and the westerly monsoonal wind (e.g., Chang and Chen 1995; Wang and Xu 1997; Chan and Evans 2002; Wu 2002; Chen and Huang 2008; Wu et al. 2012). Finally, the term monsoon trough in this paper is defined as an elongated area in a weather map showing relatively low atmospheric pressure consisting of easterly trade winds and westerly monsoonal winds.

The horizontal winds at 850 hPa and sea level pressure during boreal summer averaged from 1979 to 2016 are shown in Fig. 1a. Climatologically, the monsoon trough, depicted by the red trough line between monsoonal southwesterlies to the south and easterlies to the north, overlaps well with regions with low sea level pressure. The climatology pattern of the relative vorticity is similar to that of sea level pressure, with a spatial correlation
Previous studies have also demonstrated the viability of using relative vorticity to define the northwest Pacific monsoon trough (Wu et al. 2012; Molinari and Vollaro 2013). In this study, we show the development of a daily index based on relative vorticity and zonal winds.

Another issue is the conceptual separation between the monsoon trough and other wave-like perturbations, such as the MJO. Molinari and Vollaro (2013) define the monsoon trough as a climatological feature to avoid the separation between the monsoon trough and other wave-like perturbations. This is a feasible definition, but it may not be the best definition in terminology. Why does monsoon trough only refer to a climatology background but a trough can be identified from a daily synoptic map? Why do we need a particular definition of the term trough in the monsoon region? Conceptually, the separation between the monsoon trough and the MJO (or tropical waves) is not necessary because the former is defined based on synoptic analysis and the latter is defined by the dispersion relation. We suggest that a monsoon trough is a synoptic phenomenon that can be identified from a weather map illustrating the combined contribution of various wave-like disturbances (such as the MJO), the seasonal evolution of the atmospheric general circulation, and other variations with longer time scales (interannual, interdecadal, etc.). Consequently, the monsoon trough can be defined from a daily weather map without separation with the MJO and tropical waves. Therefore, we can unify the definition of the terms trough and monsoon trough such that the latter is the trough in the monsoon region. However, TC signals—different from tropical waves, which are identified from their dispersion relations—are not counted as a part of the monsoon trough, which will be discussed next.

### b. Extracting trough signals

The monsoon trough creates a favorable environment for TC genesis. After genesis, TC circulation has a prominent impact on the wind fields (Hsu et al. 2008; Bi et al. 2015; Cao et al. 2018), which interferes with the identification of the monsoon trough. The evolution of the monsoon trough after TC formation has been less discussed because the signal of the monsoon trough overlaps the TC signal. In this subsection, we show how the TC circulation obscures the identification of a monsoon trough and how to extract trough signals from a reanalysis dataset.

Several algorithms can estimate the contribution of TCs to environmental fields (e.g., Frank and Roundy 2006; Kurihara et al. 1993, 1995; Chen et al. 2010; Schreck et al. 2011). However, most TC circulations are asymmetric and embedded within noncircular monsoon circulation; therefore, the horizontal boundary of a TC should be carefully determined to avoid overestimating the impact of the TC. Under this consideration, the algorithm developed by Kurihara et al. (1993, 1995) is employed to remove TC components from the original fields. This method objectively identifies an asymmetric TC without monsoonal flow following this procedure: first, the wind fields are split into a basic field and a disturbance field using a filtering operator; then, the TC boundary is determined from the disturbance field by examining the profile of the tangential wind; finally, the TC component is extracted using an empirically determined function in association with the TC radius. Thus, smoother large-scale environmental fields can be extracted after removing TC signals. Figure 2 shows a case in which this TC removal method is applied. Two strong TCs appear with strong rotational flows around the TC centers over the tropical western North Pacific Ocean on 22 August 2004 (Fig. 2a). Whether a monsoon trough exists is difficult to determine from the lower-tropospheric winds. By removing these two TC components (Fig. 2b) from the original
wind fields (Fig. 2a), a northwest–southeast elongated monsoon trough can be easily distinguished from the contiguous vorticity regions (Fig. 2c).

After removing the TC components, a nine-point local smoothing is applied inside the region with positive vorticity. This smoothing method is used to eliminate high-frequency noise (Fig. 2d) in the trough region without changing the circulation patterns outside the trough. Thus, a smoothed circulation is obtained for further identification of a monsoon trough (Fig. 2e).

