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The influence of radiation flux in Northwest Pacific on the Western Pacific warm pools and typhoons over the past 170 years

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Abstract

Based on various statistical methods and empirical orthogonal function (EOF) analysis, this study analyzes the correlation of radiation flux of Northwest Pacific in the 100 years scale with the western Pacific warm pool and typhoon development. The key results are as follows. First, the surface downwelling longwave radiation (SDLR) received by key areas in Northwest Pacific significantly increased over the past 170 years. The surface downwelling shortwave radiation (SDSR) decreased, and TOA (Top of Atmosphere) incident shortwave radiation (TISR) slightly fluctuated and increased in the 11a (11 years) period. Second, there was the strongest correlation between the Western Pacific warm pool and SDLR, and both increased continuously. Third, since 1945, there has been a tendency of increasing after decreasing in the annual frequency and the share of severe typhoons, and the formation area distribution of typhoons has turned more even. Taking 1998 as a cut-off point, before 1998, there was no obvious correlation between the strong typhoon frequency and SDLR. However, such correction became stronger after 1998. They were affected by the changes of SDLR, SDSR, TISR, vapor, vorticity, vertical velocity, SST and $h_{100}$. Forth, the SDSR and TISR are major factors influencing the Western Pacific warm pool, typhoon motion and other varieties. While SDLR mainly increases in the tropical areas, TISR tends to fluctuate and increase slightly. Their changes are consistent with the change general characteristics of strengthening of typhoon.

1. Introduction

Radiation is an important energy source of atmosphere and ocean [1]. In the past century, many studies have reported significant changes in radiation in Northwest Pacific. According to the overall amount of solar radiation from the east, west south and north (from 1961 to 2002), Mao et al [2] discovered that the highest figure occurred in the coastal areas of Eastern Canton and Southwest Canton. By analyzing climate changes of Dawan district of Canton, Hong Kong and Macao, Wu et al [3] suggested that solar radiation was trending downward in Southern China. By introducing different physical parameterization in simulation, Choi et al [4] indicated that surface downwelling longwave radiation of the Florida peninsula would differ under different weather conditions. Budyko [5] pointed out that changes of shortwave radiation and atmospheric transparency can induce a huge effect on climate changes. Vázquez [6] also indicated the dominance of radiation changeability in changes of climate. Using CMIP5 simulation, Jia et al [7] noted the occurrence of positive changes of radiation flux in the Northern Hemisphere (roughly 10°S−50°N).

Typhoon is one of the main meteorological disasters. West Pacific is the most active area of typhoon, and Eastern Asia is often affected by typhoon from Northeast Pacific. Severe TC (STC) or super TC can cause massive destruction and severe economic losses. In the context of climate change, typhoon activities in Northwest Pacific have changed significantly. Despite the reduced typhoon quantity, the affected areas have expanded to the north, and the intensity has increased. From literature, potential damage index (PDI) can sufficiently capture the
interdecadal changes. After 1998, PDI has significantly increased [8–10]. Choun et al [11] reported that the increase of SST in Western Pacific caused warm pool and typhoon to head north under global warming. Based on EMIC an MIP6 model, Zhao et al [12] simulated the effect of Western Pacific warm pool caused by global warming. To analyze the intensity and structure of typhoons, Pan et al [13] used the WRF medium resolution model and GSI data assimilation system to construct the East Asia reanalysis system (EARS). From studying the Indo-Pacific warm pool and the correlation between summer monsoon and TC, Masson et al [14] indicated that the central regions of TC precipitation and paths of landing could differ under the conditions of subtropical high pressure, warm pool and uneven summer monsoon distribution. Ji et al [15] also confirmed the noticeable relationship between Southern Sea TC frequency and relative SST index.

Moreover, radiation, warm pool and TC can interact evidently. Cravatte et al [16] indicated strong fluctuation of warm pool scope and intensity, and high average temperature of warm pool induced the amount and intensity of TC. Using empirical formula of underlying surface shortwave radiation and wind speed, Qin et al [17] analyzed the heat events related to the Western Pacific warm pool regions and extremely high SST (with 30 °C or so), and reported that high radiation quantity and low wind speed were in favor of daytime temperature rising of seawater around the warm pool region. Tang et al [18] studied the influence of tropical cyclone formation, intensity and structure caused by diurnal radiation changes and suggested that radiation variation could alter the intensity of initial vortex and affect the double-eyewall replacement cycle.

