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Influence of Synoptic-Scale Waves on the Interdecadal Change in Tropical Cyclone Activity Over the Western North Pacific in the Early 2010s

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Key Points:

- The interdecadal change in tropical cyclone (TC) activity exhibited a meridional tripole pattern after the early 2010s over the western North Pacific
- Over the last decade (2011–2021), frequent TC occurrences have affected East China, Korea and Japan
- During the 2011–2021 period, tropical synoptic-scale waves tended to propagate northward, which led to more northward-moving TC tracks

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract In this study, we investigated the interdecadal change in tropical cyclone (TC) activity over the western North Pacific (WNP) in the early 2010s. At the western boundary of the WNP, the interdecadal change in TC activity exhibited a meridional tripole pattern. In contrast to the reduced activity over the northern South China Sea (SCS) and Taiwan, TC activity increased over the southern SCS and to the north of Shanghai after the early 2010s. Herein, we focused on the northern WNP. Over the last decade, frequent TC occurrences have affected East China, Korea and Japan. In this work, we examined the influence of synoptic-scale waves (SSWs) on the interdecadal change in TC activity. During the 2011–2021 period, SSWs tended to propagate northward, resulting in more TC tracks affecting the northern WNP and surrounding countries. In contrast, the westward-propagating SSWs before the early 2010s were more likely to favor westward-moving TCs.

Plain Language Summary Previous studies has revealed that tropical cyclone (TC) activity increased over the southern South China Sea (SCS) and decreased over the northern SCS and Taiwan since the early 2010s. In warming climates, TC activity shows significant poleward extension. Thus, in this study, we broadened the study area to 50°N and focused on the TC activity over the northern western North Pacific (WNP), where most populous region went through increased TC occurrences in the recent decade (2011–2021). The interdecadal change in TC activity exhibited a meridional tripole pattern after the early 2010s over the WNP. Considering tropical synoptic-scale waves (SSWs) can reflect the general atmospheric inner process, this study investigated the role of SSWs in the interdecadal change in TC activity in the 2010s. During the 2011–2021 period, SSWs tended to propagate northward, resulting in more TC tracks affecting the northern WNP and surrounding countries. In contrast, the westward-propagating SSWs before the early 2010s were more likely to favor westward-moving TCs. The synoptic-scale processes can explain most of the interdecadal changes in the relative vorticity over the northern WNP, showing the critical role of the SSWs on the interdecadal change of TC activity over the WNP in the early 2010s.

1. Introduction

Tropical cyclones (TCs) are the most devastating disasters that occur in tropical and subtropical regions and can generate fierce winds, flooding and waterlogging of coastal cities, storm surge, etc. At the interdecadal timescale, TC activity has exhibited several significant shifts within the recent century, all related to the Pacific decadal oscillation (PDO) and Atlantic multidecadal oscillation (AMO) (He et al., 2015; Liu & Chan, 2013; Matsuura et al., 2003; Tu et al., 2009; Zhang et al., 2018; Zhao et al., 2018). The negative phase of the interdecadal Pacific oscillation (IPO) since the late 1990s has led to strengthened Walker circulation and suppressed TC genesis over the eastern tropical western North Pacific (WNP), leading to suppressed TC activity over the WNP after 1998 (Liu & Chan, 2013; Zhao et al., 2018). Interdecadal sea surface temperature (SST) warming in the North Atlantic intensified the vertical wind shear in the southeastern WNP, which played a dominant role in the decrease in the TC frequency after the late 1990s (Zhang et al., 2018). Zonal shifts in the monsoon trough (MT) and MT-related environmental factors can be attributed to the key atmospheric processes related to interdecadal TC activities (Chan, 2005, Hsu et al., 2014; Huangfu, Huang, Chen, 2017a, 2017b; Huangfu, Huang, Chen, Feng, & Wu, 2017).

Concurrent with the developing phase of the IPO in the early 2010s, scientists noticed that the TC activity over the southern part of the WNP experienced another interdecadal shift (Liu & Chan, 2020; Wang & Wang, 2022). Wang and Wang (2022) suggested that TCs over the WNP had entered another active period since 2010 and related this interdecadal change to the significantly increased TC genesis over the southern part (6°N–14°N, 100°E−130°E) of the South China Sea (SCS). Additionally, the number of TC landfalls in South China has increased, and the corresponding annual maximum landfall intensity has increased since the early 2010s (Liu & Chan, 2020). However, the mechanism of the change in TC activity over the northern WNP in the early 2010s remains unclear.