The reliability of the current trough-isolation method was tested for all TC days from 1979 to 2016. This method is useful to isolate a monsoon trough from complex lower-tropospheric circulations. Figure 2f shows the result of simply applying a 10-day low-pass filter to the original fields, which was used in some previous studies to

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**FIG. 2.** The horizontal wind field (vectors) and relative vorticity (shading; $10^{-5} \text{s}^{-1}$) at 850 hPa on 22 Aug 2004: (a) original fields, (b) TC components, (c) fields after removing TC components, (d) perturbations by spatial smoothing, (e) fields after removing TC and perturbation components, and (f) fields by applying a 10-day low-pass filter to the original data. Typhoon symbols denote the centers of TCs “Chaba” and “Aere” in the best track data. Orange circles denote the boundaries of each TC, which are determined by the TC removal algorithm (Kurihara et al. 1993, 1995).
extract environmental fields (Feng et al. 2014; Zong and Wu 2015a). Although a monsoon trough can be recognized from the spread of positive vorticity, two cyclonic vortices with centers at 24°N, 124°E and 18°N, 139°E appear in the trough region, complicating identification of the monsoon trough line (Fig. 2f). These two cyclonic vortices are attributed to the contribution of TC signals to the 10–25-day variances (Hsu et al. 2008; Aiyyer et al. 2012) and cannot be entirely removed using a 10-day low-pass filter. Instead, using a 20-day low-pass filter, the wind pattern is similar to Fig. 2e, in which the TC signal is mostly removed (not shown).

On the other hand, the daily variance in the relative vorticity is substantially impacted by tropical cyclone tracks. Figure 3a shows the horizontal wind, relative vorticity, and standard deviation at 850 hPa without removing TCs, which are averaged from May to October from 1979 to 2016. The largest standard deviation of relative vorticity occurs in the subtropical regions near 25°N (Fig. 3a). If a daily index is directly calculated by using the original relative vorticity without removing TCs, the index primarily represents the variability in higher latitudes other than the monsoon trough. After removing the TC signals, the structure of the mean horizontal winds (Fig. 3b) is similar to that of the original winds (Fig. 3a). However, the standard deviation of the relative vorticity is greatly reduced, and the peak variance is confined to the monsoon trough region. Since TC signals are removed from the original fields, the relative vorticity over the western North Pacific can represent the variance in the monsoon trough.

c. Definition of a daily index

The western North Pacific monsoon trough is characterized by its large-scale cyclonic shear with westerlies to the south and easterlies to the north (Fig. 1). Thus, a daily monsoon trough index is calculated using the relative vorticity after applying the above two-step preprocessing approach:

$$I_{MT} = \sum_{n=1}^{N} \zeta_{850},$$  

(1)

In Eq. (1), \( \zeta_{850} \) is the relative vorticity at 850 hPa, and \( N \) is the grid point that satisfies the following two criteria: 1) westerlies exist \( (u > 0) \) and 2) the relative vorticity exceeds a certain threshold \( b \) inside the tropical northwestern Pacific domain \( (5°–25°N, 120°E–180°) \), that is, \( \zeta_{850} > b \). The selection of this extended area is due to the daily movement of the monsoon trough over the northwest Pacific. For example, Lander (1996) shows a reverse-oriented monsoon trough that extends northward to approximately 25°N. Wu et al. (2012) show that the monsoon trough can extend to the date line during some months. The threshold \( b \) is set to 0.1 \( \times 10^{-5} \) s\(^{-1}\). The choice of the threshold \( b \) will be discussed later. The sum of the relative vorticity is used rather than the average because the former provides information regarding the horizontal extension of the monsoon trough.

To simplify, \( I_{MT} \) is the sum of the relative vorticity at each grid point where westerlies exist with a relative vorticity at 850 hPa greater than 0.1 \( \times 10^{-5} \) s\(^{-1}\). This value measures the strength of the cyclonic sheared flow induced by westerlies over the tropical northwest Pacific. In the following, we will discuss other considerations in the choice of the criteria.

d. Choice of the criteria

The chosen criterion of \( u > 0 \) is derived from the seasonal cycle. The most problematic issue in developing a daily monsoon trough index is that the seasonal cycle of the monsoon trough is misrepresented by the relative vorticity in the lower troposphere. Another simple daily index (marked as \( I_{VR} \)), which is defined by the average of the positive relative vorticity at each grid
point over the northwest Pacific ($5^\circ$–$25^\circ$N, $120^\circ$E–$180^\circ$), will be used to illustrate the interference of easterly related points in representing the seasonal evolution of the monsoon trough.