As mentioned above, some noticeable changes to radiation, Western Pacific warm pool and TC activities have appeared in recent years. However, limited studies have explored the influential mechanism of TC activities under the changes. This paper intends to adopt various statistical methods and EOF analysis to investigate how radiation changes can strengthen TC development.

2. Data and method

2.1. Data

TC data were downloaded from IBTRACS (http://ibtracs.unca.edu/), which records the location and intensity of tropical tornado over Northwest Pacific [19]. The temporal resolution is 6 h. We obtained the information of 4193 tropical cyclones in all happening over Northwest Pacific from 1884 to 2020.

By comparing BCC-CSM, CNRM, MRI-ESM and GFDL-ESM, we confirm the relatively small error of BCC–CSM in simulating SDSR, SDLR, TISR and TOLR in the subtropical and tropical Western Pacific. Moreover, in terms of SST simulation, the data of BCC-CSM, MRI-ESM and GFDL-ESM are scored. The scoring criteria include the proportion of simulated Summer SST ≥ 29 °C in the area with typhoon generation number greater than 400 and 200; the difference between the simulated SST and Hadley Center SST results; and the impact of cold and warm current flowing through the area on SST. The scoring process indicates that BCC-CSM has the highest simulation score on SST in the study area. In addition, the SST and SDLR data of ERA5 reanalysis, NOAA observation and BCC-CSM-MR are compared by decades. It is found that the difference between them does not increase with time, which confirms the time stability of the data. Therefore, the BCC-CSM series in CMIP6 data has demonstrated climate simulation consistent with the actual situation in history, these data from 1850 (including SDLR, SDSR, TISR, SST, specific humidity and 100 hPa height data) are applied with BCC-CSM-MR_historical_r3i1p1f1 (http://cmip.bcc.cma.cn/thredds/fileServer/cmip6_data/CMIP/BCC/BCC-CSM2-MR/historical/r3i1p1f1/Amon/, all simulated by BCC). They are based on the fact that greenhouse gases, solar constants, volcano movements, ozone, aerosol are forced with history observation data. [20, 21] Then, the simulation was performed (using per month averaged data from 1850 to 2014 divided into 19 layers vertically, and a spatial resolution of 1° × 1°). The data (spatial resolution: 0.25° × 0.25°) of above element fields from 2014 to 2020 (except SST) were extracted from ERA5 reanalysis data (https://cds.climate.copernicus.eu/). Another SST field (spatial resolution: 1° × 1°) to test was gathered from the data of Met Office Hadley Center. Furthermore, we obtained the water vapor flux, relative vorticity and vertical velocity while STC occurred in 1950–2020 (spatial resolution: 0.25° × 0.25°) from the ERA5 reanalysis data [22].

2.2. Method

First, we perform statistical analysis on the averaged distribution of SDLR, SDSR, TISR, TOLR; changes of 170a; and the change in Western Pacific warm pool in the past 170 years. Then, we examine the changes of severe TC frequency on the entire Western Pacific. We analyze the influential mechanism of the TC development caused by the changes of radiation and warm pool; and calculate the correlation coefficient between occurrence frequency of severe TC, SST and relative variety and every radiation flux. Next, we obtain the EOF decomposition [23] of SDLR and TISR which have greater effect on TC. The formulas for performing the EOF analysis are:
where \( A \) is the real symmetric matrix, \( V \) is the feature vector of \( A \), \( B \) is the diagonal matrix of \( A \) which is composed of feature figures, and \( Z \) is the time coefficient matrix.

3. Analysis of radiation, warm pool and TC features in Western Pacific

3.1. Radiation flux interannual features

Using the 1850–2020 data of BCC-CSM-MR_historical_r3i1p1f1, the averaged distributions of SDLR, SDSR, TISR, TOLR in the key areas of Western Pacific were calculated. These results are depicted in figure 1.