The background of the interdecadal variations in the TC activity in the early 2010s is profound (Cheng et al., 2022; Zhang et al., 2019). The global warming hiatus ceased in the early 2010s, and global temperatures entered a reacceleration warming period. In contrast to the typical SST anomaly distribution of the warm PDO phase, the western WNP has exhibited higher SSTs during the developing phase of the IPO since the early 2010s (Tang et al., 2020). Higher SSTs in subtropical regions have led to poleward extension of the maximum potential TC intensity and have encouraged higher-latitude TC genesis (Song & Klotzbach, 2018). Consistent with the poleward extension of the intertropical convergence zone, the linear trend of the TC track density exhibits a tripole pattern distribution over the WNP, with negative anomalies over the northern SCS and positive anomalies over the southern SCS. This pattern is especially pronounced in the northern WNP, which more notably enhances the interannual TC risk in the most populous regions than in recent decades (Studholme et al., 2021). Therefore, the interdecadal change in TC tracks over the northern WNP after the 2010s should be carefully investigated.

Tropical synoptic-scale waves (SSWs) and the boreal summer intraseasonal oscillation (BSISO) notably impact TC activity over the WNP (e.g., Yoshida et al. (2014) and Klotzbach and Oliver (2015)). The climatological means and interannual variations in the intensity of SSWs over the WNP are greater than those in the intensity of BSISOs (Huangfu, Cao, et al., 2022). SSW activity can reflect the general atmospheric inner process, including all disturbances at the synoptic time scale. Approximately 83% of TCs over the WNP are formed within active SSWs (Wu & Takahashi, 2018). According to previous studies (Zhou, Lu, & Chen, 2018; Zhou, Lu, Chen, & Wu, 2018), the leading two modes of SSWs in the WNP include the subtropical WNP (accounting for 32.3% of the total variance) and SCS branches (accounting for 18.1% of the total variance). These modes encourage northwestward (toward eastern China, Korea and Japan) and westward (toward southern China and Vietnam) shifts in TC tracks. Thus, SSWs should be regarded as the background or environment of TCs, although TCs contribute a large portion of the energy of SSWs. Moreover, the role of SSWs in the interdecadal change in TC activity in the 2010s should be investigated. Resolving this issue is beneficial for revealing the atmospheric dynamic mechanism and deepening our understanding of the interdecadal changes in TC activity over the WNP.

This paper is structured as follows: the datasets and methods are introduced in Section 2. In Section 3, we present an investigation into the interdecadal change in TC activity and SSWs over the WNP in the early 2010s, especially the northern WNP. Then, the results are summarized and described in Section 4.

2. Data Sets and Methods

2.1. Data Sets

In the present study, the following datasets are employed:

1. The International Best Track Archive for Climate Stewardship (IBTrACS; data version: v04r00) was provided by the National Oceanic and Atmospheric Administration (NOAA) (Knapp et al., 2010, 2018). TC wind speeds and central pressures from 1979 to 2021 were retrieved from the IBTrACS data set using US agency (NOAA and Joint Typhoon Warning Center (JTWC))-reported data. In the present study, we focused only on TCs at tropical storm strength (TS; wind speeds higher than 34 knots) or above.
2. The ERA5 data set was provided by the European Centre for Medium-Range Weather Forecasts (ECWMF; Hersbach et al., 2020). Daily wind, vorticity, divergence and relative humidity data from 1979 to 2021 at a 2.5-degree resolution were employed to investigate the synoptic-scale changes in environmental factors.

3. Outgoing longwave radiation (OLR) data were also provided by the NOAA (Liebmann & Smith, 1996). Daily OLR data from 1979 to 2021 at a 2.5-degree resolution were employed to reveal the synoptic-scale changes in convection over the WNP.

2.2. Methods

The TC activity investigated in the present study largely pertains to the peak TC season (July–August–September–October or JASO). To investigate the interdecadal changes in TC tracks, the WNP was divided into 2° × 2° grids to determine the TC occurrence.

In addition, the accumulated cyclone energy (ACE; Bell et al., 2000) is considered a reflection of TC energy, which can be calculated based on the sum of the squares of the maximum sustained TC wind speed passing within the aforementioned 2° × 2° grids.