As depicted in Fig. 4, a monsoon trough, which is represented by the artificially analyzed trough line, appears over the tropical northwest Pacific during boreal summer (Fig. 4a) and vanishes during boreal winter (Fig. 4b). The seasonal cycle of the monsoon trough (Figs. 4c–h) has been revealed in various studies (e.g., Lander 1996; Wu and Wang 2001; Wang and LinHo 2002; Wu 2002; Chen et al. 2004; Wang et al. 2004). However, this seasonal evolution is misrepresented by the index $I_{VR}$ (Fig. 5). Two false peaks appear in the seasonal cycle of $I_{VR}$, which occur during November and early January when winter-monsoonal northeasterlies prevail. In boreal winter, trade easterlies induce strong cyclonic vorticity near the equatorial region with

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**FIG. 4.** The long-term mean (1979–2016) Pacific relative vorticity ($10^{-5}$ s$^{-1}$) and the mean horizontal winds (vectors) at 850 hPa in (a) boreal summer, (b) boreal winter, (c) May, (d) June, (e) July, (f) August, (g) September, and (h) October. The thick dashed line denotes the axis of the monsoon trough. Blue dots denote grid points with westerlies and positive vorticity greater than $0.1 \times 10^{-5}$ s$^{-1}$. The averaged index $I_{MT}$ is shown in the upper right of each panel ($10^{-4}$ s$^{-1}$).
southward cross-equatorial flows (Fig. 4b). These regions with cyclonic vorticity are overlapped with easterlies and are not related to the western North Pacific summer monsoon. If these grid points with easterlies are utilized to calculate the monsoon trough index, the seasonal cycle will be distorted, as depicted by $I_{VR}$. Practically, the period of the western North Pacific summer monsoon, which varies from year to year, should be predefined before calculating $I_{VR}$ to avoid the misrepresentation of the evolution of the monsoon trough when the monsoon shifted to the winter monsoon.

The index $I_{MT}$ is applicable in an entire year. As shown in Fig. 4, the grid points with positive vorticity and westerlies nearly perfectly reproduce the evolution of the monsoon trough. As illustrated in Fig. 5, the index $I_{MT}$ remains low during January and May. After June, the value of $I_{MT}$ increases. The abrupt increase in the $I_{MT}$ value occurs around mid-July, which indicates a change in the large-scale background circulation over the western North Pacific. This date is consistent with the sudden jump in the monsoon trough from the South China Sea to the Pacific Ocean. The intensity of the monsoon trough reached its maximum in early August and gradually decreased during September and October as revealed by the variation in $I_{MT}$. In late October, the value of $I_{MT}$ sharply decreased. This result is consistent with the onset and withdrawal of the western North Pacific summer monsoon (Wang and LinHo 2002). Therefore, the new index $I_{MT}$, which only utilizes westerly-related grid points, sufficiently captures this seasonal migration of the monsoon trough as the westerlies are an essential indicator of the northwest Pacific summer monsoon. The better capability of $I_{MT}$ to characterize the seasonal cycle of the monsoon trough is ascribed to the elimination of the grid points with easterlies. This leads to the first criterion ($u > 0$) in the selection of points.

The second criterion is the threshold $b$. In previous studies, $b$ was set to $0.0 \times 10^{-5}$ s$^{-1}$ so that all grid points with positive relative vorticity were employed to calculate the index for the seasonal mean or climatological mean (Wu et al. 2012; Molinari and Vollaro 2013). Considering that the spatial distribution of vorticity is much noisier in a daily map, a nonzero value should be assigned to $b$ to reduce the number of discrete grid points. Values of $b$ from $0.0$ to $0.2 \times 10^{-5}$ s$^{-1}$, with an increment of $0.02 \times 10^{-5}$ s$^{-1}$, were tested by creating monthly averaged $I_{MT}$ values. As shown in Fig. 5, the seasonal cycle of $I_{MT}$ is not sensitive to the selection of the threshold $b$. Finally, the threshold $b$ is set to $0.1 \times 10^{-5}$ s$^{-1}$.

4. Climatology and variability

a. Climatology

Using the daily index $I_{MT}$, the occurrence, strength, and spatial distribution of the monsoon trough can be examined statistically. Figure 6 shows the probability distribution of the daily $I_{MT}$ value during boreal summer. The mean value is $2.50 \times 10^{-4}$ s$^{-1}$, with a standard deviation of $2.34 \times 10^{-4}$ s$^{-1}$. The distribution density gradually decreases with the increase in the value of $I_{MT}$. The values of one-third of the samples are less than $1.0 \times 10^{-3}$ s$^{-1}$, and the values of another one-third are greater
than $3.0 \times 10^{-4}$ s$^{-1}$. The median value is $1.88 \times 10^{-4}$ s$^{-1}$, which divides the entire boreal summer into more-active days and more-inactive days based on the state of the monsoon trough. Furthermore, we define the value of $2.0 \times 10^{-4}$ s$^{-1}$, approximately representing the 52nd percentile value, as the criterion for determining whether an active monsoon trough exists over the northwest Pacific.

