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A Study on Tropical Cyclone Genesis Characteristics in the Northwest Pacific Based on Multidimensional Analysis Using EWM and TOPSIS Methods

Yaokang Xu *, #, Yichun Wei #, Shiyu Wu #

School of Science, Shanghai Maritime University, Shanghai, China, 201306

* Corresponding author: 202211010058@stu.shmtu.edu.cn

#These authors contributed equally.

Abstract. Against the backdrop of global climate change and data inflation, exploring new technologies to handle the growing amount of meteorological data effectively is crucial to enhancing global disaster prevention and mitigation capabilities and advancing climate research. This study investigates seasonal and regional variations in tropical cyclone (TC) genesis in the Northwest Pacific, using a multidimensional analysis of TCs from 2022 and 2023. Using the entropy weight method (EWM) and TOPSIS method combined with five essential environmental and storm predictors, this study quantitatively assesses the potential of TC generation, i.e., the Tropical Cyclone Emergence Index (TCEI), in different regions of the northwestern Pacific Ocean. The results, such as 0.7750 and 0.4624 for other areas in May 2023, show that TC generation peaks in summer and weakens significantly in winter. It is also found that the TC emergence indices of different regions in the same month vary significantly, which indicates that the climatic conditions for TC generation are more complicated and diversified. The findings of this study not only provide a reference for improving the regional meteorological disaster warning capability and lay a foundation for further understanding the impact of climate change on TCs.

Keywords: Tropical Cyclone; EWM; TOPSIS; Emergence Index; Multidimensional Analysis.

1. Introduction

Global climate change has made the frequency and intensity of TCs a central topic in climate research, particularly concerning their impacts on coastal areas. TCs, especially in the Northwest Pacific region, not only pose a great threat to the economic development and social stability of coastal cities but also in the context of frequent occurrence of extreme weather events, which poses a new challenge to climate prediction models and disaster preparedness. Therefore, an in-depth study of the generation, development, and evolution of TCs in the Northwest Pacific is of crucial importance for improving the early warning capability of meteorological disasters around the world, especially in China, formulating strategies for disaster prevention and mitigation, and promoting the study of global climate change.

In recent years, with the advancement of observation technology and data analysis methods, big data technology has been widely applied to the study of TC characterization and generation. With the maturity of big data technology, EWM has significant value in objectively quantifying the relative importance of different factors. Previous research has extensively studied TC activity in this region. For instance, Jia et al. and Lu et al. identified key factors influencing TC intensity [1-2]. Meanwhile, along with the development of meteorological monitoring technology, people can obtain richer and more accurate values of meteorological indexes, which makes it complicated to investigate meteorological changes from physical processes. The TOPSIS method becomes an effective and simplified way to carry out objective evaluation from a purely mathematical point of view, which is especially suitable for multi-indicator evaluation [3]. Pan et al. use the TOPSIS method to calculate the weight of the indicators of the three aspects of the TC to obtain the comprehensive TC disaster risk index [4]; Mengyang Yang utilized the TOPSIS method to comprehensively evaluate the vulnerability and adaptability of TC disasters in 21 districts in Guangdong Province, and proposed strategies and approaches to improve the resilience of TC disasters based on the evaluation results[5]. Further, Chao et al used the EWM-based TOPSIS evaluation model to assess the TC hazard vulnerability level of urban and rural areas in nine cities in Fujian Province and realized the premium determination accordingly [6]; Sheng Liu used the game theory empowerment method combined with the TOPSIS method to quantify 20 key factors to determine the slope stability class [7].

In this work, this study first analyzes a multidimensional comparison of the generation and development patterns of TCs in 2022 and 2023. Subsequently, based on the basic theories and conditions of TC generation, the five influencing factors of the NWP TC emergence index are analyzed, and the importance of each indicator is quantified using the EWM. Finally, the month-by-month NW Pacific TC emergence index for 2023 is proposed to be obtained by the TOPSIS method based on the past indicator data.

2. Cyclone Characteristics in 2022 and 2023

The research data in this part are obtained from the TC Optimal Path Dataset of the TC Data Center of the China Meteorological Administration (CMA) https://tcdata.typhoon.org.cn/index.html. This part will describe and compare the characteristics of the TC generation and evolution of 2022 and 2023 in terms of the time scale, spatial distribution, and intensity performance, respectively.

