Increasing Trend of Summertime Synoptic Wave Train Activity over the Western North Pacific since 1950

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ABSTRACT

The change of summertime synoptic-scale wave train (SWT) activity over the western North Pacific (WNP) since 1950 was investigated based on the NCEP–NCAR reanalysis data. It is found that the intensity of SWT has a rising trend, while its structure and phase propagation characteristics remain unchanged. Environmental factors responsible for the rising trend are investigated. By separating the whole period into three warming phases (P1: 1950–1958, P2: 1978–1986, and P3: 2006–2014), we found that even though the vertical velocity shows a rising trend, the background low-level vorticity over the monsoon trough region increases from P1 to P2 but decreases from P2 to P3, and so is the low-level barotropic energy conversion (CK). Thus, just the environmental dynamic factor could not explain the continuous rising SWT trend. On the other hand, thermodynamic factor, such as the sea surface temperature (SST), moisture, and atmospheric instability, shows a clear step-by-step increasing trend. A non-dimensional synoptic activity index (SAI) that combines the dynamic and thermodynamic factors is then proposed. This index well captures the observed long-term trend of the SWT intensity.

Key words: global warming, synoptic wave train, barotropic energy conversion (CK), atmospheric instability parameter, synoptic activity index (SAI)

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1. Introduction

The dominant pattern of summertime synoptic-scale variability over the western North Pacific (WNP) is a northwest–southeast oriented synoptic wave train (SWT; Lau and Lau, 1990; Li and Hsu, 2017). The wave train has a typical period of 3–8 days and zonal wavelength of 2500–3000 km. It contains the alternating cyclonic and anticyclonic circulations, and its signal can be identified from either low-level vorticity or meridional wind fields (Lau and Lau, 1990; Tam and Li, 2006). The cause of frequent occurrence of SWT in the WNP is attributed to the instability of summer mean flow in the presence of a moisture–convection–circulation feedback (Li, 2006) or energy conversion from the low-level background mean flow (Lau and Lau, 1992; Maloney and Hartmann, 2001).

As an important seed disturbance, SWT often triggers tropical cyclones in the WNP (Wallace, 1971; Zehr, 1992; Holland, 1995; Ritchie and Holland, 1997; Li and Wang, 2005; Li and Fu, 2006; Fu et al., 2007; Chen and Huang, 2009; Chen and Chou, 2014; Serra et al., 2014). The structure and intensity of SWT are often modulated by the low-frequency variability in the tropics. For instance, Sobel and Maloney (2000) revealed that the genesis location of SWT moved eastward and its intensity increased under an El Niño condition. During an active phase of local atmospheric Intrasessional Oscillation (ISO), the monsoon trough is enhanced, and so is the

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The remaining part of this article is organized as follows. We intend to reveal whether SWT has experienced a significant change, and if it has, what causes such a change. Global warming, possibly due to the bias of general circulation models (GCMs) in capturing realistic SWT patterns (Huang, P. et al., 2013; Fukutomi et al., 2016; Zhao et al., 2016). It has been shown that some of the SWTs were originated from the mixed Rossby–gravity (MRG) waves that developed over the equatorial region and then shifted to the off-equatorial region (e.g., Liebmann and Hendon, 1990; Dunkerton, 1993; Takayabu and Nitta, 1993; Dunkerton and Baldwin, 1995; Dickinson and Molinari, 2002; Aiyyer and Molinari, 2003; Li, 2006; Zhou and Wang, 2007; Chen and Huang, 2009). Some of the SWTs may arise from the Rossby wave energy dispersion of a preexisting tropical cyclone (TC; Holland, 1995; Ritchie and Holland, 1999; Li et al., 2003; Li and Fu, 2006; Li et al., 2006) or energy accumulation of easterly waves (Tai and Ogura, 1987; Kuo et al., 2001; Tam and Li, 2006). From the energetic point of view, two major energy sources are crucial to sustain the eddy kinetic energy (EKE). The first is the barotropic energy conversion (CK) from the mean flow, and the second is the baroclinic energy conversion (CA) from the eddy available potential energy (EAPE; Lau and Lau, 1992; Maloney and Hartmann, 2001; Maloney and Dickinson, 2003; Hsu et al., 2011).

