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Research on the Dynamic Process of Ocean-Atmosphere Interaction Based on Satellite Data Fusion

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Abstract:

This paper aims to study the dynamic process of ocean-atmosphere interaction based on satellite data fusion. By integrating multi-source satellite data, the interactions such as heat, momentum, and mass exchanges between the ocean and the atmosphere are analyzed, and their dynamic change laws and impacts on the global climate system are explored. The research results contribute to a deeper understanding of the ocean-atmosphere coupling mechanism, improve the accuracy of climate prediction and marine environmental monitoring, and provide a scientific basis for addressing global climate change and marine disasters.

Keywords:

Satellite data fusion
Ocean-atmosphere interaction
Dynamic process
Climate prediction

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1. Introduction

The ocean and the atmosphere, as two important components of the Earth's climate system, their interaction has a profound impact on global climate and weather changes. The ocean regulates the atmospheric temperature and circulation by absorbing, storing, and releasing heat, while the atmosphere affects the movement and physical-chemical properties of the ocean through processes such as wind stress and precipitation. With the development of satellite remote-sensing technology, a large amount of observational data on the ocean and the atmosphere have been obtained, providing a rich information basis for studying the dynamic process of ocean-atmosphere interaction.

2. Satellite data fusion methods

Satellite data fusion, as a key technical means, is committed to comprehensively processing observational data from different satellite sensors, so as to obtain more comprehensive and accurate information related to the ocean-atmosphere.

2.1. Spatio-temporal fusion

High-spatial-resolution remote-sensing satellite image data can provide very rich surface information and has a stronger ability to identify ground objects. However, its revisit period is relatively long. Coupled with the influence of external environments such as rain and snow, high-spatial-resolution remote-sensing satellite image data are scarce, unable to meet the needs of dynamic monitoring of time-series data in the study area in practical applications. Moreover, some high-resolution remote-sensing satellite image data are very expensive and cannot be widely promoted in reality. High-temporal-resolution remote-sensing data, although having a relatively short revisit period, have a low spatial resolution. In the actually captured image data, one pixel may contain several different types of ground objects, which is not conducive to practical applications such as ground-object classification. Therefore, researchers can only choose between temporal resolution and spatial resolution in applications [1]. The spatio-temporal fusion method focuses on integrating satellite observational data with different temporal and spatial resolutions, so as to improve the continuity and accuracy of the data in the spatio-temporal domain. Specifically, taking the Kalman filter algorithm as a typical example, this algorithm can deeply explore the hidden spatio-temporal correlations in the observational data. With this characteristic, it can methodically carry out optimization processing and error correction procedures for the original measurement data. Through a series of rigorous calculations and derivations, more accurate and reliable estimates of ocean-atmosphere parameters can be finally obtained, providing a solid data foundation for subsequent in-depth research.

2.2. Multi-sensor fusion

Different types of satellite sensors each exhibit unique performance characteristics and advantageous scopes, and can accurately and specifically observe various physical quantities in the ocean-atmosphere system. By implementing a technical strategy of fusing the data collected by multiple sensors, the inherent advantages of each sensor can be deeply explored and fully utilized, and a more complete and detailed information complex can be obtained. For example, by organically integrating key data such as sea-surface temperature and sea-surface height obtained from ocean-satellite monitoring with core data such as atmospheric temperature, humidity, and wind speed accurately captured by meteorological satellites in a scientific and reasonable way, the dynamic evolution process of heat and momentum exchange at the ocean-atmosphere interface can be understood from a more in-depth, comprehensive, and systematic perspective, laying a foundation for accurately explaining their interaction mechanism [2].

3. Analysis of the dynamic process of ocean-atmosphere interaction

This chapter details the interaction between the ocean and the atmosphere, covering heat, momentum, and mass exchanges. Using high-resolution satellite data, it shows the impact of sea-surface temperature fluctuations on atmospheric temperature and circulation and explores the impact of extreme wind events on ocean dynamics. At the same time, this chapter also examines the exchanges of carbon dioxide, water vapor, and aerosols in the ocean-atmosphere system, aiming to clarify the contributions of these exchanges to global climate change.