The occurrence frequency of the active monsoon trough in a month is shown in Fig. 6b. The occurrence frequency of an active monsoon trough in a month can be divided into the following three categories based on the percentage density distribution: lower tertile, middle tertile, and upper tertile. The value of the upper tertile is 19 days in a month; thus, the month is considered active if the monsoon trough exists over the western North Pacific for more than 19 days in a month. The seasonal cycle and standard deviation of the occurrence frequency in each month (Fig. 7b) are similar to those of the monthly averaged $I_{MT}$ value (Fig. 7a).

How well do these statistical results match the in situ distribution and intensity of the monsoon trough? Usually, a monsoon trough is recognized from a weather map by analyzing the trough axis featuring a shear line between easterly trade winds in the north and monsoonal southwest flow in the south. Although such analysis of the trough axis remains subjective, the results are used to evaluate the monsoon trough index $I_{MT}$. Figures 8a and 8b show composite maps when the daily value of $I_{MT}$ is equal to $0.0 \times 10^{-4}$ s$^{-1}$ and less than $1.0 \times 10^{-4}$ s$^{-1}$, respectively. When $I_{MT}$ is less than $1.0 \times 10^{-4}$ s$^{-1}$, easterlies prevail over the entire tropical western North Pacific. No monsoon trough can be identified in the composite map, which accounts for 32.57% of the total days. When the daily $I_{MT}$ value is between $1.0 \times 10^{-4}$ and $2.0 \times 10^{-4}$ s$^{-1}$, the composition shows that a weak monsoon trough exists over the Philippine islands (Fig. 8c). When the daily $I_{MT}$ value is greater than $2.0 \times 10^{-4}$ s$^{-1}$, the monsoon trough extends eastward, with its eastern end reaching approximately 150°E (Figs. 8d,e). Figure 8f shows the pattern of extreme cases, which account for 14.47% of the total samples. Here, the daily $I_{MT}$ value is greater than $5.0 \times 10^{-4}$ s$^{-1}$, which exceeds the value of one standard deviation. These cases represent abnormally intense monsoon troughs. An abnormally strengthened monsoon trough may be associated with the westerly phase of the MJO (Maloney and Hartmann 2001; Hogsett and Zhang 2010; Molinari and Vollaro 2017), favorable interannual
and interdecadal background (Chou et al. 2003; Wu et al. 2012; Huangfu et al. 2017), and other high-frequency fluctuating phenomena.

Linking the circulation pattern of a monsoon trough to the daily index can help investigate the climatology. Statistically, there are no monsoon troughs in one-third of the days during boreal summer (Figs. 8a,b). Approximately one-fifth of the days exhibit a weak monsoon trough confined near the Philippine islands (Fig. 8c). These samples are categorized as inactive. Active monsoon troughs appear in only approximately one-half of the summer days. However, if such statistical analysis is performed by analyzing daily weather maps using a dataset without the removal of TCs, the percentage with active monsoon troughs may be greatly reduced, as the trough signal is overridden by TCs in daily maps.

b. Establishment and decay of the active monsoon trough

Similar to the consideration of the onset date of the South China Sea summer monsoon (e.g., Wang et al. 2004), the active period of the monsoon trough can be determined by identifying the establishment and decay dates for each year from 1979 to 2016. An active monsoon trough period should be characterized by firm establishment of a steady circulation pattern similar to the monsoon trough for at least several weeks. As the index $I_{MT}$ corresponds well with the daily advance of the monsoon trough, some objective criteria are produced to define the establishment of the monsoon trough. The establishment of the monsoon trough is defined by the first day after 1 May (as we focused on boreal summer) that satisfies the following three criteria: 1) the $I_{MT}$ value is greater than $2.0 \times 10^{-4} \text{ s}^{-1}$ on the establishment day, 2) the $I_{MT}$ value is greater than or equal to $2.0 \times 10^{-4} \text{ s}^{-1}$ on the following four consecutive days after establishment, and 3) the $I_{MT}$ value is greater than $2.0 \times 10^{-4} \text{ s}^{-1}$ on at least 20 of the subsequent 30 days.

The first criterion is used to identify active monsoon troughs, as shown in Figs. 6a and 8. The third criterion mainly refers to the upper tertile value of the monthly

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**Fig. 8.** Composited relative vorticity (shaded; $10^{-5} \text{ s}^{-1}$) and the mean horizontal winds (vectors) at 850 hPa for cases (a) $I_{MT} = 0$, (b) $0 < I_{MT} < 1$, (c) $1 < I_{MT} < 2$, (d) $2 < I_{MT} < 3$, (e) $3 < I_{MT} < 5$, and (f) $I_{MT} > 5$. The units for $I_{MT}$ are $10^{-4} \text{ s}^{-1}$. Blue dots denote grid points with westerlies and positive vorticity greater than $0.1 \times 10^{-5} \text{ s}^{-1}$. 