Following Wu and Cao (2017), the intensity of SSWs is represented by the eddy kinetic energy (EKE) and can be calculated as follows:

$$\mathrm{EKE} = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2}\right)$$

where u and v denote the horizontal winds. The overbar denotes the JASO mean, and the prime denotes the 3- to 10-day bandpass filtered anomalies (Duchon, 1979; Kiladis et al., 2009), which represent the daily changes in SSWs.

Similarly, the 3- to 10-day bandpass filter was applied to the daily vorticity, divergence, relative humidity data obtained from the ERA5 data set and the OLR data retrieved from the NOAA for the extraction of synoptic-scale signals.

Regression was conducted of the filtered horizontal wind and OLR data to reveal the interdecadal difference in SSW propagation. We investigated the relationship between the TC activity and SSW intensity based on correlation analysis. The interdecadal warming in the early 2010s and its possible influence on SSWs and thus TC activity were analyzed via correlation analysis. All correlation and regression analyses were examined by Student's t test.

3. Results

3.1. Interdecadal Change in TC Occurrence and ACE Over the WNP

In this section, we focus on the recent interdecadal change in the early 2010s by comparing the differences between the recent decade (2011–2021) and the preceding decade (2000–2010). This division is consistent with recent studies (Liu & Chan, 2020; Wang & Wang, 2022). In addition, we expand the northern boundary of the study area to 50°N. More information on the TC occurrence to the north of 30°N is shown in Figure 1a. The dashed box in Figures 1a and 1b indicates the regions where TCs most commonly affect China. A meridional tripole pattern was observed in this region. Consistent with the aforementioned studies, the TC occurrence over the SCS has increased since the early 2010s. In contrast, the number of TCs affecting Taiwan and areas south of Shanghai has decreased. Of greater interest, the TC occurrence to the north of 30°N has significantly increased after the early 2010s. Note that the distribution of TC occurrences shown in Figure 1a resembles the linear trend of the TC track density reported in Studholme et al. (2021). Considering that the results in Studholme et al. (2021) are based on long-term data collected from 1980 to 2019, the TC occurrence over the northern WNP has more greatly increased in recent decades. Additionally, this interdecadal increase is significant over the Korean Peninsula and South Japan. Moreover, the interdecadal change in the TC ACE exhibits a similar distribution in Figure 1b. The TC ACE anomalies are greater in tropical regions than at higher latitudes. The TC ACE exhibits a significant increase after the early 2010s, resulting in an increased destructive potential in East China, Northeast China and South Japan. We confirmed the robustness of the interdecadal change in TC activity over the northern WNP (as shown in Figure S1 in Supporting Information S1). As shown in Figure S1 in Supporting Information S1, the minimum t values occurred in 2010/2011 and exceeded the 0.1 p value threshold, suggesting that the area-averaged TC occurrence and ACE over the northern WNP experienced an abrupt decadal increase in 2010/2011. Moreover, the difference in the TC occurrence between 2000–2010 and 2011–2021 is significant at