3.1. Heat exchange process

In the complex framework of the ocean-atmosphere coupled system, the heat-exchange mechanism between the ocean and the atmosphere undoubtedly constitutes one of the core links. The high-resolution and continuous data obtained from the satellite observation platform strongly indicate that the dynamic fluctuations of the sea-surface temperature have a significant modulating effect on the distribution of the atmospheric temperature field and the shaping process of the circulation pattern, thus exerting a crucial and far-reaching impact on the long-term evolution of the global climate. Taking the El Niño, a typical climate-abnormal phenomenon, as an example, during its occurrence and development, the sea-surface temperature in the specific sea area of the equatorial central and eastern Pacific shows a significantly abnormal warming trend. This abnormal temperature signal is like a “fuse”, quickly triggering significant distortions in the structure and path of the atmospheric circulation. This distortion effect, like a “domino”, continues to spread along the transmission path of the atmospheric circulation, ultimately driving a series of complex chain-like dynamic changes in the global climate pattern [3]. According to rigorous and detailed relevant statistical data, the global ocean, as the core hub-like regulator of the Earth system's heat budget balance, absorbs about 90% of the net heat increment. The variability of its heat content in the spatio-temporal dimension is not only closely related to the rise of the global sea - level but also plays an irreplaceable and crucial role in the macro-process of climate change. With the help of cutting-edge satellite data fusion technology, researchers can break through the limitations of traditional observation methods and can monitor the dynamic change trajectory of ocean heat content and its feedback loop to the atmosphere in real-time and with higher precision, thus providing essential key evidence for climate prediction models, effectively improving the accuracy and reliability of climate prediction work, and providing solid scientific support for addressing the challenges of global climate change [4].

3.2. Momentum exchange process

Under the dynamic framework of the ocean-atmosphere coupled system, the process of atmospheric wind stress acting on the ocean surface constitutes the dominant transmission path of momentum exchange between them. With the wide-area coverage and continuous dynamic observation capabilities unique to satellite remote-sensing technology, the fine distribution characteristics of the sea-surface wind field in the spatio-temporal dimension can be captured with extremely high precision. Taking this key observation point as an entry point, the internal mechanism of the dynamic driving of the ocean by the atmosphere can be deeply explored. At present, a large number of cutting-edge research results have indisputably revealed that the outbreak of extreme strong-wind events can often trigger a series of violent response processes on the ocean surface. On the one hand, it promotes the generation and continuous development of ocean waves. On the other hand, it strongly drives significant changes in the direction and velocity of the ocean-current system, thus exerting a far-reaching reshaping effect on the internal heat-transfer path and material-distribution pattern of the ocean, profoundly rewriting the internal energy and material balance of the ocean [5]. For example, a typhoon, as a typical product of the high-intensity coupled and synergistic action between the ocean and the atmosphere, during its complete life cycle, the strong wind concentrated in the core area of the typhoon continuously acts on the ocean surface, causing the seawater to be violently stirred and deeply mixed, generating a large number of sea - spray droplets. This complex physical process not only significantly improves the exchange efficiency of heat and material fluxes at the air-sea interface but also has powerful disturbance energy, which can deeply touch the root of the original ocean-circulation structure, change its trajectory, and at the same time, strongly reshape the vertical distribution of the ocean mixed-layer, comprehensively impacting the stability of the marine ecological environment and the inherent order of marine physical processes, triggering a series of chain-like ecological and physical responses.

3.3. Mass exchange process

In the complex coupled system composed of the ocean and the atmosphere, there are complex and diverse dynamic mass-exchange processes, and its key components include carbon dioxide, water vapor, aerosols, etc. [6] Relying on its unique high-altitude platform advantages and advanced and precise detection means, satellite observation technology has the excellent ability to monitor the transmission path, concentration - gradient distribution, and real-time flux dynamics of the above-mentioned substances at the ocean-atmosphere interface in real-time and with high precision. Specifically, aerosol particles in the atmospheric environment can penetrate the air-sea interface through the sedimentation process and enter the ocean water environment. These external substances input from the atmosphere constitute a key nutrient source for the growth and reproduction of marine phytoplankton, and thus, in a potential and far-reaching way, regulate the overall structure and functional operation mode of the marine ecosystem. At the same time, characteristic gas substances such as dimethyl sulfide produced by the metabolic activities of the marine biological community, when released into the atmospheric environment, will inevitably have a non-negligible impact on the stable state of the atmospheric chemical composition and the internal balance pattern of the climate system, continuously driving the complex process of ocean-atmosphere interaction to evolve in depth and maintaining the dynamic balance of the Earth's climate and ecosystem [7].