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occurrence of an active monsoon trough (Fig. 6b), which ensures that the northwestern Pacific monsoon trough is firmly established. The conditions are also tested for a duration range of 15–25 days out of 30 days for this criterion. Although the establishment dates in several years change with the change in the criterion (using 15 or 25 days instead of 20 days), the results do not change in more than 75% of the years. Therefore, the active monsoon trough has a firmly established circulation background that is not sensitive to the definition in most years. The second criterion is chosen to avoid the misidentification of the establishment date. In some cases, such as an isolated active day followed by 9 inactive days and 20 additional active days, the first day is rejected as being included in the active period by this criterion.

Similar to the establishment date of a monsoon trough, a decay date is also defined to represent the end of the active monsoon trough period. The decay date of a monsoon trough is defined by the following criteria: 1) the $I_{MT}$ value is greater than $2.0 \times 10^{-4}$ s$^{-2}$ but less than $2.0 \times 10^{-4}$ s$^{-2}$ on the following day, 2) the $I_{MT}$ value is greater than $2.0 \times 10^{-4}$ s$^{-2}$ on at least 20 of the previous 30 days, and 3) if one specific day is satisfied by the above two criteria for the last time in a year, then the following day is defined as the decay date. These criteria were chosen based on those for the establishment date.

Figures 9a and 9b show the establishment and decay dates of the active monsoon trough in 2002 and 2016. The active monsoon trough periods were determined from 23 June to 23 October in 2002 and from 2 August to 11 November in 2016. These two cases imply that an active monsoon trough episode represents a period dominated by a persistent active monsoon trough (Fig. 9a) or by the occurrence of an alternative establishment–break–establish trough (Fig. 9b).

Table 1 shows the establishment and decay dates during each year from 1979 to 2016. After division of the months into three 10-day periods, the establishment and decay dates of the active monsoon trough are summarized in Fig. 10. During most years, the monsoon trough begins to be active during late June to mid-July (Fig. 10a). Among these years, seven events were established in mid-July, which corresponds to the climatological establishment date. In a particular year (e.g., in 1980 or 2013) the establishment of the monsoon trough occurs very late in September. This does not mean that there is no monsoon trough before these dates. It means the monsoon trough was not active until September in these years (not shown). After establishment, the monsoon trough usually decays during mid-October, late October, and early November (Fig. 10b). The trough may also decay very early in September or August (e.g., 1999 and 2000) or persist until late December (1986). In most years, the active monsoon trough persists for 80 to 160 days over the western North Pacific, which is approximately three to five months (Fig. 10c). Over six special years (1983, 1988, 1995, 1998, 2008, and 2010), no active period can be determined, as the monsoon trough remains inactive rather than absent throughout the boreal summer (not shown). As revealed by the change in the Niño-3.4 index (Table 1), five of the six no-MT events occurred during the transition years from El Niño to La Niña (1983, 1988, 1995, 1998, and 2010), implying that the ENSO system induced an abnormally weak summer monsoon trough in the northwest Pacific during the El Niño to La Niña transition years (Chou et al. 2003).

The activity of the monsoon trough is related to the activity of the MJO during boreal summer (Maloney and Hartmann 2001; Maloney and Dickinson 2003; Hogsett and Zhang 2010; Cao et al. 2014b). Figure 11 presents an MJO phase diagram showing the MJO phases on the establishment days from 1979 to 2016. A large cluster containing 14 cases (37%) in a total of 38 years appeared during MJO phase 5. Twelve cases (32%) occurred during MJO phases 3 and 4. Only six cases occurred during the other five MJO phases. When the MJO-related convection moves from the Indian Ocean to the Maritime Continent, anomalous westerlies advance from the South China Sea to the western North
Pacific, which is accompanied by the eastward retreat of anomalous easterlies over the central Pacific. This event favored the establishment of an active monsoon trough with enhanced convective activities over the western North Pacific. Another notable feature is that for most cases occurring during MJO phases 3 and 4, such as those occurring in 1986, 1987, 1979, 2002, and 2003, the MJO amplitude is slightly larger than that for those cases occurring during phase 5, which may be ascribed to stronger westerly anomalies induced by a stronger MJO, thus inducing the early establishment of an active monsoon trough.

c. Multiscale variability

As the current index $I_{MT}$ is successively defined on daily time scale, spectral and wavelet analyses have been applied to determine the dominant periodicity of the multiscale variabilities in the monsoon trough. Figure 12 shows the spectrum of $I_{MT}$ after removing the seasonal cycle from the original time series. There are three main periodicities in the variation of the monsoon trough. A significant periodicity is found at 1.5–4 years, with a peak near 2.5 years, which is the most dominant period of the monsoon trough. Another significant periodicity appears at approximately 10 years, indicating that an interdecadal shift exists in the monsoon trough. In the intraseasonal band, the spectrum shows several significant periodicities ranging from 10 to 60 days, indicating that the monsoon trough is impacted by tropical intraseasonal oscillations in various time scales (e.g., the MJO and the tropospheric quasi-biweekly oscillations) (Chen and Sui 2010; Wang and Chen 2017). This result demonstrates that the monsoon trough exhibits significant intraseasonal, interannual, and interdecadal variabilities, which supports previous studies (Cao et al. 2014a,b; Wu et al. 2012; Huangfu et al. 2017).