2.1. Spatial distribution

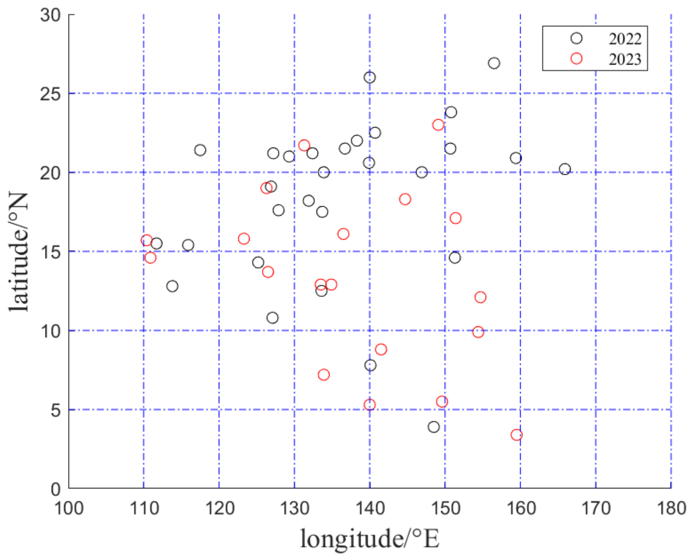

Figure 1. Distribution of TC Genesis Points in the Northwest Pacific (2022-2023)

Statistically, a total of 29 TCs were generated in the northwestern Pacific Ocean in 2022 and 20 in 2023. By calculating the arithmetic average of latitude and longitude of all the initial observation points of TCs, the average generation position of TCs in 2022 is (136.33°E, 18.30°N), and that of 2023 is (137.49°E, 13.32°N), and the results show that the average generation position of TCs in 2023 is shifted to the south. However, according to the literature, the average generation position of TCs in the NW Pacific has shown a northward trend in recent decades [8], and the anomaly of the average generation position of TCs in 2023 contradicts the long-term trend, and this result highlights the importance of further research on the generation of TCs in 2023.

Figure 1 shows that the TC generation location in 2023 is significantly more dispersed in the western side of the NW Pacific compared to that in 2022, which is concentrated in (15°N -25°N, 120°E -160°E). It has been shown that the TCs in the NW Pacific show a significant westward shift in several indicators between 1982 and 2020 [9]. This trend is consistent with the results of Fig. 1 in this study, which further suggests that environmental conditions regulate the location of TC generation.

Further counting the average total length of TCs in the two years, the average total length of TCs in 2022 is 3125.23km, and the average total length of TCs in 2023 is 3733.99km, which shows that there is a significant increase in the length of TCs in 2023 compared with that in 2022.

Meanwhile, the number of TCs reaching the 48-hour warning line in 2022 is 19, and the number of TCs further reaching the 24-hour warning line is 14; the number of TCs reaching the 48-hour warning line in 2023 is 13, and the number of TCs further reaching the 24-hour warning line is 9. Through the ratio of the number of TCs reaching the warning line to the total number of TCs generated in a year, the number of TCs reaching the 48-hour warning line in 2022 accounts for about 65.51%, and the number of TCs reaching the 24-hour warning line accounts for about 48.28%; in 2023, the number of TCs reaching the 48-hour warning line accounts for about 65.00%, and the number of TCs reaching the 24-hour warning line accounts for about 45.00%. 45.00%. It can be seen that, although the total number of TCs generated in 2023 is significantly lower than that in 2022, the proportion of TCs reaching the 24-hour and 48-hour watch is relatively stable in these two years.

In 2022, the number of TCs directly generated within the 24-hour warning line is 4, accounting for about 13.79% of the total number of TCs generated in that year; in 2023, the number of TCs directly generated within the 24-hour warning line is 2, accounting for about 10.00% of the generation ratio in that year. From the results, it can be seen that the number of directly generated TCs within the 24-hour warning line in 2023 is slightly lower than that in 2022, but the difference is not significant.