The results show that SDSR and TOLR are the strongest in the subtropical zone, which is consistent with the stronger West Pacific subtropical high. They imply that the radiation flux is not only closely related to the East-West movement of the subtropical high, but also related to the North-South movement of the subtropical high and the area and intensity of the subtropical high. When the radiation flux is large, the development of the subtropical high is strong, especially near 30°N [24]. Nevertheless, the strongest location of SDLR is in the south, which is basically at the same location of Western Pacific warm pool. By contrast, the distribution of TISR (which represents natural variety of solar radiation), the highest figures of other radiation occur in Western Pacific warm pool and some region dominated by subtropical high. They provide the energy and circulation conditions for the formation and development of TC. In this sense, each radiation flux plays an indispensable role in the development of TC.

The area (100°–160°E, 10°–30°N) with higher average figures of four kinds of radiations is identified as the key area of radiation changes. It is used to study the changes of radiation flux of hundred years and the relation to
The changes of distance figures apart from the average of SDLR, SDSR, TISR, TOLR in the area from 1850 to 2020 are shown in Figure 2.

As displayed in Figure 2, SDLR has increased significantly over the past 170 years. Using 1980 as a cut-off point, the upward trend is very clear. Nevertheless, SDSR trended downward after 1980. This is related to greenhouse gas emissions which can block incident shortwaves so as to strengthen atmospheric inverse radiation. TISR reflects the natural changes of solar radiation intensity which are relatively steady compared to warm pool and TC.

Figure 3. The first principal component (PC1) of EOF analysis (a) of SDLR from 1850 to 2020; the PC1 vector (b); the second principal component (PC2) (c); and the PC2 vector (d).
other radiation flux. This can be observed from 11a variety period. The changes of TOLR and SDSR are the same with similar correlation coefficient of 0.7856, energy of which is positively correlated.

### 3.2. EOF analysis of radiation flux

Since SDLR is highly correlated with the distribution scale of warm pool, SDLR of the key area is decomposed using the EOF analysis. The result is shown in figure 3 (note that the SDLR in figure 3 subtracts the seasonal mean).

Figure 3 shows that the PC1 of SDLR is mainly positive, the high figure zone lies in the land, and variance devoting rates are 39.41%. Among the PC2, land and coastal areas are negative and the ocean areas are positive. The variance devoting rates of PC2 are 13.77%, the variance devoting rates of components other than PC1 and PC2 are less than 5%. While the first and second principal component vectors tend to increase, the increase of SDLR in the ocean is obvious. The SDLR on land mainly increases, but the probability of extreme continuous cloudy days or extreme dry weather also increases [25–27]. The distributions of PC1 and PC2 of SDLR come from the heating of sea surface due to longwave radiation, so that Western Pacific warm pool and TC can gain more energy to strengthen themselves.

In addition to SDLR, natural change of solar radiation also has an important effect on warm pool and TC. Thus, we also perform an EOF analysis on the TISR area. The result is presented in figure 4 (note that the TISR in figure 4 subtracts the seasonal mean).

In figure 4, the PC1 of TISR is mainly positive. Positive wave-like figures occur at low altitude, and the PC1 vector tends to rise with the 11a-to-be period. This means that TISR tends to fluctuate and increase with about 11a-to-be period at low altitude. By contrast, the PC2 of TISR is positive (negative) at high (low) altitude. The closer it gets to the polar, the greater the positive figure. Negative wave-like figures appear in the low altitude zone close to the equator. This is due to the seasonal change of the subsolar point. When the subsolar point is near the Tropic of Cancer, the energy received by the upper boundary of the atmosphere near the equator is less than that on both sides, resulting in a low value center receiving low energy on the equator. Since the data used here

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**Figure 4.** The PC1 of EOF analysis (a) of TISR from 1850 to 2020, the PC1 vector (b), the PC2 (c) and the PC2 vector (d).
are monthly data, they can reflect the change of TISR caused by seasonal variation. In general, TISR at low altitude has attenuation in some years, but it has a tendency to increase year by year. This enhances the interannual variability of typhoon activities in the tropical zone of Northwest Pacific. In the subtropical zone, changes of TISR are less noticeable, and tend to increase slightly. However, TISR has little effect on the frequency of TC activities in the subtropical zone.
3.3. Interdecadal features of the Western Pacific warm pool