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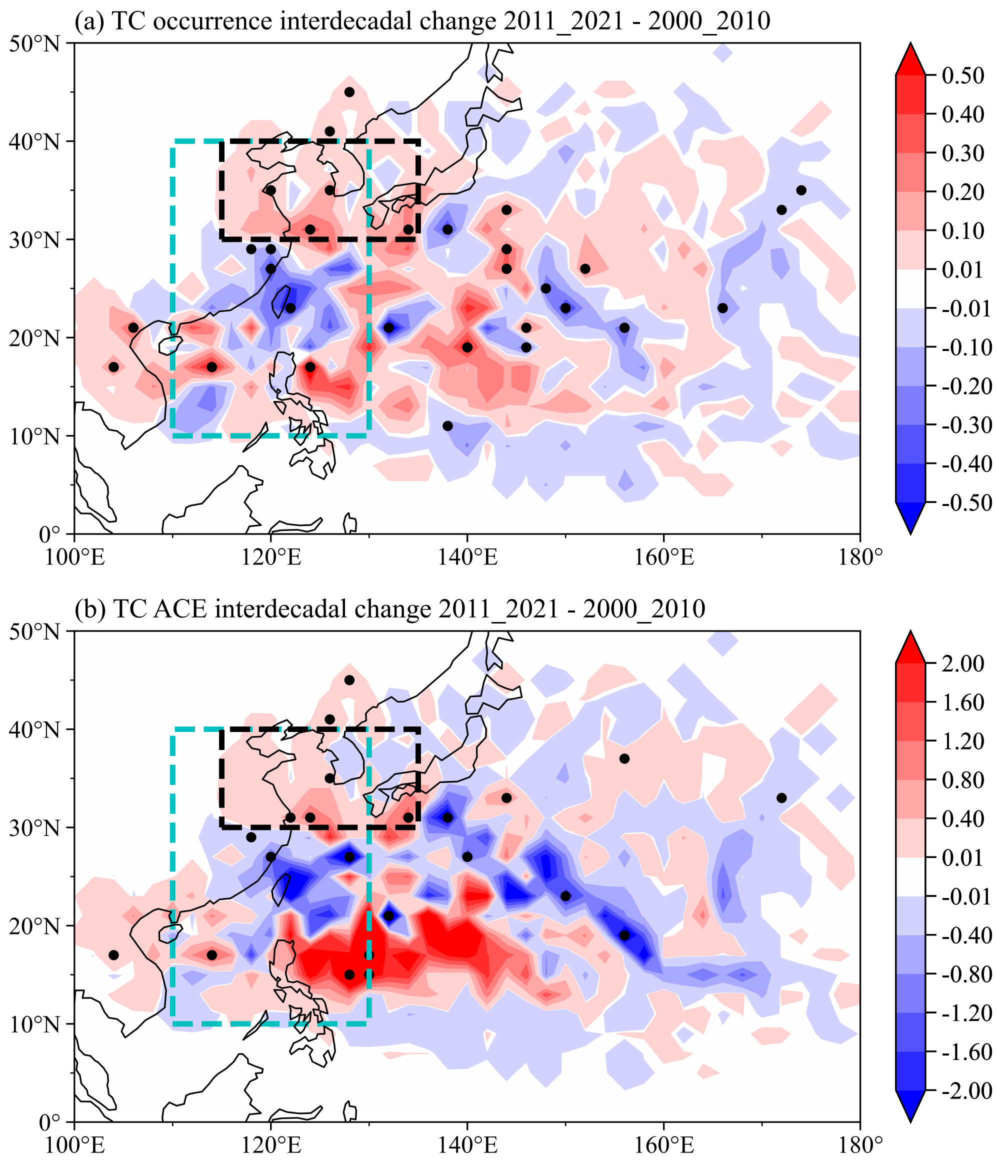

Figure 1. Interdecadal change (2011–2021 minus 2000–2010) in (a) the TC occurrence (units: monthly changes in the TC occurrence) and (b) TC ACE (units: 10^3 kt^2). The blue boxes denote the 10°N–40°N, 110°E−130°E region, and the black boxes denote the 30°N–40°N, 115°E−135°E region. The stippling denotes significance at the 90% confidence level according to Student's *t* test.

the 10% level, as is the difference in the TC ACE, based on a two-sided Student's *t* test. According to the statistical results, it is reasonable to propose that the TC activity over the northern WNP exhibited significant interdecadal changes in 2010/2011, consistent with the selection of the turning year in the present study.

3.2. Interdecadal Change in SSWs and Its Influence on the TC Activity Over the WNP

The northern WNP (30°N–40°N, 115°E−135°E; the black dashed box in Figures 1 and 2) was selected as the main focus in the present study since the TC activity in this area has increased (Figures 1a and 1b). Furthermore, we investigated the correlation between the area of the mean TC activity and the intensity (measured by the synoptic-scale EKE) of SSWs over the WNP. As shown in Figure 2a, the TC occurrence over the northern WNP is highly related to the local SSW intensity, suggesting that more TCs can be observed over the northern WNP when the intensity of local SSWs is high. Moreover, it is instructive to explain that the northwest–southeast-oriented positive correlation coefficients indicate that the enhanced SSWs over the southeastern WNP are positively