A wavelet analysis shows a similar periodicity to that in Fig. 12, where the monsoon trough exhibits significant periods of approximately 2 and 10 years and a weaker peak at approximately 50 days (Fig. 13). However, the 10-yr period is significant only after the early 1990s. This finding is consistent with the interdecadal shift in the thermal conditions of the tropical Pacific Ocean, which have been reported in a large number of papers (e.g., Liu et al. 2012; Gu and Philander 1997). In addition, the 2-yr period, which represents the relationship between the monsoon trough and ENSO, is significant during 1980–87, 1993–2000, and after 2002. However, from 1987 to 1993, no significant 2-yr fluctuation can be found. Instead, a significant 4-yr periodicity exists since 1979 and disappears after 2000. The 4-yr periodicity is identical to the period of the South China Sea summer monsoon during the same decades, which was revealed by Zhou and Chan (2007). The change in the dominant interannual period implies that an unstable relationship exists between the ENSO and the northwest Pacific monsoon trough. Such an unstable relationship may be ascribed to the interdecadal shift of environmental backgrounds.

When investigating the variability on the interannual time scale or longer, an annual index is more convenient than a daily index. Following Wu et al. (2012), a simple

<table>
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<th>Year</th>
<th>Establishment</th>
<th>Decay</th>
<th>Niño-3.4 index</th>
<th>Year</th>
<th>Establishment</th>
<th>Decay</th>
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<td>2000</td>
<td>28 Aug</td>
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Average 11 Jul 1 Nov Std dev (day) 29.9 29.9
annual index (hereafter \( I_{AVG} \)) can be calculated by averaging the positive relative vorticity at 850 hPa in the region 5°–25°N, 120°E–180° from 1 June to 31 October of each year. This definition is based on a fixed period that approximately covers the boreal summer season. However, as is discussed in section 3, the establishment date of the monsoon trough varies from year to year. If a fixed season is used for averaging, then the signal of the active monsoon trough may be smoothed by those periods without an active monsoon trough. The intensity of the monsoon trough may be weakened, and the information regarding the establishment and decay dates is missing. Therefore, an annual index should be produced by only considering those periods when the monsoon trough is active. Thus, the annual monsoon trough index is calculated by averaging the daily index \( I_{MT} \) during the active period of the monsoon trough (hereafter \( I_{MTA} \)). In six years (1983, 1988, 1995, 1998, 2008, and 2010), no active monsoon trough can be identified. Therefore, the index \( I_{MTA} \) is zero in these six years.

Figure 14 illustrates the interannual variation in the standardized \( I_{MTA} \) and \( I_{AVG} \). These two indices show similar variations with a correlation of 0.88 during most of the years from 1979 to 2016. Nevertheless, in some years, the indices differ considerably. For example, in the year 2000, the standardized \( I_{AVG} \) was 0.19, whereas the standardized \( I_{MTA} \) was 0.79. A negative \( I_{AVG} \) implies that the monsoon trough is slightly weaker than those during normal years. A positive \( I_{MTA} \) indicates that the monsoon trough is stronger than normal after trough establishment. However, the active period is quite short, lasting only 29 days during 2000 (Table 1). Remarkable differences between \( I_{MTA} \) and \( I_{AVG} \) can also be found in the years 1980 and 2013. The correlation coefficient reaches 0.32 between the \( I_{MTA} \) and the Niño 3.4 index, which exceeds the 95% significance level. In contrast, the correlation is only 0.17 between the index \( I_{AVG} \) and the Niño 3.4 index. The newly defined annual monsoon trough index \( I_{MTA} \) correlates better with the ENSO phases, implying that the ENSO-related
oceanic thermal state in winter impacts both the intensity and active period of the monsoon trough. The index $I_{MTA}$ provides a proxy to investigate the effect of ENSO on the establishment and intensity of the monsoon trough.

d. Interaction with TCs

The establishment of the monsoon trough indicates the outbreak of the western North Pacific summer monsoon. More importantly, the establishment also marks the beginning of an active season of TCs over the western North Pacific, especially for multiple tropical cyclone events (Gao and Li 2011; Krouse and Sobel 2010; Schenkel 2017). Figures 9a and 9b show that TC formations were more active during the active periods in 2012 and 2016. The establishment of the active monsoon trough in early August 2016 supports the findings that the monsoon trough strengthened substantially after late July, thus causing the abnormal TC formation in 2016 (Zhan et al. 2017; Chen and Wang 2018; Huangfu et al. 2018).