As the global mean surface temperature rises in the past century, an interesting question that can be raised is how SWT would change under the global warming. Previous studies mostly focused on the change of TC and Madden–Julian Oscillation (MJO). For instance, Emanuel (2005) and Webster et al. (2005) pointed out that the number of strong TCs had increased in the past several decades, although such a claim was challenged by data accuracy in the prior-satellite era (Chan and Liu, 2004). Climate models tended to project an eastward shift of the TC genesis frequency from the WNP to central North Pacific (Li et al., 2010). Both the intensity (Liu et al., 2013; Arnold et al., 2015) and propagation speed (Cui and Li, 2019) of MJO are projected to increase in climate models under global warming. So far, few studies have focused on examining the change of SWT due to global warming, possibly due to the bias of general circulation models (GCMs) in capturing realistic SWT patterns (Huang, P. et al., 2013; Fukutomi et al., 2016; Zhao et al., 2016).

The objective of the current study is to investigate the trend of SWT over the WNP during the past 60–70 years. We intend to reveal whether SWT has experienced a significant change, and if it has, what causes such a change. The remaining part of this article is organized as follows. In Section 2, datasets and methods are described. In Section 3, the observed evolution characteristics of SWT including its intensity and structure since 1950 are examined. This is followed by discussion of the physical mechanism responsible for such a change in Section 4. Finally, the conclusion and summary are given in Section 5.

2. Data and methods

2.1 Data

Primary datasets used for the current study consist of (1) the daily mean products of the atmospheric wind, specific humidity, relative humidity, and vertical velocity (omega) at 17 vertical pressure levels from the NCEP–NCAR reanalysis (Kalnay et al., 1996), (2) monthly sea surface temperature (SST) field from the extended reconstruction of global SST version 5 (ERSST v5) dataset derived from NOAA (Huang, B. Y. et al., 2017), and (3) land surface temperature from the NASA Goddard Institute for Space Studies (GISS) Surface Temperature Analysis (GISTEMP; Hansen et al., 2001). Except for the land surface temperature dataset that has a 2° × 2° latitude–longitude grid, all the other data have a spatial resolution of 2.5° × 2.5°.

2.2 Methods

The empirical orthogonal function (EOF) analysis is performed onto the Lanczos 3–8-day band-pass filtered 850-hPa vorticity field over 0°–30°N, 110°–170°E, to extract leading modes of the synoptic-scale variability in boreal summer (June–September) in the WNP. As shown in Section 3, the first two leading modes have a similar variance and represent the northwestward-propagating SWT. Both the standard deviation (STD) of the 3–8-day filtered vorticity and the square root of principal components (PCs) of the two leading EOF modes are used to represent the intensity of SWT each year. Mann–Kendall (M–K) trend test (Mann, 1945; Hirsch et al., 1982; Es- terby, 1996) is further utilized to check whether or not the trend of SWT intensity since 1950 is statistically significant.

To understand how the SWT intensity and associated environmental conditions change with time, the entire analysis period is separated into three warming phases with an equal time interval. The first, second, and third periods are 1950–1958 (P1), 1978–1986 (P2), and 2006–2014 (P3).

By separating a dependent variable into two timescale components: a synoptic-scale component (3–8 days; denoted by a prime) and a low-frequency background state
component (greater than 10 days; denoted by an overbar), one may calculate the CK term at a constant pressure level as follows:

$$CK = u^2 \frac{\partial u}{\partial x} + v^2 \frac{\partial v}{\partial y} + 2uv \frac{\partial u}{\partial y} \frac{\partial v}{\partial x},$$  \hspace{1cm} (1)$$

where \((u', v')\) denote the synoptic-scale zonal and meridional winds and \((\bar{u}, \bar{v})\) denotes the corresponding low-frequency background state components. The CK term is the major term of energy transfer from the large-scale environmental flow to synoptic-scale motion, which reflects the eddy–mean flow interaction.