In study, we define the high figure zone of SDLR distribution in the TC active season in July to September from 1850 to 2020 (i.e., 115°−155°E, 5°−20°N) as the key area of Western Pacific warm pool changes. We estimate monthly averaged SST in the region from July to September in the past 170 years in order to use it as the feature index $t$. Figure 5 describes the interannual and interdecadal changes of $t$.

Table 1. Interannual changes of ratio of severe TC in the Northwest Pacific.

| decade          | 1945–1972 | 1973–1998 | 1999–2020 |
|-----------------|-----------|-----------|-----------|
| $F_{rv}/F_{tc}$ | 0.4704    | 0.3421    | 0.4144    |

Figure 7. SST and SDLR in Northwest Pacific from July to September of 1850–2000 (/30a) and 2001–2020.
Figure 5 indicates that the SST in the key area of Western Pacific warm pool has a tendency to increase. According to the tendency after 30-point smoothing, the growth speed gets faster. Therefore, SST changes of the key area of Western Pacific warm pool can be divided into three phases based on the turning point of 30a smoothing tendency line. Before the 1920s, SST in the key area of Western Pacific warm pool demonstrated little change. After that, temperature apparently increased. In the 1970s, a small low trough appeared. Since then, SST increased at a higher speed (especially after 21th century). The prompt changes at the end of the 20th century and at the beginning of the 21st century are consistent with the rapid increase of SDLR during the period, and the ratio of severe TC to all TC increased.

3.4. Interannual characteristics of STC in the Northwest Pacific

Here we define the formation frequency of TC in the entire Northwest Pacific as \( f_{tc} \), formation frequency of STC as \( f_{vtc} \). To understand the change of severe TC in the Northwest Pacific, we calculate annual frequency of severe TC and the ratio of severe TC (with the maximum wind speed of TC \( > 41.5 \text{ m s}^{-1} \)) and other typhoons (with the maximum wind speed of TC \( < 41.5 \text{ m s}^{-1} \)) in the entire Northwest Pacific after 1945 (figure 6).

According to changes of severe TC year by year and the frequency tendency of severe TC after 7-point smoothing (see figure 5), turning points appeared at the beginning of 1970s and around 1998 (using the calculation method of annual and 7a changes). The two points are used as the cut-off points of TC activities changes to divide the formation frequency and ratio changes of severe TC in the Northwest Pacific into three phases. In the first phase, formation frequency and ratio of severe TC reached the highest figures around 1960s. In the second phase, they started to decrease in the 1970s. In the third phase, they fluctuated and trended downward. In 1998, they hit the lowest figure and increased again. Since the destructive power and influential force of typhoon are positively correlated to the formation frequency of TC and the effect of TC on Southeast coastal region is strong, these are consistent with the potential damage index (PDI) of the Northwest Pacific [10].

According to the three phases (see figure 6), we calculate the forming frequency ratio between severe TC and all typhoons in every decade (table 1). We find that the frequency affected by severe TC in the entire Northwest Pacific has been from high to low and again to high after 1945. Since the early 21th century, the ratio of severe TC has increased significantly [9] (compared to that of 1973–1998).

Overall, the increase of ratio of severe typhoon in the 21st century is related to the external force, especially in East Asia.