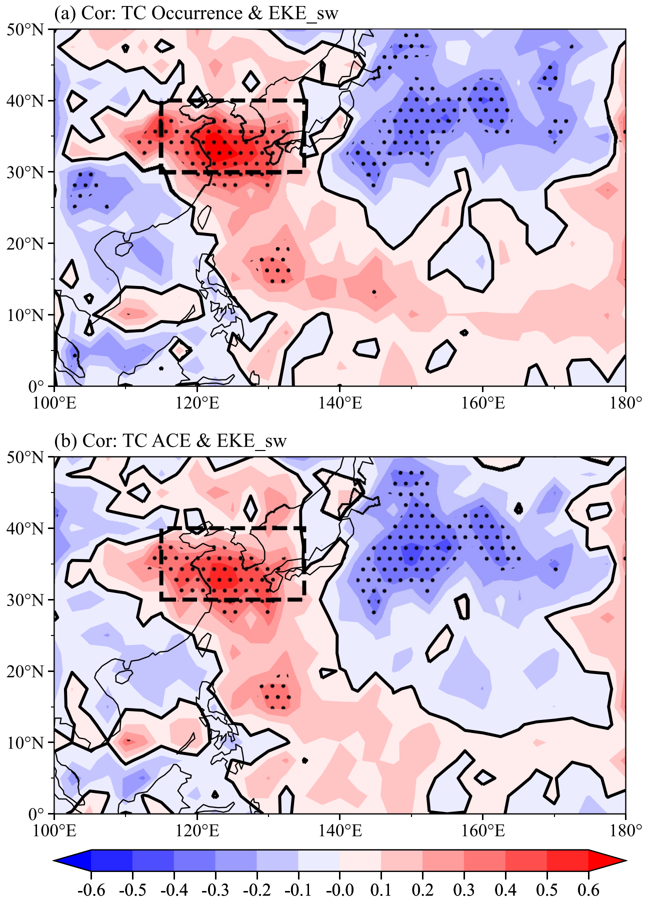

Figure 2. Correlation between the intensity of SSWs and (a) the TC occurrence and (b) TC ACE during JASO from 1979 to 2021. The stippling denotes significance at the 90% confidence level according to Student's *t* test. The black boxes denote the 30°N–40°N, 115°E−135°E region.

related to the frequent TC occurrences over the northern WNP on an interannual timescale. Considering that the southeastern quadrant of the WNP is an important SSW source region, we could infer that after the early 2010s, more TCs followed northwest tracks (Figure 1a) because more tropical SSWs propagated toward higher latitudes. In addition, the distribution of the correlation coefficients exhibits a tripole pattern at the western boundary of the WNP, which is consistent with the analysis results shown in Figure 1. Similarly, the correlation between the TC ACE and SSWs (Figure 2b) is highly consistent with that of the TC occurrence (Figure 2a).

Next, we calculated the interdecadal change in the SSW intensity (Figure 3; 2011–2021 minus 2000–2010). The distribution was similar to, but not as complex as, that shown in Figures 1a and 1b. Along the western boundary of the WNP, a clear tripole pattern could be observed. Moreover, the SSWs over the middle WNP were significantly enhanced after the early 2010s. As the key wave source, the enhancement in off-equatorial SSW events could provide more energy for northwest-moving TCs. Combined with the results shown in Figures 2a and 2b, the most influential region for TCs moving toward the northern WNP is located to the east of 130°E. The interdecadal enhancement in SSWs over off-equatorial regions favors the northwestward movement of TCs after the early 2010s. The robustness of the interdecadal change in SSWs over off-equatorial regions was also confirmed (please refer to Figure S2 in Supporting Information S1). As shown in Figure S2 in Supporting Information S1, the most significant interdecadal turning year shown in the small box is 2009 with the minimum t value. Note that the main curve at the bottom of Figure S2 in Supporting Information S1 indicates a minimum in 2010, which also passed the significance test. Thus, it is appropriate to employ 2010/2011 as the division point.

As shown in the aforementioned figures, a meridional tripole pattern could be observed to the west of 130°E. Hence, it is meaningful to investigate the direction followed by SSWs before and after the early 2010s. Additionally, as shown in Figures 2a and 2b, the correlation coefficients between the intensity of SSWs and TC occurrence (ACE) yield significantly positive values at approximately 15°N, 130°E, where a significant interdecadal change can be observed in Figure 3. Therefore, based on the daily intensity at 15°N, 130°E, we regressed the lead-lag convection (represented by OLR) and wind anomalies during the first decade (2000–2010). As shown in Figure 4a (0-day lead), SSWs could be observed to the east of the Philippines, centered at 15°N, 130°E, with the associated cyclonic wind vortex coupled with positive convection (negative OLR anomaly), which favors TC development. At a 2-day lag (Figure 4b), the SSWs shifted westward by approximately 10°, centered near Taiwan. We noted that the vortex shifted to the west of Taiwan at approximately 22°N, 117°E after a lag of 4 days (Figure 4c), which affects South China and the northern SCS. At a lag of 6 days, both the wind vortex and convection anomaly weakened and moved further westward into the northern SCS. In conclusion, the first decade (2000–2010) favored westward-moving SSWs, with the northern edge of the convection anomaly confined to the south of 30°N after a lag of 4 days.