3. Trend of the SWT intensity since 1950

The global mean surface temperature shows a clear rising trend since 1950 (Fig. 1). In order to examine the physical mechanism responsible for the change of SWT characteristics at different periods, we separate the entire analysis period (1950–2014) into three warming phases (with an equal time interval of 9 yr), as described in Section 2. Relative to the global mean temperature in the first period (P1), the average warming is 0.24°C in P2 and 0.68°C in P3.

Figure 2 displays spatial patterns of the two leading EOF modes of the summertime (June–September) 3–8-day band-pass filtered vorticity field at 850 hPa. The upper (lower) panels show the first (second) EOF mode during the three warming phases. The two leading modes contribute to 17%–18% of the total synoptic variance during the three periods. EOF patterns reveal a clear characteristic of SWT in the WNP, with a northwest–southeast oriented wave train structure. The wavelength is approximately 2500 km, which is estimated from the distance between two adjacent centers.

The bottom panels of Fig. 2 show lagged correlation coefficients between time series of the two leading EOF modes. A significant lagged correlation is found between the two leading modes, implying that they are the same physical mode and represent the northwestward-phase propagation. Note that the propagation direction and wavelength of SWT are quite similar among the three warming phases. This suggests that the SWT structure and propagation characteristics barely change during the 65-yr period (1950–2014) under global warming.

In contrast, the intensity of SWT experienced a significant upward trend (Fig. 3). Two different methods have been adopted to measure the intensity of SWT. One is according to STD of the 3–8-day filtered vorticity averaged over the WNP monsoon trough region (5°–25°N, 120°–160°E). The other is based on the square root of PCs of the two leading EOF modes. Both of the intensity indices exhibit a rising trend. The M–K test was further applied to test the statistical significance of the trend. The results show that both of the intensity indices pass the significant test at the 99% confidence level. To examine whether the rising trend is caused by interdecadal modes such as the interdecadal Pacific oscillation (IPO) and Atlantic multidecadal oscillation (AMO), we calculated correlations between the SWT intensity indices and IPO/AMO time series (here IPO and AMO were derived based on the EOF analysis of the 8-yr low-pass filtered SST during 1950–2014). The correlation coefficients are small and do not pass the significance test, which implies that IPO and AMO are not responsible for the rising trend of the SWT intensity.

Figure 4 shows the area-averaged intensity indices during the three warming phases. Both indices exhibit a greater increase rate during the period from P1 to P2 than that during the period from P2 to P3. The average increase rate is 10% from P1 to P2, while it is much smaller (about 5%) from P2 to P3.

To examine whether or not the rising trend of the SWT intensity depends on the reanalysis product, we conducted a parallel analysis by using the ECMWF reanalysis data (by combining ERA-40 for the period of 1958–1978 and ERA-interim for the period of 1979–2016). The result shows that both intensity indices calculated based on the ECMWF reanalysis show a rising trend from 1958 to 2016, which is statistically significant and passes the 99% confidence level.