4. Correlation of radiation flux in the key area of Northwest Pacific with Western Pacific warm pool and severe TC

4.1. Correlation of the change feature of Western Pacific warm pool with radiation

From our calculation, correlation coefficient of \( t \) with time series SDLR, SDSR, TISR and TOLR is 0.5957, −0.1263, 0.4950 and 0.0879, respectively. Moreover, the correlation coefficient of warm pool with SDLR and TISR passed the 99% significance test. From above, the temperature change of warm pool is related to longwave radiation and natural variability of solar motion. Since SDLR is the most correlated to the warm pool, we calculate the SST and SDLR in the Northwest Pacific with every 30a (the closest is 20a) after 1850, and mark the areas of SST \( \geq 28 \degree \text{C} \) with contours (figure 7).
From 1850 to 2020, the region in Northwest Pacific with SST $\geq$ 28 °C and the region of SDLR greater than 420–430 W m$^{-2}$ showed expanding trend. The central intensity of warm pool and the highest figure zone of SDLR showed constant strengthening tendency. The speed and rate of SDLR strengthening were faster than the warm pool, and the border of warm pool scale turned to coincide with 430 W m$^{-2}$ isopleth index line from the SDLR 420W m$^{-2}$ line. In other words, with the SDLR of Western Pacific warm pool greatly strengthening in the 21st century, the warming of the Western Pacific warm pool would become more noticeable, which would provide severe typhoon with additional energy.

Warm pool and warm water are expected to enhance TC when SST $\geq$ 29.5 °C [28]. At the beginning of the 19th century and in the early 20th century, the zone of SST $\geq$ 29.5 °C was limited near the equator. Entering the

| Year and decade | 1884–1910 | 1911–1940 | 1941–1970 | 1971–2000 | 2001–2020 |
|-----------------|-----------|-----------|-----------|-----------|-----------|
| Zone            |           |           |           |           |           |
| 110°–120°E, 0°–10°N | 6 (1.28%) | 1 (0.13%) | 13 (1.10%) | 19 (1.59%) | 11 (1.84%) |
| 110°–120°E, 10°–20°N | 92 (19.57%) | 91 (12.20%) | 157 (13.31%) | 126 (10.54%) | 65 (10.85%) |
| 120°–130°E, 0°–10°N | 7 (1.49%) | 12 (1.61%) | 12 (1.02%) | 9 (0.75%) | 15 (2.50%) |
| 120°–130°E, 10°–20°N | 153 (32.55%) | 122 (16.35%) | 88 (7.46%) | 95 (7.95%) | 53 (8.85%) |
| 120°–130°E, 20°–30°N | 46 (9.79%) | 35 (4.69%) | 34 (2.88%) | 41 (3.43%) | 20 (3.34%) |
| 130°–140°E, 0°–10°N | 13 (2.77%) | 43 (5.76%) | 76 (6.44%) | 73 (6.11%) | 34 (5.68%) |
| 130°–140°E, 10°–20°N | 53 (11.28%) | 125 (16.76%) | 132 (11.19%) | 103 (8.62%) | 75 (12.52%) |
| 130°–140°E, 20°–30°N | 50 (10.64%) | 30 (4.02%) | 41 (3.47%) | 26 (2.18%) | 10 (1.67%) |
| 140°–150°E, 0°–10°N | 4 (0.85%) | 56 (7.51%) | 99 (8.39%) | 92 (7.70%) | 43 (7.18%) |
| 140°–150°E, 10°–20°N | 21 (4.47%) | 154 (20.64%) | 144 (12.20%) | 122 (10.21%) | 58 (9.68%) |
| 140°–150°E, 20°–30°N | 9 (1.91%) | 22 (2.95%) | 38 (3.22%) | 19 (1.59%) | 13 (2.17%) |
21st century, SST of 29.5 °C simultaneously appeared in the zone where the kuroshio which of warm ebb spreads to the North flows. During this time, in the zone of kuroshio and East China, ratio of forming severe TC evidently increased. [9] This is related to the increase of average SST in the zone of the kuroshio. Figure 8 presents the total area of SST ≥ 29.5 °C zone of active TC seasons in the Northwest Pacific every decade in figure 7. It can be seen that the total area of SST ≥ 29.5 °C zones has increased over decades, especially after 2000 (>8,000,000 km²).

