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The Formation Patterns of Tropical Cyclones in the Northwest Pacific and the Modulation Mechanisms of Their Environmental Fields

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Abstract. Tropical cyclone genesis (TCG) in the Northwest Pacific is strongly influenced by the interaction of large-scale oceanic and atmospheric environmental fields. This study investigates the spatiotemporal characteristics of TCG from 1991 to 2020 and examines the modulation mechanisms of major environmental factors. Tropical cyclone records from the China Meteorological Administration best-track dataset are combined with NOAA ERSST.v5 sea-surface temperature data and ERA5 atmospheric reanalysis fields. The analysis focuses on the effects of the El Niño–Southern Oscillation (ENSO) and tropospheric vertical wind shear (VWS), while relative humidity, low-level vorticity, low-level convergence, and upper-level divergence are included as supporting diagnostic variables. Environmental conditions are extracted within a 5° × 5° region around each genesis location during the 48–24 h period before genesis. Sen's slope estimation, the Mann–Kendall trend test, composite analysis, partial correlation, and bootstrap methods are employed to examine long-term variability, spatial migration, and statistical relationships. The study aims to clarify how ENSO-related sea-surface temperature anomalies and VWS jointly modulate the frequency and spatial distribution of TCG. The proposed framework provides a basis for improving environmental diagnosis, short-term climate prediction, and tropical cyclone risk assessment.

Keywords: Tropical cyclone genesis, Northwest Pacific, ENSO, Vertical wind shear, Environmental modulation

1. Introduction

The Northwest Pacific is the ocean area where tropical cyclones (TCs) occur most frequently and with the greatest intensity worldwide, representing about one-third of the total number of such cyclones each year. The strong winds, heavy rains and storm surges associated with the landfall of tropical cyclones continue to pose a serious threat to the economic and social development of coastal areas as well as to the safety of life and property. It is an important subject in the field of atmospheric science to study the spatiotemporal distribution patterns of tropical cyclone formation (TCG) in the Northwest Pacific and the mechanisms by which large-scale environmental conditions

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influence it, since this knowledge forms the scientific basis for improving short-term climate prediction and for making decisions regarding disaster prevention and mitigation.

The formation of tropical cyclones is a physical process that depends on interactions between the ocean and the atmosphere at multiple scales. Conventionally, a sea-surface temperature of 26.5°C is regarded as an empirical threshold for the development of tropical cyclones. In reality, though, the process of genesis is affected by a number of factors such as ocean heat content, mid- and lower-tropospheric humidity, low-level relative vorticity and tropospheric vertical wind shear (VWS). In the context of climate change, the impact of large-scale climate phenomena like the El Niño–Southern Oscillation (ENSO) on the activity of tropical cyclone genesis in the Northwest Pacific shows complex changes. In order to examine the main driving processes more thoroughly, it is necessary to consider mid- and lower-tropospheric humidity and low-level vorticity as background environmental conditions, to regard sea-surface temperature anomalies and vertical wind shear as the two main factors, and to analyse how these factors influence the frequency and the spatial locations of tropical cyclone genesis.

The study uses the spatial distributions of sea-surface temperature anomalies and wind shear as the basis of its analysis, examining the interannual and seasonal changes in the frequency and position of tropical cyclone formation in the Northwest Pacific. By making use of long-term sea-surface temperature datasets and ERA5 reanalysis data along with the CMA best-track dataset, it assesses the statistical relationships between environmental factors and genesis activity and looks into how the major environmental fields control tropical cyclone formation.

2. The sources of the data and the statistical definitions

In order to carry out a quantitative analysis, the boundaries of the area under study and the operational definition of tropical cyclone genesis events have to be standardised so that external systems or disturbances which do not satisfy the criteria are not included in the sample.

2.1. The statistical domain and operational definition of TCG

In order not to count systems which migrate into the area from other regions as genesis events in this basin, the spatial domain is limited to the Northwest Pacific (0°–40°N, 100°E–180°). A TCG event is considered to have taken place when a tropical cyclone system first attains tropical depression (TD) status, this being defined as a maximum near-centre wind speed of 10.8–17.1 m/s, and when its first recorded latitude and longitude lie within the said domain [1].