Figure 15a illustrates the statistics of the daily $I_{MT}$ value on each genesis day during boreal summer (June–November) from 1979 to 2016. A total of 493 (62.2%) TCs formed when the daily index $I_{MT}$ was greater than $2 \times 10^{-4} \text{ s}^{-2}$. As discussed in section 4, a monsoon trough is defined as active when the $I_{MT}$ value is greater than $2 \times 10^{-4} \text{ s}^{-2}$, implying that approximately 60% of TC formations may be associated with an active monsoon trough during boreal summer. This proportion is slightly less than that reported in previous studies, which suggested a percentage of 70% (Ritchie and Holland 1999; Molinari and Vollaro 2013; Feng et al. 2014; Yoshida and Ishikawa 2013; Zong and Wu 2015b). One of the possible reasons is the different methods for identifying an active monsoon trough. The present definition of an active monsoon trough is slightly stricter than those in previous studies because a constraint is placed on the intensity of the monsoon trough in which the strength must be greater than $2 \times 10^{-4} \text{ s}^{-2}$. Another issue is that the TC formations outside the trough region were counted as being in association with the monsoon trough if the monsoon trough is classified as active on that day. Nevertheless, the present study suggests that over 60% of TC formation events are related to the monsoon trough. There are 300 genesis events without an active monsoon trough. These TC genesis events may be attributed to the tropical upper tropospheric trough (Briegel and Frank 1997) or tropical waves (Ritchie and Holland 1999; Wang et al. 2012; Frank and Roundy 2006; Chen and Chou 2014; Wu and Takahashi 2018). It should be noted that the signals of tropical waves contribute to the identification of the monsoon trough, and these waves may also affect TC genesis events with an active monsoon trough.

![Wavelet power of the daily monsoon trough index $I_{MT}$ from 1979 to 2016. The seasonal cycle has been removed from the original time series. Stippling denotes anomalies significantly above the 95% confidence level.](image-url)
Figure 15a also shows the change in the DGR with the monsoon trough index $I_{MT}$. The DGR is 8.3% when $I_{MT}$ is less than $2.0 \times 10^{-4}\text{s}^{-1}$. Approximately eight TCs form every 100 days. This percentage is slightly less than the climatological DGR (11.4%). When $I_{MT}$ increased to between $2.0 \times 10^{-4}$ and $4.0 \times 10^{-4}\text{s}^{-1}$, the DGR increased to 13.0%, and the significance exceeded the 95% level. Further increases in the DGR were accompanied by an increase in the $I_{MT}$ value. The peak DGR (20.9%) appears when $I_{MT}$ is between $6.0 \times 10^{-4}$ and $8.0 \times 10^{-4}\text{s}^{-1}$, indicating that approximately one TC forms every five days. This finding indicates positive correlation between an active monsoon trough and TC genesis when the $I_{MT}$ value is greater than $2.0 \times 10^{-4}\text{s}^{-1}$. This result also supports the selection of a threshold of $2.0 \times 10^{-4}\text{s}^{-1}$ to represent the active monsoon trough.

Section 4 defined an active period of the monsoon trough by tracing the abrupt change in the index $I_{MT}$. This active period can be used as a proxy to distinguish the active period of TC formations. Table 2 shows the DGR during the 15 days before and after the establishment or decay date. Before the establishment of an active monsoon trough, the DGR is 10.2%. However, the DGR increased to 19.0% in the 15 days after the establishment date. Before decay, the DGR is 11.0%. Subsequently, the DGR decreased to 7.5% after the decay date of the trough. The changes in TC genesis frequency before the establishment date and after the decay date are +8.8% and −3.5%, respectively. In comparison, if the establishment and decay dates are set to the climatological dates (15 July and 31 October, respectively), the frequency changes are +4.9% and −1.5%.

This result indicates that the definition of the active monsoon trough period better captures the outburst of TC activities during an individual year.

The present index can also be used to investigate the interaction between the monsoon trough and TCs due to...
the removal of TC signals. Figure 15b shows the index \( I_{MT} \) varies with the daily ACE during TC days and provides some clues regarding the influence of TCs on the monsoon trough. The linear regression shows a significant positive correlation between the daily \( I_{MT} \) and ACE (which exceeds the 95% confidence level). It is speculated that TCs support the maintenance of the monsoon trough through upscale dynamic processes. This result may differ from that of Ko et al. (2012), who speculated that TCs neither feed energy to nor gain energy from large-scale circulation. Some detailed calculations should be carried out to validate this upscale effect in the future.