### 4.2. Correlation analysis of radiation, typhoon and related variables

#### 4.2.1. Correlation analysis of radiation and typhoon development

According to the data of IBTRACS, we find that over time, the location of typhoon generation became more uniform in the Northwest Pacific, rather than concentrated in the area where most typhoons generated in the early stage (120°–150°E, 10°–20°N). This finding is consistent with Huo [29]. Moreover, the area of typhoon generation is expanding. Figure 9 shows the change of the percentage of typhoon generation outside the above areas over decades and the change of the area where typhoon generation would occur (taking the average TC generation per 10 years in the range of 5 °N–5 °S as the standard) with decades. We also calculate the interdecadal change distribution maps (figure 9) of locations of TC formation in the TC active seasons (July-September) (table 2).

As illustrated in figure 9, the scope of locations of TC formation basically corresponded with the brink of warm pool (figure 7) With the strengthening of warm pool and area expansion, TC formation locations enlarged more evenly.

Tropical cyclone formation rate in 140°–150°E enlarged as the warm pool expanded eastward. This kind of TC formation in the remote ocean passed over more warm waters to gain more energy to develop itself into severe TC.

We define averaged specific humidity in the scope of warm pool key area as q and the height data at 100hPa as \( h_{100} \). We calculate the correlation coefficient of these varieties and 1884–2020 TC formation frequency in the Northwest Pacific, and annual frequency of severe typhoon in 1998 with radiation flux (table 3).

As shown in table 3, SDLR and TISR were slightly negatively correlated with the TC formation frequency before 1998. This means that radiation strengthening was not the key driver of TC strengthening. However, after 1998, radiation strengthening played a pronounced role in TC strengthening, and became one of the main reasons of influencing severe TC formation frequency in the Northwest Pacific.

| Table 3. Correlation coefficients of SDLR, SDSR, TISR and TOLR with the Western Pacific warm pool and TC correlation element field. |
|-----------------|--------|--------|--------|--------|
| SDLR            | SDSR   | TISR   | TOLR   |
| \( f_{ec}(1884–2020) \) | 0.2501 | 0.114 | 0.4415 | 0.2237 |
| \( f_{ec}(1945–1998) \) | −0.203 | −0.0461 | −0.1784 | −0.1258 |
| \( f_{ec}(1999–2020) \) | 0.3473 | −0.0703 | −0.0212 | 0.0995 |
| q               | 0.698 | −0.3592 | 0.3493 | −0.0987 |
| \( H_{100} \)   | 0.7122 | −0.338 | 0.6293 | −0.0163 |

* Presents passing 80% the two-sided test level of significance.

b 90%.

c 95%.
Table 4. The correlation coefficients of the time series in the specific zones of water vapor flux integral, relative vorticity and vertical speed with radiation flux.

| Relative coefficient | SDLR  | SDSR  | TISR  | TOLR |
|----------------------|-------|-------|-------|-------|
| 145°−160°E, 15°−25°N water vapor flux integral | 0.1613° | −0.2066b | 0.0942 | −0.1098 |
| 110°−140°E, 10°−20°N relative vorticity | 0.0976 | −0.0367 | 0.2162c | −0.0335 |
| 110°−130°E, 20°N vertical speed | −0.556e | 0.2108b | −0.7207c | −0.0974 |

° Represents passing the two-sided test of significance.

b 90%.
c 95%.

Different from severe TC, during 1884−2020, SDLR and TISR were both positively correlated to the formation frequency of TC of the entire Northwest Pacific. This means that SDLR and TISR always have positive devotion to TC in the Northwest Pacific region. The continuous expansion of SDLR TISR could strengthen the activity of TC in the Northwest Pacific zone. Whilst SDLR and TISR are positively correlated to water vapor q and h_{100}, SDSR is negatively correlated with these variables. With the strengthening of longwave radiation, additional energy absorption at the sea surface leads to higher SST. The increase of aerosols causes the condensation nucleus to increase and water vapor content q to rise. The higher SST and q allow the TC to gain more energy and enhance the upward convergence [30]. Accompanying the strengthening of warm high pressure caused by additional radiation energy, h_{100} tends to increase, which is in favor of divergence of upper atmosphere and convergence of lower atmosphere to provide convective condition for TC development. In the Western Pacific margin, subtropical high pressure and warm pool strengthening are in favor of TC developing and landing, especially in the eastern China (where severe TC quantity or severe TC ratio tends to increase). Different radiations influence TC activity and development in this way.