In addition, it was statistically found that six TCs made landfall in China in both 2022 and 2023, which suggests that each TC making landfall in China in 2023 has a greater potential impact in terms of economic losses and land damage [10].

From the above analysis, it can be seen that although the total number of TCs generated in 2023 is less than that of 2022, the TCs in 2023 will move over long distances and have a random distribution, thus posing a great potential threat to the economy and humanities.

2.2. Time scale

The number of TCs generated in each month of 2022 and 2023 is counted, as shown in Fig. 2.

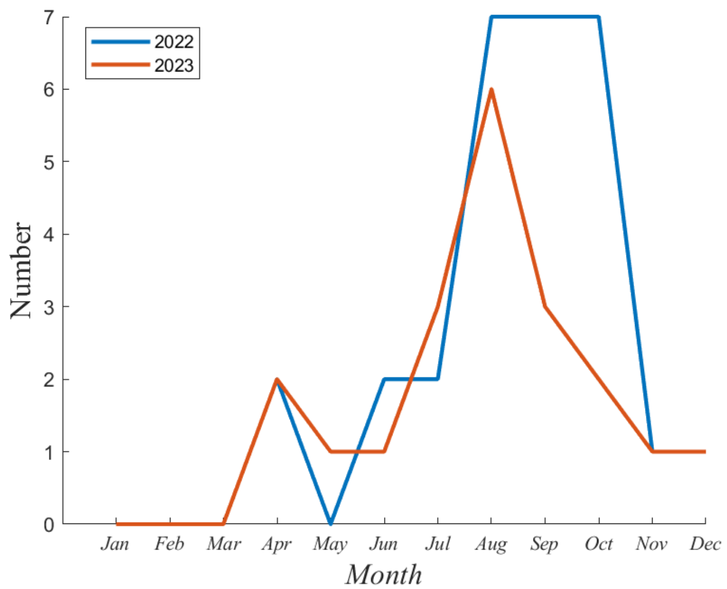

Figure 2. Monthly TC generation in 2022 and 2023

Figure 2 shows that the monthly trends in the generation of TCs in 2022 and 2023 are roughly similar, with more TCs forming in July, August, and September.

In addition, this study found that the average generation time of TCs in 2022 was about 136.24 hours, and in 2023 it was about 206.85 hours. This shows that the average duration of TCs in 2023 was longer.

Overall, the trend of TC generation in 2022 and 2023 remained stable in terms of time, but the duration of TCs in 2023 was longer, resulting in a higher risk of greater economic losses.

2.3. Strength performance

According to the CMA classification of TC intensity levels, there were 12 TCs with an intensity of "typhoon", 7 "strong typhoons" and 4 "super typhoons" in 2022; in 2023, there were 11 TCs with an intensity of "typhoon", 10 "strong typhoons" and 8 "super typhoons". It is not difficult to see that the intensity of TCs in 2023 is greater.

At the same time, it was found that the shortest time interval between the formation of "super typhoons" Nanmadol (NO.2214) and Noru NO. (2216) in 2022 was 7 days and 18 hours; in 2023, the shortest time interval between the formation of DOKSURI (NO.2305) and KANUN (NO.2306) will be generated in 5 days and 18 hours, which is more concentrated in the time distribution of TCs in 2023.

In summary, the three-dimensional analysis and comparison show that TCs in 2023 will show a significant increase in strength compared to the previous year, an increase in total length and period, and a shorter and more rapid generation time. In other words, TCs in 2023 have a greater potential to cause deeper economic and human losses in China.

2.4. Determination of the study area

Based on the statistics of the initial observation points of TCs in the North-West Pacific from 1949 to 2023, the study area shown in Figure 3 is determined here to simplify this study.

