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Multi-source Data Analysis of the Ocean-Meteorology Coupling Mechanism from the Perspective of Satellite Observations

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Abstract:

This paper aims to analyze the ocean-meteorology coupling mechanism from the perspective of satellite observations through multi-source data. By using multi-source data such as satellite remote-sensing data and *in situ* observation data, the interaction relationships between oceanic and meteorological elements and their coupling mechanisms are deeply explored. The research results contribute to a better understanding of the ocean and meteorological systems, improve the capabilities of climate prediction and marine environmental monitoring, and provide a scientific basis for addressing climate change and marine disasters.

Keywords:

Satellite observations
Ocean-meteorology coupling mechanism
Multi-source data

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1. Introduction

There is a close interaction and coupling relationship between the ocean and meteorology, which has a profound impact on the global climate system and the marine environment. With the continuous progress of satellite observation technology, a large amount of oceanic and meteorological data can be collected, providing solid support for in-depth exploration of the coupling mechanism between them. Through the comprehensive analysis of multi-source data, the complex interactions between the ocean and meteorology can be revealed more comprehensively and accurately, thus deepening the understanding of the operation laws of the Earth system.

2. Application of satellite observation technology in ocean and meteorology research

2.1. Types of satellite remote-sensing data

Satellite observations provide diverse data support for academic research in the fields of ocean and meteorology, covering key parameters such as sea-surface temperature, sea-surface wind field, ocean color, atmospheric aerosol optical thickness, and cloud cover. China's Fengyun series of geostationary and polar-orbiting meteorological satellites mainly provide visible light, infrared, and water vapor channel cloud images with a spatial resolution of about 1 km and a time interval of about 5–30 minutes. Higher-spatial-resolution cloud images and other remote-sensing products, such as sea-surface temperature, aerosol optical thickness, etc., as well as infrared and microwave remote-sensing of atmospheric temperature and water vapor profiles [1]. Taking sea-surface temperature data as an example, it accurately reflects the thermal dynamic distribution pattern of the ocean surface, providing a direct basis for understanding the heat budget balance of the ocean and its thermal radiation effect on the surrounding environment. Sea-surface wind-field data, from a dynamic perspective, powerfully interprets the momentum transfer process between the atmosphere and the ocean at the interface, clearly showing the driving effect of atmospheric circulation on the flow of ocean water and the series of ocean-dynamic responses it triggers.

2.2. Advantages of satellite observations

Compared with traditional *in situ* observation methods, satellite observations stand out in ocean and meteorology research due to their unique characteristics. On the one hand, it has an extremely wide coverage area, capable of spanning intercontinental and ocean boundaries, achieving comprehensive and synchronous monitoring of the global ocean-atmosphere system. This greatly expands the research vision, enabling the complete presentation of macro-scale climate phenomena and ocean processes. On the other hand, satellite observations have high spatiotemporal resolution. Whether it is to capture sudden changes in meteorological elements and instantaneous changes in ocean phenomena in a short time, or to precisely analyze the subtle differences in the long-term climate evolution process and the gradual changes in the marine environment, it can be done accurately. This provides rich data details for studying the complex behaviors of the ocean and meteorology at different spatiotemporal scales [2]. In addition, satellite observations also have the advantage of continuous data acquisition. Relying on a stable orbital operation mechanism, observation data can be continuously collected and transmitted back according to a fixed time sequence, ensuring the coherence and integrity of the information required for research, and thus laying a foundation for analyzing the continuous evolution laws of the ocean and meteorological systems.

3. Theoretical basis of the ocean-meteorology coupling mechanism

3.1. Basic principles of air-sea interaction

The ocean and the atmosphere, as two closely connected key spheres in the Earth system, construct a complex and subtle interaction network through the exchange processes of heat, momentum, and matter. Specifically, the ocean, as a huge absorber of solar energy, after receiving solar radiation, the sea-surface temperature changes accordingly. This change, as a key thermal signal, is transmitted upward and deeply disturbs the thermal structure of the atmosphere, triggering a series of chain reactions such as vertical convection in the atmosphere and adjustment of the thermal gradient, and then driving the remodeling of the atmospheric circulation pattern. Conversely, the atmosphere, through wind stress as a medium, exerts a dynamic effect on the ocean surface, causing the flow of ocean water. This not only gives rise to the operation of the ocean circulation system but also stimulates the generation and propagation of ocean waves. This two-way exchange of energy and matter between them constitutes the basic dynamic framework of air-sea interaction.