4.2.2. Mechanism analysis of radiation and STC

We analyze the water vapor flux integral (1000−100 hPa), vorticity and wind field (850 hPa), and the vertical wind shears of 200 hPa and 850 hPa in the Western Pacific region when the typhoon with the maximum wind speed ≥ 1.2 times (124.5 kts) of the average wind speed (103.8 kts) during severe typhoon activity in the Northwest Pacific since 1950. We also examine the circulation background to severe typhoon and its relationship with radiation (figure 10).

When a TC occurs (see figure 10), synthesis field of water vapor flux integral shows transportation of plenty of water vapor over the marine continent and Northwest Pacific, especially in zone of 145°−160°E, 15°−25°N. This supplies adequate water vapor and energy for STC and super TC. Anticyclone circulation fields and large negative vorticity zones exist at 850 hPa in the Southeast Japan of Northwest Pacific. There are obvious cyclonic circulation fields and large positive relative vorticity regions in the South China Sea and the Northwest Pacific east of the Philippines (mainly distributed in 110°E−140°E, 10°−20°N). In 20°N of 110°−130°E, the vertical wind shear is small and the vertical velocity is quite large (marked in figure 10). Within this zone of 110°−130°E, 20°N, the vertical velocity is the highest at 850 hPa−200 hPa around 124.5°−127.5°E. These zones (marked with red frame in figure 10) are conductive to the upward convergence of water vapor and energy so as to enhance the strength of TC. We calculate the time series in the marked zones of water vapor flux integral, relative vorticity, and vertical velocity. Then, we quantify the correlation coefficients with SDLR, SDSR, TISR and TOLR. The result is shown in table 4.

As demonstrated above, water vapor flux is mainly correlated to longwave or shortwave radiation, noticeably positively correlated to longwave. Shortwave increases with decreasing water vapor and increasing cloud. Hence, water vapor flux is evidently negatively correlated to shortwave radiation. A variety of relative vorticity is mainly correlated to natural change ratio of solar activity; upward ascending movement is highly correlated to SDLR, TISR; SDSR tends to be related to descending movement.

5. Conclusion

In summary, the main findings of this study are:

1. The SDLR has been rising since 1850, and this upward trend became more pronounced after 1980. The SDSR trended downward after 1980. The TISR has change of 11 a period. In addition to TISR, other high figure zones of radiation flux appeared in the region where Western Pacific subtropical high and Western Pacific warm pool control. The PC1 and PC2 of the EOF analysis of SDLR and TISR are consistent with the above change.
2. From 1850 onward, the Western Pacific warm pool has expanded with significant increase in intensity. From 1945 to 2020, severe TC formation frequency over the Western Pacific first dropped and then increased. The TC formation place distribution scope basically followed the scope of Western Pacific warm pool in the active seasons (July-September). The zone of TC formation became more uniform, and the number of typhoons from the far ocean increased significantly, which strengthened the typhoon activities.

3. Radiation variety can influence the intensity and scope of Western Pacific warm pool, among which SDLR is the strongest correlated to the key area of Western Pacific warm pool, both of which tend to fluctuate and increase in favor of severe TC. The SDLR, SDSR, TISR with SST, specific humidity, 100 hPa height field and water vapor flux in the target distribution during the period of severe TC activity, relative vorticity, vertical velocity and physical quantity so on, play a remarkably important role in the development of TC. Besides, changes of radiation flux indirectly lead to the development and strengthening of TC through the effect of above mentioned variety.

Whilst this study offered some explanation on the effects of SDLR, SDSR, TISR and TOLR on the Western Pacific warm pool and TC strengthening, their changes and other radiation flux also play different roles in the changing process in other systems of Western Pacific and climate change. These require further investigations. Moreover, it would be interesting to explore how to define Western Pacific warm pool, subtropical high, intensity of radiation flux and intensity of TC activity so as to conduct a study on the interactions between these element fields.

Data availability statement

The data that support the findings of this study will be openly available following an embargo at the following URL/DOI: https://doi.org/10.5061/dryad.xksn02vhk.

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