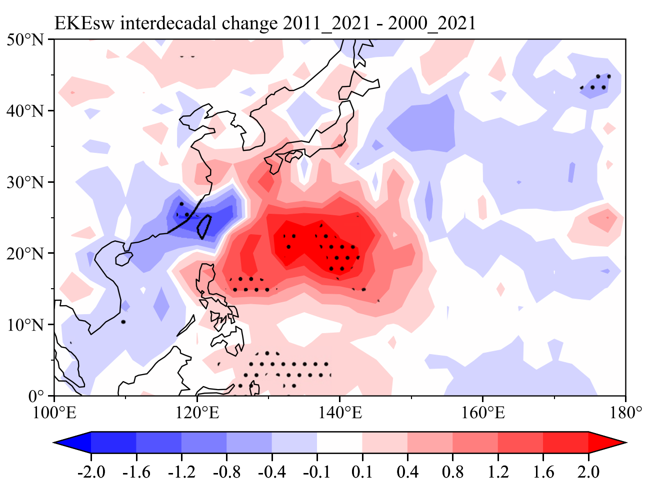

Figure 3. Interdecadal change (2011–2021 minus 2000–2010) in the intensity of SSWs (units: m^2/s^2). The stippling denotes significance at the 90% confidence level according to Student's *t* test.

In comparison, we used the same point (15°N, 130°E) to conduct a similar regression analysis over the recent decade (2011–2021). The SSWs at a 0-day lead (Figure 4e) highly resembled those in the 2000–2010 decade (Figure 4a). However, the cyclonic vortex center did not exhibit a significant zonal shift at a 2-day lag (Figure 4f), which is when the long axis of the vortex rotates anticlockwise. Moreover, the vortex shifted northward by approximately 5°. At a