4. Change of environmental mean states associated with the SWT trend

The change of SWT activity is possibly caused by the change of background mean states. Thus, to understand
the physical mechanism responsible for the rising trend of SWT, we examine the change of key dynamic and thermodynamic mean states in boreal summer. The environmental variables to be examined include the SST, vorticity, specific and relative humidity, divergence/vertical motion, and atmospheric static stability. The effect of SST on the tropical perturbation and tropical cyclone development has been proposed by various previous theoretical studies (e.g., Lindzen and Nigam, 1987; Emanuel and Nolan, 2004). The background cyclonic vorticity is conducive to the organization of tropical disturbances through the vorticity segregation process (Schecter and Dubin, 1999; Li, 2012; Ge et al., 2013a) and CK (Malo-ney and Hartmann, 2001; Hsu et al., 2011). The role of

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**Fig. 2.** Patterns of the first (upper panels) and second (middle panels) EOF modes of the standardized summertime (JJAS) 850-hPa synoptic-scale vorticity fields and lagged correlation coefficient (bottom panels) between time series of the two leading modes at (a) P1, (b) P2, and (c) P3. The positive x-axis in the bottom panels means the first mode leading the second mode; the dashed lines represent the 95% confidence level.

**Fig. 3.** Time series of two SWT intensity indices (solid) from 1950 to 2014. The dashed lines denote linear trends of the two indices. The green curve is the intensity defined by the square roots of PCs of EOF1 and EOF2. The blue curve is the intensity defined by the standard deviation (STD) of the 3–8-day filtered vorticity. The temporal correlation coefficient between the two curves is 0.83. Yellow boxes indicate the period of P1, P2, and P3.
background moisture on tropical perturbation development is primarily through the release of condensational heating, as pointed out by many idealized numerical model experiments (e.g., Li, 2006; Ge et al., 2013b). The effect of background vertical motion on tropical perturbation development was discussed in Murakami and Wang (2010), which discussed the projected tropical cyclone change under global warming. The impact of environmental static stability is through triggering of the small-scale perturbation and convection (Holton, 2004), which may be further organized by the large-scale circulation.

Relative changes of the background mean SST field from P1 to P2 and from P2 to P3 are presented in Fig. 5. Note that the background mean SST averaged in the main monsoon trough region increases steadily from P1 all the way to P3. The area-averaged SST is 301.86 K (28.71°C) in P1, increases to 301.97 K (29.23°C) in P2 and 302.38 K (29.23°C) in P3 (Fig. 5a). The steady increase of local mean SST may partially explain the rising trend of SWT during 1950–2014.

In contrast, the background low-level vorticity shows a distinctive evolution characteristic. The present-day mean climate in the WNP is characterized by a monsoon trough with the cyclonic vorticity and anticyclonic circulation associated with the subtropical high to its north (Fig. 5a). The area-averaged environmental absolute vorticity shows an increase from P1 to P2 but a decrease from P2 to P3 (Fig. 6b).

The distinctive change of background vorticity during the two transition periods (P1 to P2 and P2 to P3) is well reflected in the CK term. Figure 7 shows horizontal distributions of the CK term. A positive EKE tendency occurs over most of the WNP region, regardless of the warming period (Fig. 7), which means that synoptic eddies always obtain the barotropic energy from the large-scale background mean flow. Areas with the largest energy conversion are along the WNP monsoon trough.

Compared to the CK term in P1, it was much stronger in P2. However, it appeared weakened from P2 to P3. Such an evolution feature is consistent with the background vorticity change. The result suggests that the barotropic energy conversion played a role in the SWT intensification from P1 to P2, but did not contribute to the growth of SWT from P2 to P3. It explains why the increase rate of SWT slowed down from P2 to P3 (Fig. 4), even though SST continued increasing throughout the entire analysis period (Fig. 6a).

Whereas the CK term reflects the eddy–mean flow interaction, the CA term represents a conversion from EAPE to EKE and is determined by the eddy–eddy interaction (Hsu et al., 2011). The calculation of CA term at 850 hPa shows that the amplitude of area-averaged CA over the WNP is much smaller than that of CK.

The steady increase of SST leads to continuous increase of the specific humidity in the WNP from P1 all the way to P3, as seen from the horizontal maps of the 700-hPa specific humidity field (Fig. 8). The background low-level specific humidity increases over most of the WNP region, in response to SST warming. The SST–water vapor relationship can be inferred from their similar horizontal patterns shown in Figs. 5b, c; 8b, c.