For borderline cases, the following rules apply: any tropical disturbances which never attain TD status are omitted from the TCG statistics. Systems which have already reached TD status in the Central Pacific or in the Southern Hemisphere and then move into the Northwest Pacific are considered as entering that region and are not included in the TCG statistics for this area [2]. Systems that develop at the end of December and continue into January of the following year are allocated to the year and month corresponding to the exact time when they first become TD status. The tropical cyclone track and intensity data are taken from the China Meteorological Administration (CMA) tropical cyclone best-track dataset for the period 1991 to 2020 [3].

2.2. Datasets relating to the oceanic and atmospheric conditions

To extract the environmental fields, it is necessary to use oceanic and atmospheric reanalysis data that have a high spatial and temporal resolution.

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The sea-surface temperature and the ENSO indices make use of the NOAA Extended Reconstructed Sea Surface Temperature dataset (NOAA ERSST.v5), which has a spatial resolution of 2.0° × 2.0° [4]. The Oceanic Niño Index (ONI) is calculated as the three-month running mean of the sea-surface temperature anomalies (SSTA) in the Niño 3.4 area (5°N–5°S, 170°W–120°W), as issued by NOAA. The climatological baseline period is taken as the arithmetic mean for the years 1991 to 2020 [5, 6].

The monthly and daily ERA5 reanalysis datasets produced by the ECMWF, which have a spatial resolution of 0.25° × 0.25°, are used in order to obtain the horizontal wind fields (u, v) at 200 hPa and 850 hPa, the relative humidity at 700 hPa, and the relative vorticity and divergence fields at 850 hPa [7].

2.3. The phases of ENSO events and their stage classification

Since ENSO develops over calendar years and is phase-locked to the seasonal cycle, determining whether a year is an El Niño or La Niña year on the basis of the calendar year alone (from January through December) may mask the seasonal signals. The classification is therefore made on the basis of the ONI and the stage of the seasonal cycle.

An El Niño (La Niña) event is defined as an ONI value reaching or exceeding +0.5°C (or being equal to or below −0.5°C) for five months or more.

The stages are distinguished by the fact that the summer and autumn of the year in which El Niño develops (from May to October) are different from the mature winter period (from November to January of the following year).

Since Northwest Pacific TCG occurs mainly during the months of summer and autumn (June to October), the composite analysis identifies its samples by combining the three-month running ONI value at the same time with the development-stage characteristics, in order to pick up the climatic background signal during the period of peak genesis.

3. The methods of analysis and the framework for diagnosis

3.1. The rules concerning spatiotemporal sampling for the extraction of environmental fields

To capture the environmental background before system formation while reducing the influence of local feedback from the outbreak of strong convection on the large-scale environmental fields, the following extraction rules are applied.

The time window involves extracting the 24-hour mean fields from 48 to 24 hours before the TCG event (from t−48 h to t−24 h) in order to eliminate the influence of the system's own cyclonic circulation following the formation of the tropical cyclone.

For the spatial window, the area-weighted average of the environmental variables within a 5° × 5° grid area surrounding the latitude and longitude of the TCG event—that is, a rectangular region extending ±2.5°—is calculated [8].

3.2. The calculation of vertical wind shear (VWS)

Tropospheric vertical wind shear is defined as the magnitude of the vector wind difference between 200 hPa and 850 hPa:

$$VWS = \sqrt{(u_{200} - u_{850})^2 + (v_{200} - v_{850})^2} \quad (1)$$

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There is no fixed shear threshold applied. Rather, the response range of TCG to VWS under different oceanic regions and seasons is determined by means of the spatial distribution of the full-domain field and its probability density function [9].

3.3. The mechanistic diagnostic framework and the classification of variables

Environmental variables are classified according to their physical diagnostic roles. Core explanatory factors: ENSO (ONI) and tropospheric vertical wind shear (VWS). The diagnostic factors that are mechanical include the relative humidity at 700 hPa, the relative vorticity at 850 hPa, the low-level convergence at 850 hPa and the upper-level divergence at 200 hPa. The diagnostic procedure does not assume there is a one-way causal relationship. To begin with, composite analyses are carried out for the summers and autumns of both El Niño and La Niña years in order to establish the abnormal composite responses of SSTA, the low-level wind fields, VWS, moisture and vorticity. These responses are then combined with spatial matching patterns in order to examine the physical processes which underlie changes in the location and frequency of genesis.

