2024 Volume 5, Issue 2
Satellite Oceanography and Meteorology
ISSN(Online): 2424-9505
ISSN(Print): 2424-8959

Spatiotemporal Coupling Characteristics and Influences of Satellite-observed Ocean-Meteorological Elements in the Western Pacific Ocean

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Abstract:

This paper aims to explore the spatiotemporal coupling characteristics and influences of satellite-observed ocean-meteorological elements in the Western Pacific Ocean. Through the analysis of relevant satellite observation data and re-analysis data, the coupling relationships of elements such as sea-surface temperature, sea-level pressure, and wind field in this region on different time scales and spatial distributions are revealed, as well as the significant impacts of these coupling characteristics on regional climate and ocean circulation. This provides a scientific basis for a better understanding of the changes in the climate system and the evolution of the marine environment in the Western Pacific Ocean.

Keywords:

Western Pacific Ocean
Satellite observations
Ocean-meteorological elements
Spatiotemporal coupling characteristics

Online publication: December 27, 2024

1. Introduction

The Western Pacific Ocean, as an important part of the global ocean system, plays a crucial role in global climate and marine environmental changes. There are complex interactions and spatiotemporal coupling relationships among the ocean-meteorological elements in this region. These relationships not only affect regional climate changes but also have an important feedback effect on the global climate system. With the continuous development of satellite observation technology, it provides a rich data source for in-depth research on the spatiotemporal coupling characteristics of ocean-meteorological elements in the Western Pacific Ocean.

2. Spatiotemporal coupling characteristics of ocean-meteorological elements in the Western Pacific Ocean

2.1. Temporal coupling characteristics

In the Western Pacific Ocean, the interaction between ocean and meteorological elements presents a significant and orderly change pattern on seasonal and inter-annual time scales. Specifically, in terms of seasonal changes, the sea-surface temperature shows obvious seasonal fluctuations, being relatively low in winter and relatively high in summer. This phenomenon is closely related to the seasonal shift of the atmospheric circulation. In the cold winter, under the dominance of the Siberian High, strong northerly winds blow over the sea surface, taking away the heat from the sea surface and leading to a decrease in the sea-surface temperature. On the contrary, in the hot summer, the strengthening of the subtropical high-pressure is accompanied by the prevalence of southerly winds, which transport warm and humid air to the ocean surface, thus increasing the sea-surface temperature. At the same time, the intensity and direction of the sea-surface wind field also change with the seasons. The wind is strong in winter and relatively weak in summer, and the wind direction also changes. These changes are intertwined with the seasonal fluctuations of the sea-surface temperature, jointly forming the unique seasonal coupling characteristics of the Western Pacific Ocean. On the inter-annual time scale, the ENSO phenomenon plays a key role and has a profound impact on the variability of ocean-meteorological elements. El Niño and La Niña events lead to abnormal increases and decreases in sea-surface temperature respectively. This abnormal temperature fluctuation not only changes the heat exchange between the ocean and the atmosphere but also triggers corresponding adjustments in the atmospheric circulation, such as the weakening or strengthening of the Walker Circulation. These changes in the atmospheric circulation further act on meteorological elements such as the sea-surface wind field and precipitation, thus affecting the climate pattern on a larger scale. Specifically, in the winter of an El Niño year, the abnormally warm sea temperature in the equatorial central and eastern Pacific excites abnormal low-altitude cyclone responses on both sides of the equator, strengthening the trade winds on both sides of the equator. The strengthened trade winds increase the latent heat flux from the ocean to the atmosphere, thus reducing the local sea temperature in the northwestern Pacific. The abnormally cold sea temperature in the northwestern Pacific then excites an abnormal low-altitude anticyclone near the Philippine Sea in its northwest, promoting the release of latent heat flux from the ocean to the atmosphere, which helps to maintain the negative sea-temperature anomaly in the northwestern Pacific region [1].