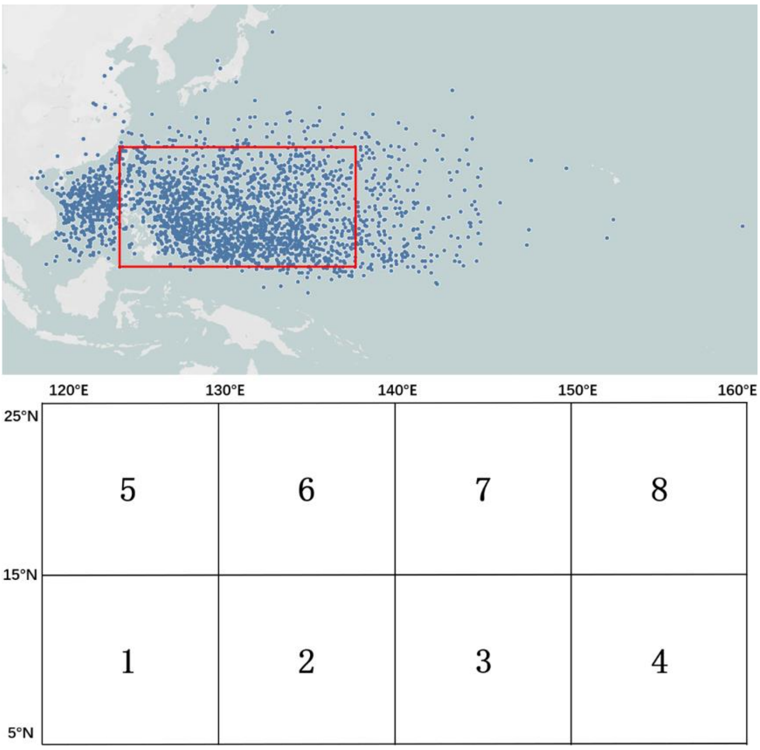

Figure 3. Initial observation points of TCs in the North-Western Pacific from 1949 to 2023 Map source from Tableau

As shown in Figure 3, the study area for this project is (5°N -25°N, 120°E -160°E). To further simplify the data and calculation process, the study area is further divided into eight study areas.

3. Quantifying Cyclone Formation Conditions

3.1. Analysis of the theory of TC formation

Gray (1968, 1975, 1979) studied the formation and occurrence conditions of TCs and found that specific climatic factors play a key role in the formation of TCs [11]. At the same time, a study used fuzzy c-means clustering to cluster historical TC path data and found that several common climatic factors had a significant impact on the genesis of different types of TCs [12]. This finding provides strong support for further research on the genesis mechanism of TCs under comprehensive environmental conditions.

1) TCs usually form from tropical disturbances. Tropical disturbances are formed by the coupling and integration of convective cumulus clouds and vortices over tropical ocean surfaces [13]. Although only a small proportion of tropical disturbances develop into TCs, tropical disturbances are still an important source of TCs.

2) The lower and middle troposphere is rich in water vapor and humidity. The main energy source of TCs is the release of latent heat, which depends on the abundance of water vapor, and atmospheric humidity is an important factor.

3) The potential instability of the upper layer of the atmosphere is strong. Only a strong potential instability can promote convection and updrafts within the disturbance, bringing moist air upwards, condensing, and releasing latent heat, providing energy.

4) The energy of TCs mainly comes from the warm ocean. Studies have shown that higher sea surface temperatures can promote the coupling of low-level TCs and high-level anticyclonic circulation, thereby strengthening the link between the frequency of TC formation and SST [14].

5) Weak vertical wind shear is the key to the formation of a warm core in a TC. A warm core is a sign that the TC is forming and gaining energy. Strong wind shear can cause strong ventilation effects, which diffuse latent heat and prevent the formation of a warm core. TCs usually form in an environment with a vertical shear of less than 6 m/s.

6) About 91% of TCs in the northwestern Pacific Ocean originate from the ocean surface at 5° to 22°N. 80% of their initial embryos come from the equatorial convergence zone or monsoon trough, and 10% come from fluctuations in the deep easterly belt.

A TC is the product of the interaction of several conditions. These conditions can therefore be used to diagnose whether a tropical disturbance will develop into a TC.

After the above analysis, this study uses the following five indicators to construct the Northwest Pacific TC germination index: sea surface temperature (SST), vertical rate of decrease in atmospheric temperature (ATLR), atmospheric Vertical Rate of Decrease of Atmospheric Relative Humidity (AHVR), Vertical Wind Shear (VWS), and Equatorial and Peripheral Atmospheric Circulation (EPAC).

3.2. Calculation based on EWM indicator weights

The data for this section comes from the Fifth Generation of the European Center for Medium-Range Weather Forecasts Reanalysis (ERA5) https://cds.climate.copernicus.eu/.