3.2. Coupling characteristics at different time and space scales

At multiple spatiotemporal dimensions, the coupling mechanism between the ocean and meteorology shows significant differential characteristics. From the time-scale analysis, in the short-term, extreme weather events such as typhoons and the ocean show an immediate response linkage [3]. When a typhoon passes through a sea area, the strong wind stress intensifies the mixing of the upper-layer ocean and causes a sudden drop in the sea surface temperature. In return, the ocean feeds back with enhanced water vapor evaporation, continuously supplying energy to the typhoon system. The two interact and evolve together. In the long-term, against the background of global warming, the ocean and the atmosphere embark on a slow and far-reaching process of coordinated adjustment. The ocean circulation gradually changes due to the imbalance of heat budget, and then remodels the global heat distribution pattern. The atmospheric circulation also adjusts adaptively, driving a series of slow-changing phenomena such as the displacement of global climate zones and the change of precipitation patterns. From the spatial-scale perspective, on a large scale, the giant ocean circulation systems, such as the equatorial warm current and the westerly drift, and the planetary-scale atmospheric circulation, such as the Hadley circulation and the Ferrel circulation, are closely intertwined and mutually restricted, jointly regulating the global climate pattern. In the mesoscale range, ocean eddies, with their high-efficiency aggregation and transportation of heat and matter, frequently exchange and redistribute energy and water vapor with the accompanying atmospheric disturbances, such as mesoscale convective complexes. They play a key role in regional climate regulation and the shaping of the marine ecological environment, demonstrating a local but crucial coupling influence [4].

4. Collection and organization of multi-source data

4.1. Data sources

The multi-source data system is the cornerstone of the research on the ocean-meteorology coupling mechanism. It mainly includes three core types of data: satellite remote-sensing data, *in situ* observation data, and re-analysis data. In the field of satellite remote-sensing data, advanced sensors such as the Moderate-Resolution Imaging Spectroradiometer (MODIS) developed by the National Aeronautics and Space Administration (NASA) of the United States and the Spinning Enhanced Visible and Infrared Imager (SEVIRI) operated by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) play a crucial role. These sensors can accurately capture a large amount of oceanic and atmospheric parameter information, providing a high spatiotemporal resolution and wide coverage dynamic data stream for global-scale research, enabling the monitoring and understanding of large-scale environmental changes [5]. *In situ* observation data rely on the global network of ocean buoys, which are long-term anchored in key sea areas, real-time monitoring the changes of ocean-hydrological and meteorological elements. In addition, ships sample the ocean conditions along their voyages, and coastal observation stations record the ecological and meteorological parameters of the near-shore sea areas at fixed points. These first-hand data collected on the spot provide high-credibility information for regional fine-scale research and are indispensable for understanding local marine environmental changes. Re-analysis data, as an important pillar of modern climate research, are reconstructed through advanced numerical models, combined with multi-source and multi-time-period observation data. Taking the ERA5 dataset developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) as an example, it integrates global observation information and generates comprehensive data products with continuous time-space and strong physical consistency through complex algorithms and physical models [6]. These data products not only provide researchers with the ability to trace back historical climate conditions but also provide strong support for analyzing long-term climate change trends and mechanisms, thus playing a crucial role in the field of ocean-meteorology coupling research

4.2. Data pre-processing

Due to the wide range of sources and diverse characteristics of multi-source data, strict data pre-processing is required before applying them to research. This process involves key links such as data quality control, data fusion, and spatiotemporal interpolation, aiming to ensure data quality and research accuracy. Taking satellite remote-sensing data as an example, the interference of clouds with sensor signals is a common problem. Therefore, cloud detection and removal are the primary steps of pre-processing. Using algorithms such as multi-spectral analysis and threshold discrimination, data pixels contaminated by clouds can be accurately identified and excluded, greatly improving data purity and accuracy, which is crucial for ensuring the reliability of analysis results. When integrating sea-surface temperature data from different sources, considering their complementary nature in spatiotemporal coverage, data-fusion technology is particularly important. Through steps such as weight allocation, spatial registration, and uncertainty assessment, multi-source data can be effectively integrated to form a more complete, continuous, and accurate sea-surface temperature field [7]. Such data integration deepens the understanding of the changes in the ocean thermal structure and provides a solid foundation for exploring the interaction between sea-surface temperature and meteorological elements. The application of spatiotemporal interpolation technology helps to fill data gaps and smooth fluctuations, generating a more continuous and uniform spatiotemporal dataset. The finely pre-processed data provide a powerful tool for studying the ocean-meteorology coupling mechanism and support scientific research on climate prediction and environmental management.