2.2. Spatial coupling characteristics

From a horizontal perspective, the sea-surface temperature decreases gradually from the equator to the poles, forming a significant latitudinal temperature gradient zone. This gradient zone is like one of the core “engines” driving the operation of the atmospheric circulation. In the equatorial Pacific region, the significant east-west difference in sea-surface temperature is like a key “trigger” for atmospheric motion, giving rise to the iconic Walker Circulation. Specifically, in the warm water area, abundant heat causes the air to rise due to heating, converging to form a low-pressure area. Correspondingly, in the cold water area, due to relatively scarce heat, the air cools and sinks, creating a high-pressure-dominated area. Such a distinct pressure contrast continuously shapes the basic structure and trend of the atmospheric circulation. It is worth noting that the western boundary currents, such as the well-known Kuroshio and its extension, are like the “ocean thermal-power conveyor belt”, which have a significant reshaping effect on the horizontal distribution patterns of the sea-surface temperature and the sea-surface wind field. Taking the Kuroshio as an example, it is like a surging “ocean warm-current artery”, continuously transporting warm seawater northward, significantly increasing the sea-surface temperature of the sea area it passes through. This, in turn, like a “chain reaction”, deeply disturbs the local atmospheric circulation and prompts an adaptive adjustment of the distribution of meteorological elements [2]. Switching to a vertical perspective for in-depth analysis, the vertical distribution patterns of key elements such as temperature, salinity, and density in the upper ocean precisely define the stratification characteristics of seawater. This characteristic, like a cornerstone, has a profound impact on the rhythm of ocean circulation and the interaction between the ocean and the atmosphere. Focusing on the key area of the tropical Western Pacific, the deep and active thermocline is like a “key bridge” connecting the ocean and the atmosphere, forming the core interface of air-sea exchange. The fluctuations in its depth and strength are like a precise "regulating valve", directly controlling the two-way exchange flux of heat and matter between the ocean and the atmosphere. When the thermocline becomes shallower, the "channel" for the ocean to transfer heat to the atmosphere is blocked, and the heat supply is correspondingly reduced. Conversely, if the thermocline deepens, it will open a more abundant "valve" for heat transfer. In either case, it will trigger a chain reaction in the atmospheric circulation, causing an adaptive change in the climate pattern [3]. At the same time, the structural configuration of the atmospheric boundary layer and the vertical distribution of meteorological elements are closely intertwined with the real-time conditions of the ocean surface. Factors such as the roughness of the ocean surface and subtle temperature changes are like "invisible regulating hands", finely regulating the height expansion and contraction of the atmospheric boundary layer, the speed of the wind, and the change of turbulence intensity. And the dynamic changes of these parameters are like an "echo wall", which in turn feedback to the formation and development processes of the atmospheric circulation and the weather system. In conclusion, the vertical structural characteristics of the ocean-meteorological elements in the Western Pacific Ocean do not exist in isolation. They not only deeply reveal the intricate internal mechanisms in the air-sea interaction process but also, like a "far-sighted watchtower", provide an essential key perspective for a comprehensive understanding of the dynamic evolution of regional and even global climate changes. It urgently requires the academic community to continuously delve into and deeply explore the scientific mysteries hidden within.

3. Influences of spatiotemporal coupling of ocean-meteorological elements in the Western Pacific Ocean

3.1. Influences on regional climate

In the vast and complex marine environment of the Western Pacific Ocean, the spatiotemporal coupling characteristics of ocean-meteorological elements, like a set of precise control systems, have a profound and multi-dimensional impact on the East Asian Monsoon and tropical cyclone activities, deeply reshaping the regional climate pattern. The transportation of warm and humid airflows and the rhythm of water-vapor convergence change, and the movement and intensity of the rainbelt also fluctuate. The chain reaction caused by abnormal sea temperature exacerbates climate extremism, bringing new challenges to disaster prevention and mitigation in coastal cities, agricultural production planning, and marine fishery fishing. Focusing on the East Asian Monsoon system, the abnormal fluctuations of the sea-surface temperature in the Western Pacific Ocean are like a "climate baton", which can directly trigger subtle changes in the atmospheric circulation in this region, and then precisely regulate the intensity level and movement path of the winter monsoon. In winter, the warm pool area, as a sensitive and key zone of sea-surface temperature, the high or low-temperature situation is like a "switch" triggering atmospheric convective activities, driving the atmospheric convective activities to develop in the direction of strengthening or weakening respectively. Through a series of complex atmospheric dynamic conduction processes, it deeply affects the strength of the winter monsoon [4]. In summer, the dynamic changes of the sea-surface temperature are like a key "piece" in the "climate jigsaw puzzle". By influencing the position shift and intensity fluctuation of the subtropical high-pressure, a core atmospheric circulation system, it subtly controls the advancement rhythm of the summer monsoon and the spatial distribution pattern of precipitation. It is particularly noteworthy that the ENSO event, as a strong signal of global climate inter-annual variability, through the complex transmission chain of ocean-meteorological elements in the Western Pacific Ocean, has a prominent inter-decadal-scale impact on the onset time, intensity peak, and spatio-temporal distribution of precipitation of the East Asian summer monsoon. Taking the typical research period from 1986–2010 as an example, during this period, the ENSO had a particularly significant delaying effect on the onset of the summer monsoon in central India. In-depth exploration reveals that this phenomenon is closely related to the strengthening of the tropical Indian-Western Pacific capacitor mechanism during this period, which contains the coordinated linkage of multiple complex physical processes such as the accumulation of ocean heat content and the feedback regulation of the atmospheric circulation [5]. Switching the perspective to the field of tropical cyclone activities, the Western Pacific Ocean, as a "hotbed" of high-frequency tropical cyclone breeding in the world, the coupling characteristics of its ocean-meteorological elements are like a set of "decisive programming codes", comprehensively dominating the birthplace, growth trajectory, and movement path of tropical cyclones. The long-term maintenance of the sea-surface temperature in the warm value range provides an indispensable energy source and abundant water-vapor supply for the incubation of tropical cyclones. Especially when the sea-surface temperature is abnormally high, it is like injecting "high-energy fuel" into the growth of tropical cyclones, greatly boosting their intensity. At the same time, the vertical shear of the sea-surface wind field, the change of the atmospheric circulation situation, and other multiple meteorological elements' dynamic changes are like "variable roadblocks" set on the moving path of tropical cyclones, precisely influencing the development process, moving path, and intensity evolution of tropical cyclones. Especially during the periodic disturbances of the ENSO event, the structural changes in the atmospheric circulation situation are like redrawing a "navigation map", directly causing the offset of the tropical cyclone's formation position and the reshaping of its moving path, and thus having a crucial impact on the disaster-risk situation in coastal areas [6]. In general, the spatiotemporal coupling characteristics of ocean-meteorological elements in the Western Pacific Ocean are like the "central hub" of the regional climate system, deeply embedded in and regulating many key climate processes. It is of inestimable strategic significance for accurately predicting the trend of climate change and scientifically and efficiently responding to natural disaster challenges. It urgently requires researchers to deeply explore and continuously discover more potential relationships and laws.