First, the VWS, ATLR, and AHVR mentioned in the previous section are given by the following formulas:

$$VWS = \sqrt{(V_{850} - V_{200})^2 + (U_{850} - U_{200})^2} \tag{1}$$

Here, $U_{850}\,V_{850}$ use the U-shaped and V-shaped variables of the $850hPa$ wind, andU_{200} and V_{200}

correspond to $200hPa$, both m/s .

$$ATLR = \frac{\Delta AT}{\Delta H} \times 100\% \quad (2)$$

The height difference betwee $850hPa$ $500hPa$ n kilometers are given by ΔH ; The atmospheric temperature difference at these heights is denoted as ΔAT (K).

$$AHVR = \frac{\Delta ARH}{\Delta H} \times 100\% \quad (3)$$

The height difference between $850hPa$ and $700hPa$ in kilometers is given by ΔH; The relative atmospheric humidity difference at these heights is denoted as ΔARH (K).

For the quantification of EPAC, since there is currently no clear indicator, this study will consider it as two parts: the equatorial convergence zone and the equatorial peripheral air pressure zone and wind zone. First, let's look at the equatorial convergence zone, which is a convergence zone formed by the southerly airflow south of the subtropical high. Its position moves north and south with the seasons, averaging about 5°S in January and 12° to 15°N in July, with a maximum difference of 35° in latitude. This study determines that the region between 0° and 15°N is affected by the equatorial convergence zone from June to February of the following year, and is assigned a value of 0.5. In other months, the equatorial convergence zone moves southward and has no effect, so it is assigned a value of 0.

Next, the atmospheric circulation around the equator is analyzed. The subtropical high-pressure belt (subtropical high) and the tropical monsoon belt affect the study area near the equator, which generally moves north in summer and south in winter. The subtropical high moves northward from 5° to 15°N in March and April as the temperature rises, and then moves northward from 15° to 20°N in May, 20° to 25°N in June, 25° to 30°N in July, and 30° to 35°N in August. 5°N, in August it retreats southward and its intensity decreases sharply, so the value assigned to the subtropical high is 0.25; the tropical monsoon belt moves northward from 5°~10°N in January and February, to 10°~15°N in March and April, to 15°~20°N, and then southward in September and October, back to 15°~20°N in November and December, and back to 5°~10°N in January and February, assigning a value of 0.25 to the tropical monsoon belt region.

Then, the information entropy was calculated based on the data from 2000 to 2022 to quantify the influence of the above five indicators on the development of TCs in the northwestern Pacific. The results are shown in Figure 4.

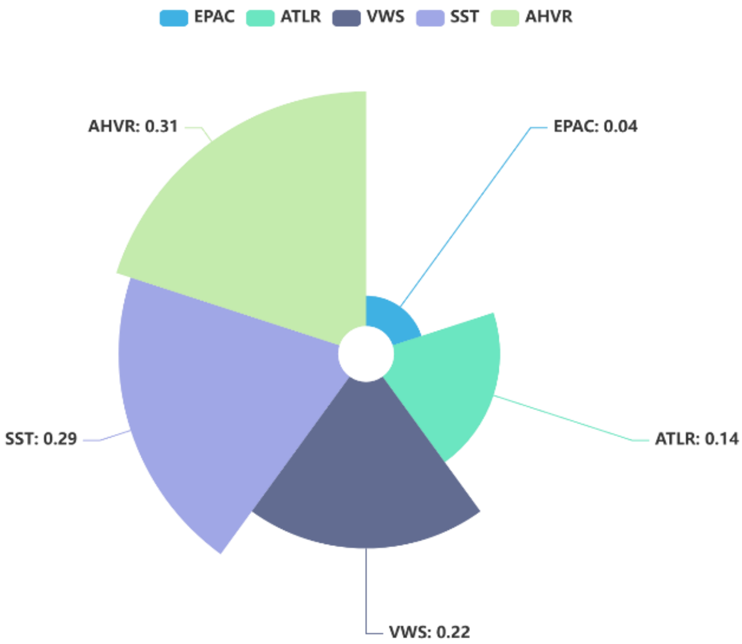

Figure 4. Weighted rose diagram of the TC germination index

Figure 4 shows that the weights of the five indicators AHVR, SST, VWS, ATLR, and EPAC decrease in order.