Physically, one may argue that the background specific humidity can modulate the strength of tropical disturbances through condensational heating because the major heat source for tropical perturbations is latent heat. Thus, increase of the background specific humidity can modulate the strength of tropical disturbances through a circulation–convection feedback (Li, 2006). The mid-tropospheric relative humidity is another important environmental parameter. It has been shown that the mid-tropospheric relative humidity is conducive to the growth of synoptic disturbances (Lau and Lau, 1990) and critical for tropical cyclone genesis (Emanuel and Nolan, 2004). Our calculation shows that the area-averaged back-
ground relative humidity exhibits a continuously rising trend (Fig. 9b), and the increase rate of relative humidity is even greater in the later period (i.e., from P2 to P3). Thus, both the background specific humidity and relative humidity favor the continuously increasing trend of the SWT activity.

The background ascending motion shows a large increase from P1 to P2 but a small increase from P2 to P3 (Fig. 9c). In the present-day climate, the WNP monsoon trough region is dominated by the large-scale ascending motion in the middle troposphere (Fig. 8a). A greater increase of the ascending motion from P1 to P2 was attributed to the increase of both the background low-level vorticity and SST in situ. The former induced ascending motion was through Ekman-induced boundary layer convergence. The latter was through the SST-gradient induced pressure gradient force (Lindzen and Nigam, 1987). The two effects were against each other during the later period from P2 to P3. As a result, a smaller increase of the ascending motion appeared.

The change of atmospheric static stability is considered as an important factor regulating the circulation response to global warming (e.g., He and Li, 2019). To reveal its effect on the SWT activity, we introduce an atmospheric instability index ($\gamma$), which is defined as the difference of background mean temperature between the lower (1000–850 hPa) and upper (400–200 hPa) tropospheres. Figure 10 illustrates this atmospheric instability index averaged over the region (5°–25°N, 120°–160°E) at the three warming phases. A positive change of the in-
stability parameter implies that the atmosphere becomes more unstable. It is noted that the WNP becomes more and more unstable from P1 to P3, which implies that the background static instability change might have a positive contribution to the rising trend of SWT.

The analysis above suggests that environmental dynamic parameters such as the vorticity and CK appear important in strengthening the SWT activity in the earlier period from P1 to P2, whereas environmental thermodynamic parameters such as the atmospheric instability, SST, and moisture play a more important role in strengthening the SWT activity in the latter period from P2 to P3. Following the idea of TC genesis potential index (Emanuel and Nolan, 2004), we introduce a non-dimensional synoptic activity index (SAI), which combines the environmental dynamic and thermodynamic factors together. The SAI is defined as below:

\[
\text{SAI} = \frac{\zeta + f}{\zeta_0} \times \frac{R_H}{R_{H_0}} \times \frac{\gamma}{\gamma_0} \times \frac{T_s}{T_{s_0}} \times \frac{|\omega|}{\omega_0},
\]

(2)

where \(\zeta_0 = 10^{-5} \text{ s}^{-1}\), \(R_{H_0} = 100\), \(\gamma_0 = 100 \text{ K}\), \(T_{s_0} = 100 \text{ K}\), and \(\omega_0 = 0.1 \text{ Pa s}^{-1}\) are characteristic scales of the environmental absolute vorticity, relative humidity, instability parameter, SST, and vertical velocity fields, respectively.

Figure 11 shows the calculated area-averaged SAI at P1, P2, and P3, respectively. With the combined dynamic and thermodynamic influence, SAI shows a continuous upward trend from P1 all the way to P3. A stronger increase rate occurs from P1 to P2, in a way similar to the SWT change. Thus, SAI can well explain the observed SWT trend in the past 65 years.