3.2. Influences on ocean circulation

In the complex ocean-atmosphere coupling system of the Western Pacific Ocean, the spatiotemporal coupling characteristics of ocean-meteorological elements have a significant impact on key ocean-circulation systems such as the Kuroshio and its extension, and the bifurcation of the North Equatorial Current. The Kuroshio and its extension, as an important ocean-circulation system in the Western Pacific region, the dynamics of its flow velocity and the direction of its path are to a large extent delicately regulated by the spatiotemporal changes of the sea-surface wind field [7]. The East Asian Monsoon, as an important component of the regional atmospheric circulation, its abnormal activities can cause changes in the sea-surface wind stress, and then through complex dynamic processes, interfere with the flow characteristics of the Kuroshio, causing adaptive changes in the Kuroshio in terms of flow velocity and flow direction deviation. At the same time, the spatial distribution pattern of the sea-surface temperature also has a profound impact on the heat-transfer efficiency of the Kuroshio and the thermodynamics and dynamics properties of the water body [8]. Research shows that once an abnormal signal appears in the sea area where the Kuroshio extension is located, it can, through ocean wave processes and the teleconnection of the atmospheric circulation, transmit this signal to the marginal sea area of East Asia, thus triggering a chain reaction in the internal circulation structure and marine ecological environment of this region, causing changes in key ocean processes such as the temperature-salinity distribution and nutrient-salt transport in local sea areas. On the other hand, the geographical position and intensity dynamic changes of the bifurcation of the North Equatorial Current are closely intertwined with the coupling effect of ocean-meteorological elements [9]. Driven by the East Asian Monsoon in a periodic manner, the bifurcation of the North Equatorial Current shows a distinct seasonal migration pattern, specifically shifting southward in the spring-summer transition and moving northward in autumn-winter. Moreover, it also exhibits significant inter-annual fluctuation characteristics. During an El Niño event, the bifurcation of the North Equatorial Current tends to migrate to a higher-latitude location; while in the La Niña stage, it stabilizes in a lower-latitude range. In-depth exploration reveals that this inter-annual change characteristic is related to the first two main Empirical Orthogonal Function (EOF) modes of the anomalous meridional velocity of the ocean east of the Philippines. This mode accurately reflects the overall change trend of the subtropical and tropical gyres and the dynamic change details of the NMK current system in the adjacent area of the western boundary of the ocean [10]. Overall, these complex interactions and dynamic changes deeply reveal the core regulatory role of the coupling characteristics of ocean-meteorological elements in the Western Pacific Ocean in optimizing the ocean-circulation pattern and reshaping the regional climate mode.

4. Conclusion

This paper explores the spatiotemporal coupling characteristics and influences of satellite-observed ocean-meteorological elements in the Western Pacific Ocean, revealing the change laws of these elements in the region on seasonal and inter-annual scales, which are closely related to the seasonal shift of the atmospheric circulation and the ENSO event. Spatially, the ocean-meteorological elements present complex distributions and coupling relationships, involving the latitudinal gradient of sea-surface temperature, the depth and intensity of the thermocline, and the vertical structure of the atmospheric circulation. These characteristics significantly affect the regional climate and ocean circulation, including the East Asian Monsoon, tropical cyclones, the Kuroshio and its extension, and the bifurcation of the North Equatorial Current, and play an important role in global climate change. Studying the coupling characteristics of ocean-meteorological elements in the Western Pacific Ocean is crucial for understanding the change mechanism of the global climate system and improving the accuracy of climate and marine environment forecasting. In the future, with the progress of satellite observation and numerical simulation technologies, the interaction of ocean-meteorological elements in this region will be further revealed, providing scientific support for addressing global climate change and marine environmental issues.

Disclosure statement

The author declares no conflict of interest.

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