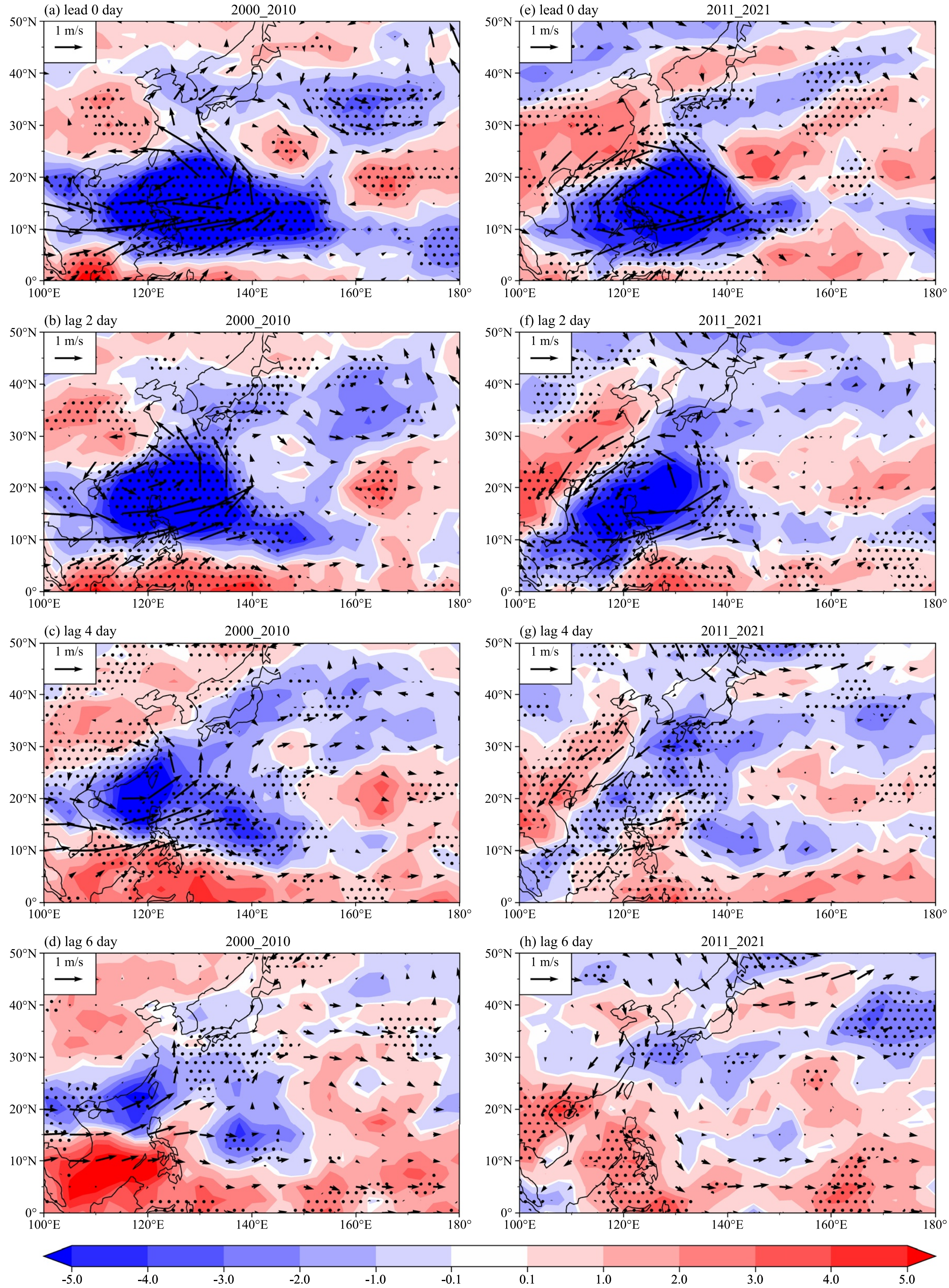

Figure 4. Anomalies of the 850-hPa horizontal wind field (vectors; units: m s^{-1}) and OLR (units: W/m^2) with lags of (a) 0, (b) 2, (c) 4, and (d) 6 days from 2000 to 2010 and (e) 0, (f) 2, (g) 4, and (h) 6 days from 2011 to 2021. The regression is based on the normalized EKE-based SSW intensity at 15°N, 130°E. The vectors and stippling denote anomalies that are significant at the 90% confidence level according to Student's *t* test.

lag of 4 days (Figure 4g), the northeast–southwest-oriented vortex moved slightly northeastward, with its northern part affecting the regions to the north of 30°N. The vortex contracted after a lag of 6 days (Figure 4h), while the convection anomaly still significantly influenced the northern WNP. The northward-moving SSWs exhibited a lower amplitude (Figures 4g and 4 h) than that of the westward-moving SSWs (Figures 4c and 4d, respectively), which is consistent with the observations. Figures 4e–4h show a notably different northward moving track from that shown in Figures 4a–4d, which indicates that northward-propagating SSWs were more notably favored in the recent decade (2011–2021) than in the preceding decade. The favorable shift in SSW tracks led to more northward-moving TCs after the early 2010s.

The interdecadal change in the relative vorticity at 850 hPa was further investigated to elucidate the modulation of SSWs on the subtropical TC activity (please refer to Figure S3 in Supporting Information S1). Figure S3a in Supporting Information S1 shows the interdecadal change in the original vorticity, in contrast to the synoptic-scale relative vorticity depicted in Figure S3b in Supporting Information S1. The greatest interdecadal vorticity anomaly could be observed to the north of 30°N over the East China Sea (Figure S3a in Supporting Information S1). Figure S3b in Supporting Information S1 shows the contribution of the synoptic-scale atmospheric inner dynamic process to the general circulation, namely, the synoptic-scale activity to the north of 30°N could explain most of the interdecadal changes in the relative vorticity over the key region, as shown in Figure S3a in Supporting Information S1. Moreover, the greater relative vorticity anomalies in the tropics observed in both Figures S3a and S3b in Supporting Information S1 reflect the eastern extension of the monsoon trough. Under these circumstances, the steering flow to the southwestern rim of the western Pacific subtropical high would favor northward-moving TCs.

4. Summary and Discussion

Scientists (e.g., Tang et al., 2020; Zhang et al., 2019) have noted climate change in the early 2010s, especially regarding the TC activity over the WNP. The interdecadal difference in the TC occurrence and ACE between two periods (2000–2010 and 2011–2021) was analyzed in this study. Note that most researchers (Li et al., 2014, 2017; Li & Zhou, 2015; Liu & Chan, 2008, 2020; Tu et al., 2009; Wang & Wang, 2022) previously focused on TC activities to the south of 30°N, exhibiting a meridional dipole pattern of the interdecadal change in TC activity in the late 1990s and early 2010s. In this study, we broadened the study area to 50°N and demonstrated that the interdecadal difference in the TC activity exhibits a meridional tripole pattern at the western boundary of the WNP. Of greater interest, however, is that we focused on TCs over the northern WNP in this study, which is the region where the most devastating TCs typically affect East China, Korea and Japan. Consistent with the TC occurrence, the TC ACE to the north of 30°N significantly increased after the early 2010s.