3.4. The use of statistical testing and the evaluation of uncertainty

Since the time period from 1991 to 2020 includes only 30 years of data, the number of composite years that can be obtained after classifying the data according to ENSO is limited, and as is often the case with meteorological time series, there is autocorrelation, so conventional Student's t-tests might overestimate the statistical significance.

In the case of the 30-year record of frequency and spatial centre, Sen's slope estimator and the Mann–Kendall trend test are applied in order to examine decadal variability and long-term linear trends, using a significance level of $\alpha = 0.05$. Since autocorrelation can cause incorrect conclusions in a trend test, the lag-one autocorrelation coefficient is first subjected to testing. Pre-whitening is employed when needed to eliminate the effect of serial autocorrelation [10].

For the production of ENSO-phase composites and when carrying out partial-correlation analysis, a non-parametric bootstrap permutation test is employed, involving 1,000 resamples and 95 per cent confidence intervals being calculated in this way in order to decrease the need for assuming that the data are normally distributed. The reliability of the statistical results is evaluated by combining the findings from the Student's t-test and the bootstrap test.

4. The main scientific questions to be examined

Based on the framework above, the analysis focuses on the following testable questions:

4.1. Spatiotemporal evolution

For Question 1a, did the frequency of tropical cyclones in the Northwest Pacific show significant periodic variations between 1991 and 2020, for example, over a 2-to-7-year period? And after the ENSO signal had been removed, did the slope of the long-term linear trend change significantly?

With regard to question 1b, what migration patterns did the spatial centre of gravity of the TCG show between summer–autumn and autumn–winter? Did the high-value areas in the genesis density field experience systematic spatial shifts on an interannual basis?

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4.2. The regulating effects of ENSO and VWS

For question 2a, during the summers and autumns of the years when El Niño developed and also during La Niña periods, how did the abnormal low-level anticyclonic circulation and the upper-level wind fields in the Northwest Pacific react to the sea-surface temperature signals in the central and eastern Pacific? Did this reaction result in a directional shift of the spatial centre of gravity of the TCG?

For Question 2b, what is the main pathway by which an increase in vertical wind shear reduces the frequency of TCGs? Does it primarily work by disrupting the dynamical structure or by strengthening the effect of dry-air ventilation?

For question 2c, to what extent does the indirect effect of ENSO on the spatial distribution of VWS—for example, via alterations in the Walker circulation—impact TCG? When the ENSO signal is eliminated using partial-correlation analysis, does VWS still have an independent statistical influence on TCG?

5. Conclusion

A systematic examination of the changes in the frequency of tropical cyclone formation and in the spatial centres of gravity from 1991 to 2020 will aid in clarifying the relationship between environmental variables and formation activity. While interpreting the results, due consideration should be given to the following limitations and possible applications.

Statistical relationships and modulation relationships between environmental variables and TCG activity are shown by means of Pearson correlation, partial correlation and composite analysis. Although VWS remains significantly correlated with TCG even after allowing for the influence of ENSO, this cannot be taken as proof of a one-way physical causal effect. There may be complex nonlinear coupling between the large-scale environmental fields and genesis activity, and the exact physical causal chain still needs to be interpreted in light of the dynamical processes.

A quantitative analysis of the way ENSO phases and the spatial distribution of VWS affect TCG can offer statistical advice regarding the dynamic identification of tropical cyclone genesis environments in the Northwest Pacific, the choice of indicators for short-term climate prediction, and the assessment of numerical model forecast performance. In future studies, high-resolution atmosphere–ocean coupled models such as WRF or CESM could be combined with numerical control experiments, after which targeted sensitivity tests—for example, those involving a modification of the wind-shear forcing or the sea-surface temperature anomaly fields—could be carried out to verify numerically the physical processes suggested by the statistical analysis.

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