Relative contributions of each factor in the right hand side of Eq. (2) are further examined, following the method employed by Li et al. (2013). The result is shown in Fig. 12. Through the diagnosis of relative contributions of each term to the SAI changes, one may understand the controlling environmental factors in causing the continuous rising trends from P1 to P2 and from P2 to P3. The lower panels of Fig. 12 show the percentage contributions of each of the five terms in the right hand side of Eq. (2) from P1 to P2 and from P2 to P3. The result shows that the vertical velocity plays a dominant role for SAI increasing from P1 to P2, whereas the relative humidity and absolute vorticity also play a role. This is in
contrast to the period from P2 to P3 when the relative humidity is the most important, followed by the vertical velocity and instability parameter. Summation of the five linear terms (blue bars in upper panels of Fig. 12) is approximately equal to the actual SAI changes [i.e., the left hand side of Eq. (2)], indicating that the linearization method is proper and the residual term is negligibly small.

In the calculations above, a 9-yr time window is used to represent three warming phases (i.e., P1, P2, and P3). To examine whether or not the result is sensitive to the choice of window length, we conducted a parallel calculation with the use of an 11-yr window (i.e., P1: 1950–1960, P2: 1977–1987, and P3: 2004–2014). The SWT intensity indices using the new time window show a similar rising trend, and so is the SAI index (figures...
To sum up, the diagnosis of observational data indicates that the background dynamic fields (such as vorticity) have a great contribution to the CK and enhanced SWT activity in the WNP from P1 to P2. However, from P2 to P3, the dynamic processes inhibit the further growth of SWT. It is the thermodynamic fields (such as the increase of SST, moisture, and atmospheric instability) that are responsible for the continuous strengthening of SWT. The overall increase of SWT during the entire period is a result of the combined dynamic and thermodynamic processes, as indicated by SAI.

5. Conclusions and discussion

In this study, the change of characteristics of summertime SWT in the WNP in response to global warming since 1950 is investigated. Diagnosis of the NCEP–NCAR reanalysis data indicates that the intensity of SWT increases significantly since 1950. On the other hand, the structure and propagation characteristics of SWT have few changes during the period.

To illustrate how the SWT activity evolves with time, the entire analysis period (1950–2014) is divided into three warming phases: 1950–1958 (P1), 1978–1986 (P2), and 2006–2014 (P3), with an equal interval of 9 yr. Relative to the global mean temperature in P1, the average warming is 0.24°C in P2 and 0.68°C in P3. It is noted that SWT exhibits a greater increase rate (about 10%) from P1 to P2 than that (about 5%) from P2 to P3.

The analysis of environmental variables shows that it is combined dynamic and thermodynamic processes that are responsible for continuous strengthening of the SWT activity throughout the 65-yr study period (1950–2014). It is interesting to note that, while the increases of SST and moisture are relatively smaller from P1 to P2 than those from P2 to P3, the low-level vorticity increases in the earlier period but decreases in the later period. The diagnosis of EKE budget shows that maximum CK overlays the region where SWT is the most active, and there is marked increase of the energy conversion from P1 to P2 but decrease from P2 to P3, suggesting that it is the mean flow that provided energy for the perturbation growth in the earlier period. In the later period, the dynamic process tended to weaken the SWT activity, while thermodynamic processes involving the SST, moisture, and atmospheric instability offset the dynamic effect. As a result, a relatively weak increase rate of the SWT intensity occurred from P2 to P3.

This study represents an attempt to reveal the long-term trend of the synoptic-scale variability over the WNP monsoon region. A limitation of the current study is the use of relatively short-term data. It is desirable to use a dataset with a longer period for a trend analysis. Another limitation of the current study is the lack of a modeling...
study to support the hypothesized dynamic and thermodynamic processes. For example, one may separate the dynamic and thermodynamic mean states in idealized numerical model experiments similar to Cao et al. (2014) and Zhao and Li (2019), to reveal their relative roles. A further diagnosis of the idealized model simulations may provide insight to understand specific processes through which the mean flow influences the SWT activity.

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