Combined with theoretical analysis, a tropical disturbance needs to have a moist and unstable vertical atmosphere, and satisfy the sea surface temperature above 26℃ and weak vertical wind shear. AHVR and ATVR can fully reflect the water vapor distribution and stability of the vertical atmosphere, while the equatorial and surrounding atmospheric circulation, although conducive to the upward movement of the lower air, thus promoting the formation of the initial disturbance, its more significant impact on TCs is reflected in its movement path, so its impact on the genesis of TCs is relatively small.

These five indicators are all directly related to the genesis of TCs, but looking at each indicator individually is not enough to determine whether the system can develop into a TC. Therefore, a comprehensive evaluation model is needed for further comprehensive consideration.

4. Evaluation of Tropical Cyclone Genesis Index

After predicting the data for each indicator in 2023, this study selected the TOPSIS method to comprehensively evaluate the TC germination index of the eight sub-regions studied.

Before applying the TOPSIS method, it is necessary to select positive (negative) alternatives to calculate their distance from the positive (negative) ideal solution c_j^* (c_j^0).

$$s_i^* = \sqrt{\sum_{j=1}^{n}(c_{ij} - c_j^*)^2}, i = 1, 2, ..., m \tag{4}$$

$$s_i^0 = \sqrt{\sum_{j=1}^{n}(c_{ij} - c_j^0)^2}, i = 1, 2, ..., m \tag{5}$$

$$f_i^* = s_i^0/(s_i^0 + s_i^*), i = 1, 2, ..., m \tag{6}$$

Based on the theoretical analysis above, SST, ATLR, and EPAC are favorable for TC development and are positive indicators. AHVR and VWS are negative indicators.

The results are visually displayed in line Figure 5.

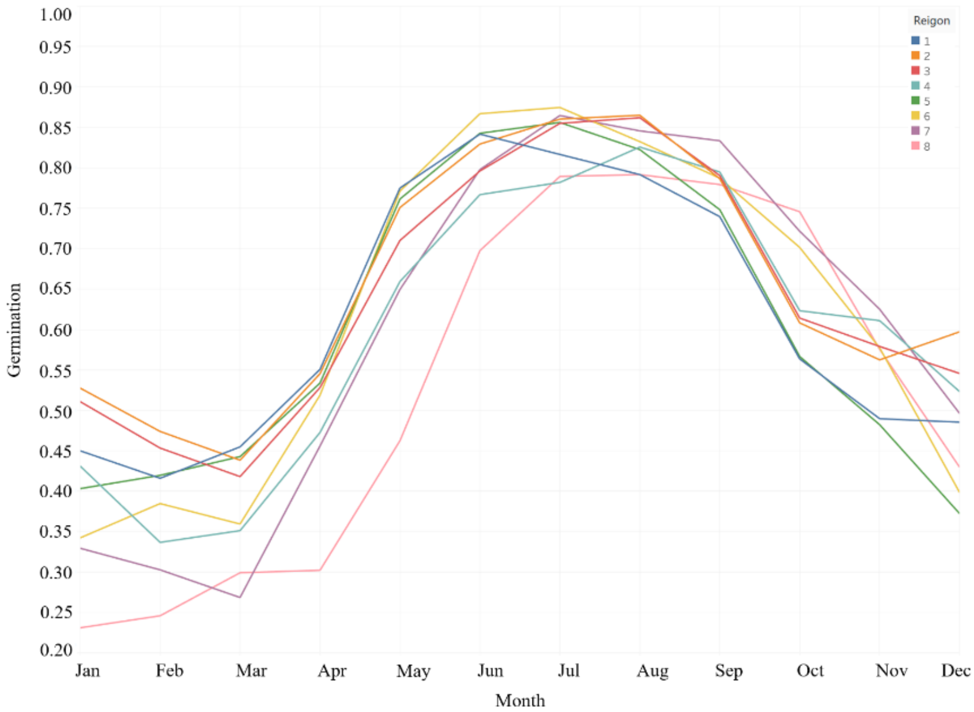

Figure 5. 2023 Monthly TC Emergence Index

From the overall trend, the TC development index in each region increased significantly in the summer (June to August), indicating that this period is a concentrated stage of TC activity. In addition, the maximum value of 0.7750 for Region 1 was reached in May, indicating that this region already had a high level of TC activity before the summer. In contrast, the maximum value of 0.4624 for Region 8 was reached in December, indicating that this region had a low level of TC activity before the winter. Overall, the maximum value of the TC activity index was reached in the summer, while it decreased significantly in the winter. This seasonal variation reflects the important role of climate conditions in the different seasons in the formation of TCs.