4. Application of satellite data fusion in ocean-atmosphere interaction research

This chapter focuses on the application of satellite data fusion technology in ocean-atmosphere interaction research, especially its role in the two fields of climate prediction and marine environmental monitoring. By integrating multi-source satellite data, this technology provides a powerful tool for an in-depth understanding of the ocean-atmosphere interaction process, thus significantly improving the accuracy of climate prediction and the real-time nature of marine environmental monitoring. The following sections will elaborate on how satellite data fusion contributes to the refined simulation and prediction of climate models, and how it plays a key role in marine disaster early-warning and ecological protection.

4.1. Climate prediction

Accurate climate prediction essentially highly depends on deep insight and thorough understanding of the complex and delicate process of ocean-atmosphere interaction. Satellite data fusion technology, as a key supporting means in the field of modern climate research, has a powerful multi-source information integration ability, can cross the barriers between different data sources, and thus accurately extract a more comprehensive and accurate set of initial state information of the ocean-atmosphere, laying a solid foundation for effectively improving the simulation precision and prediction efficiency of climate models [8]. Taking a real-world application scenario as an example, precisely positioning the satellite data that has undergone a fine-grained fusion process as the core input parameters and skillfully integrating them into the climate-model architecture can achieve high-precision tracking of the dynamic change trajectory of ocean heat content, fine-scale description of the evolution trend of atmospheric circulation, and forward-looking prediction of the long-term evolution trend of the climate system, comprehensively optimizing the simulation effect. In this way, it provides a solid, reliable, and authoritative scientific basis for carrying out short-term climate-prediction practical operations and long-term climate-change comprehensive assessment work, injects strong impetus into the progress of the climate-prediction field towards higher accuracy and stronger forward-looking, and strongly promotes the scientific development process of this field [9].

4.2. Marine environmental monitoring

Satellite data fusion technology demonstrates extraordinary effectiveness in the field of real-time marine environmental monitoring, and its scope of application comprehensively covers the entire operation system of accurate early-warning and dynamic monitoring of marine disasters. Specifically, relying on the technical superiority derived from fusing multi-source satellite data, efficient and real-time monitoring of a series of key physical quantities on the ocean surface can be achieved, such as acutely and timely capturing abnormal fluctuations in ocean-surface temperature, subtle changes in sea - surface height, and abnormal dynamic information of ocean currents in terms of direction and velocity [10]. Based on the in-depth analysis and integration of the above-mentioned monitoring data, with the help of professional prediction models and algorithms, it is possible to accurately predict the possibility of the outbreak and subsequent development of highly harmful marine disasters such as typhoons, tsunamis, and red tides in advance, effectively building an indestructible disaster - prevention and - mitigation barrier for coastal areas, and providing solid support for the stable operation of the ecological system, the stable development of the economy, and the sustainable development of society in coastal areas, maintaining the sustainable development pattern of coastal areas.

5. Conclusion

This study uses satellite data fusion technology to deeply explore the dynamic interaction between the ocean and the atmosphere. By integrating multi-source satellite data, the processes of heat, momentum, and mass exchanges are analyzed, their impacts on the global climate system are revealed, and the application value of this technology in climate prediction and marine environmental monitoring is discussed. The study finds that this technology significantly improves our understanding of the ocean-atmosphere coupling mechanism, but challenges such as data quality and algorithm optimization still need to be addressed. Looking to the future, with the progress of remote-sensing technology and the improvement of algorithms, we will obtain more accurate satellite data, providing stronger support for climate-change research and marine-resource utilization.

Disclosure statement

The author declares no conflict of interest.

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