5. Conclusions and discussion

In the present study, a daily index was developed to illustrate the state of the northwest Pacific monsoon trough. A two-step preprocessing approach is employed on the original wind field by removing the TC circulation and high-frequency noises. After preprocessing, the index is defined as the sum of the relative vorticity at each of the grid points where westerlies and remarkable cyclonic circulation exist over the tropical western North Pacific. This daily index can sufficiently illustrate the seasonal migration of the northwest Pacific monsoon trough. As this index is defined on a daily basis, the statistical characteristics of the monsoon trough are examined. These is no monsoon trough on one-third of the days of the boreal summer. Active monsoon troughs occur during half of the days. The most active month is August, in which approximately 20 days exhibit an active monsoon trough. Using this index, active monsoon trough periods were defined by determining the establishment and decay dates for every single year from 1979 to 2016. During most years, the active monsoon trough period begins in mid-July and ends in late October, persisting for three to five months during boreal summer. Although the establishment date of the monsoon trough varies from year to year, most of the establishments occur when the MJO phase is between 3 and 5. After trough establishment, the DGR increased one time more than before establishment. Therefore, the establishment of a monsoon trough is a valid indicator for the beginning of enhanced TC activities. A stronger monsoon trough results in a greater capacity for tropical cyclogenesis.

The variability in the monsoon trough is also revealed by applying spectral and wavelet analyses to the daily monsoon trough index. There are three main periodicities in the variation of monsoon trough, including intraseasonal, interannual, and interdecadal variabilities. The peak period of the monsoon trough is approximately 2.5 years, implying a close relationship between the monsoon trough and ENSO. However, the dominant interannual variability varied from 1.5 to 4 years during different decades, which implies an unstable relationship between ENSO and the interdecadal variation of the monsoon trough. This issue could be further investigated in the future. The present results support previous studies on the intraseasonal, interannual, and interdecadal variabilities in the monsoon trough (Cao et al. 2014a,b; Wu et al. 2012; Huangfu et al. 2017).

Additional analyses were also performed to show the advantage of this index. By defining the annual index based on the establishment and decay dates, the monsoon trough correlates better with the ENSO than the index averaged during a fixed period from June to October. This implies that the ENSO influences not only the intensity but also the active period of the monsoon trough. The feedback between the monsoon trough and TCs can also be represented using this daily index, although this result needs further investigation. Previous studies have revealed that breaks in the Pacific summer monsoon (e.g., Xu and Lu 2015) may lead to an inactive period monsoon trough. It is convenient to identify such breaks based on this daily monsoon trough index to investigate the cause of an inactive trough. Furthermore, occurrences of an abnormally intense monsoon trough (Fig. 8f), cases with a late-established monsoon trough or cases without an active monsoon trough (Table 1) are interesting findings. Examination of these cases may improve our understanding of the western North Pacific summer monsoon system.

Because the TC signals impact the large-scale circulation on the daily synoptic maps, the present study suggests that TCs should be removed before calculating the monsoon trough index. Another advantage of this definition is to better illustrate the evolution of the monsoon trough after TC formation. Therefore, the definition can be employed to investigate the interaction between TCs and the monsoon trough. However, the

| Table 2. Genesis frequency (%) before establishment or decay of the monsoon trough. The dates 15 Jul and 31 Oct refer to the climatology dates for the establishment and decay of the monsoon trough, respectively. Establishment and decay dates during individual years are obtained from Table 1. The symbols * and ** denote significance at the 95% and 99% confidence levels, respectively. |
|-------------------------|---------------------|----------------------|
|                         | 15 days before      | 15 days after        | Frequency change |
| Varied                  |                     |                      |                   |
| establishment dates     | 10.2                | 19.0                 | +8.8**            |
| Varied decay dates      | 11.0                | 7.5                  | -3.5*             |
| 15 Jul                  | 9.3                 | 14.2                 | +4.9*             |
| 31 Oct                  | 9.4                 | 7.9                  | -1.5              |

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requirement of TC removal in the definition may limit the usage of this daily index. The new index is defined based on the situation in the southern half of the monsoon trough, while the situation in the northern half is neglected. Although preprocesses were employed prior to calculating the index, identifying the shape of the monsoon trough objectively remains difficult. The pattern-identifying method, which was developed by Yoshida and Ishikawa (2013), may be a valid strategy to objectively determine whether an organized monsoon trough exists. Moreover, a combined index, including relative vorticity, sea level pressure, and precipitation, may be more reliable in determining the establishment and decay of the monsoon trough. Notably, the value of this index is sensitive to the horizontal resolution of the original dataset because this index is a sum of certain grid points. If datasets with different horizontal resolutions are used for comparison, the calculation of the index should include a scale parameter that equals the square of the horizontal resolution of the dataset.

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