Further analysis of the performance of different regions in the same month by the control variable method shows that there are still significant differences in the germination index of different regions even in the same season. For example, in May, the germination index of Region 1 was 0.7750, while the index of Region 8 during the same period was only 0.4624, indicating that in addition to seasonal factors, regional climatic conditions may also play an important role in the formation of TCs.

Combining the existing research results, it can be seen that these seasonal and regional differences are closely related to a variety of climatic factors. For example, the diversity of the Pacific-Japan (PJ) mode and its control over TC activity in the western North Pacific has been confirmed [15]. The diversity of the PJ mode means that different environmental conditions can lead to significant differences in the number of TCs generated, which explains why the differences in the TC genesis index in different regions in this study are partly because some regions are favored by favorable PJ modes in the summer, resulting in more frequent TCs, while other regions may be reduced due to unfavorable PJ modes.

In addition, the differences in ocean-atmosphere interaction in different regions should not be ignored. Studies have shown that this interaction significantly affects the formation of TCs by changing SST and atmospheric humidity [16]. The difference in sea-air flux in different regions, especially during the seasonal transition, leads to significant fluctuations in the TC initiation index.

At the same time, studies have shown that El Niño and the warm phase of the North Pacific Mode (NPM) significantly affect the frequency of TC formation in the fall of 2023 by changing the atmospheric circulation pattern [17]. For example, the significant difference between Region 1

(0.5635) and Region 8 (0.7456) in October in this study may be partly due to the combined effects of the El Niño event and the warm phase of the NPM.

In summary, this study reveals significant seasonal and regional differences in the genesis of TCs by analyzing the TC genesis index. Combined with the existing literature, this study further analyzes some of the possible climatic mechanisms behind this difference.

5. Conclusion

This study analyzes the characteristics of TCs in the western North Pacific in 2022 and 2023 from multiple dimensions, and the following conclusions are drawn: in terms of spatial distribution, the average location of TCs in 2023 is shifted southeastward compared to 2022, and the distribution is more dispersed. The average total length has increased, and the proportion of TCs reaching the 24-hour and 48-hour warning lines is relatively stable. In terms of time scale, the trend of TC generation in each month of 2022 and 2023 is roughly the same, with more TCs generated in July, August, and September, and the average duration of TCs in 2023 is longer. In terms of intensity, the overall intensity of TCs in 2023 is greater, and they are generated in a shorter period. In addition, the research area is clearly defined (5°N -25°N, 120°E -160°E), and it is further divided into eight sub-research areas. Through the analysis of TC genesis theory, five indicators of the Northwest Pacific TC genesis index were constructed, and the weights of the indicators AHVR, SST, VWS, ATLR, and EPAC were calculated based on EWM, which were 0.31, 0.29, 0.22, 0.14, and 0.04, respectively. Finally, this study used the TOPSIS method to calculate the monthly TC genesis index for 2023. month TC germination index, such as the July regional 6 TC germination index of 0.8746 and the August regional 2 TC germination index of 0.8650. The trend of the germination index in each region is roughly first to rise, reaching a peak in July or August, and then to decline, with relatively high values in summer and relatively low values in winter, and there are also significant differences between different regions in the same month.

This study introduces a framework for meteorology, using multidimensional feature analysis along with EWM and TOPSIS methods to develop a TC genesis index in the Northwestern Pacific Ocean. The approach effectively extracts valuable insights from big data, delves into the formation patterns of TCs, and enhances the accuracy and reliability of meteorological predictions. This method showcases the potential of integrating mathematics and big data technology in meteorology, offering new avenues for research and fostering interdisciplinary innovation in the field.

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