SSWs not only provide seeds for TC genesis but also influence the shift in TC tracks (Zhou, Lu, & Chen, 2018; Zhou, Lu, Chen, & Wu, 2018). We examined the key regions where SSWs significantly influence the TC occurrence and ACE over the northern WNP (30°N–40°N, 115°E−135°E). The results revealed that SSWs over the southeastern WNP play an important role in determining the frequency of northward-moving TCs. In general, intensified SSWs over the tropical wave source tended to favor a higher TC occurrence and enhanced TC ACE over the northern WNP. At the interdecadal timescale, SSWs over the off-equatorial middle WNP were significantly enhanced after the early 2010s, especially the key region critical to TC activity over the northern WNP. Based on the SSW intensity at the same location (15°N, 130°E), which is critical to the shift in TC tracks, we compared the different propagation characteristics of SSWs over the last two decades. Clearly, SSWs tended to travel westward from 2000 to 2010, and from 2011 to 2021, they shifted northward. The significant change in SSW propagation before and after the early 2010s led to an interdecadal increase in TC occurrence over the northern WNP.

Huangfu, Cao, et al. (2022) extended the work of Wu and Cao (2017) and compared the amplitudes of SSWs and the 10–20 days and 30–60 days intraseasonal oscillations (ISOs). The SSWs exhibited a greater climatological mean and interannual variation than those observed from the above two ISOs over the SCS and tropical WNP region. Furthermore, Huangfu, Chen, et al. (2022) revealed that frequent SSWs play a more important role than ISOs at the maintenance stage of SCSSM onset. Future work related to the present study should also include an analysis of the relative contributions between SSWs and ISOs. In this study, we followed a novel direction in understanding the interdecadal changes in TC activity over the WNP during the early 2010s, especially those concerning the northern WNP. As stated in Huangfu, Cao, et al. (2022), the intensity of SSWs over the SCS and tropical WNP region is positively correlated with the developing phase of central Pacific warming at the interannual timescale.

The relationship between the recent interdecadal SST anomalies in the early 2010s and their influence on SSWs and TC activities remains unclear. Note that Zhang et al. (2018) proposed that the Atlantic multidecadal oscillation (AMO) plays a dominant role in the interdecadal change in the TC activity after the late 1990s and suggested that the negative PDO and anthropogenic forcing fulfill only secondary roles. In contrast, according to Wang and Wang (2022), the interdecadal change in the TC frequency from 2011 to 2020 is highly related to the PDO (correlation coefficient: 0.71). Therefore, the roles of the AMO and anthropogenic forcing in determining the recent interdecadal change in TCs should be investigated. The mechanism linking patterns among interdecadal SST anomalies, changes in atmospheric circulation (including SSWs and ISOs), and TC activity response mechanisms should be further examined.

It should be noted that the meridional tripole pattern is related to the interdecadal change in the TC activity. As is commonly acknowledged, the first leading mode of the East Asian summertime circulation is referred to as the Pacific–Japan (PJ) teleconnection or East Asia/Pacific (EAP) pattern (PJ/EAP pattern), which exhibits a meridional wave train distribution and exerts an interannual influence on TC activities at the western boundary of the WNP (c.f., Choi et al., 2010). In addition, a zonally distributed dipole pattern of the correlation in the subtropical WNP can be observed in Figure 2, which agrees with the Rossby wave propagation path in the subtropical Pacific. Hence, the long-term change in the PJ/EAP wave train may be helpful to explain the meridional tripole pattern and subtropical zonal dipole pattern related to the interdecadal anomaly of the TC activity.

Data Availability Statement

The data that support the findings of this study are openly available. The IBTrACS data are freely available from the NOAA data server (https://www.ncei.noaa.gov/data/international-best-track-archive-for-climate-stewardship-ibtracs/v04r00/access/shapefile/). The ERA5 reanalysis data set is available from the ECMWF data server (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form). The OLR data can also be freely retrieved from the NOAA data server (https://downloads.psl.noaa.gov/Datasets/interp_OLR/).

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