5. Analysis of the ocean-meteorology coupling mechanism based on multi-source data

5.1. Relationship between sea-surface temperature and atmospheric circulation

Through the comprehensive analysis of multi-source data, we know that the abnormal fluctuations of sea-surface temperature are a key thermal disturbance factor, which can trigger significant adaptive adjustments of the atmospheric circulation. A typical example is during the El Niño phenomenon. The sea-surface temperature in the equatorial central and eastern Pacific Ocean continues to rise. This thermal anomaly enhances the heat transfer from the ocean to the atmosphere, thus stimulating abnormally strong atmospheric convective activities. Large-scale vertical upward airflows change the thermal and dynamic structure of the atmosphere. Through the form of atmospheric teleconnection wave trains, these effects are transmitted to distant places, ultimately leading to the chaos of the global atmospheric circulation pattern and multi-dimensional abnormal climate manifestations. By conducting a strict quantitative correlation analysis of long-time series sea-surface temperature and atmospheric circulation observation data, a highly significant linear relationship between the two is found. The correlation coefficient is stably in the range of 0.6 to 0.8, which strongly proves the close coupling relationship between sea-surface temperature and atmospheric circulation [8]. The revelation of this relationship not only deepens the understanding of the interaction mechanism between the ocean and the atmosphere but also provides an important scientific basis for predicting and responding to climate change.

5.2. Interaction between sea-surface wind field and ocean circulation

The sea-surface wind field plays a crucial dynamic role in the generation and evolution of ocean circulation. In-depth research shows that the conversion of wind direction and the dynamic changes of wind speed profoundly reshape the distribution of the ocean-surface flow field, and at the same time play a key regulatory role in the propagation path and energy transfer of ocean waves. Taking the North Atlantic Ocean as an example, the westerly belt that exists stably all year round provides a continuous source of power for the Gulf Stream and its extension with its strong and continuous wind force, promoting the large-scale northward transportation of warm water, thus shaping the unique thermohaline circulation structure of the North Atlantic Ocean [9]. This process has a profound impact on regulating the regional and even global climate. In the tropical sea areas, under the influence of the monsoon system, the wind direction reverses regularly with the seasons. This seasonal wind-stress cycle causes the surface water of the ocean to have corresponding seasonal flow-direction changes, playing a decisive driving role in the seasonal variation of the regional ocean circulation. The periodic changes of the monsoon not only affect the ocean circulation but also have an important impact on the structure and function of the marine ecosystem. Through high-precision numerical simulation technology, combined with the collaborative analysis of multi-site and multi-platform observation data, the dynamic coupling synergy between the sea-surface wind field and ocean circulation can be accurately quantified. These research results further verify the dominant position of the sea-surface wind field in the formation and evolution of ocean circulation, providing a solid scientific basis for understanding and predicting changes in the marine environment.

5.3. Association between atmospheric aerosols and marine primary productivity

Atmospheric aerosols, as a key medium for the exchange of substances between the atmosphere and the ocean, carry rich nutrients. When these aerosols settle on the ocean surface, they have a significant stimulating effect on the dynamic changes of marine primary productivity. Through in-depth analysis by integrating the high spatiotemporal resolution monitoring of multi-source satellite remote-sensing data and *in situ* fixed-point and underway observation data, the results clearly show that there is a significant positive correlation between the optical thickness of atmospheric aerosols and the concentration of ocean chlorophyll within a specific sea area range. Taking the northwestern Pacific Ocean as an example, aerosols from high-intensity human-activity emissions or natural-source releases in North China reach the airspace above this sea area under the transportation of the atmospheric circulation. As these aerosols settle, the chlorophyll concentration in the ocean surface shows a trend of rising synchronously with the optical thickness of aerosols within a time lag of 1–2 months. Through statistical analysis, the correlation coefficient between the two is as high as 0.7–0.8, which convincingly reveals the long-range regulatory mechanism of atmospheric aerosols on marine primary productivity. This discovery not only deepens the understanding of the role of atmospheric aerosols in the marine ecosystem but also provides an important scientific basis for evaluating the impact of human activities on the marine environment [10].

6. Conclusion

This paper reveals the complex interaction relationships between oceanic and meteorological elements by analyzing multi-source data from the perspective of satellite observations. Key factors such as sea-surface temperature, sea-surface wind field, and atmospheric aerosols play important roles in the coupling of the ocean and meteorology at different time and space scales, and the results of numerical simulations further confirm the scientific rationality of this coupling mechanism.

Disclosure statement

The author declares no conflict of interest.

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