2023 Volume 4, Issue 2
Satellite Oceanography and Meteorology
ISSN(Online): 2424-9505
ISSN(Print): 2424-8959

Exploration of the Correlation between Satellite Remote-sensing Data of Sea Ice Dynamics and Polar Meteorological Conditions

Corinne B. Hall*
School of the Earth, Ocean, and Environment, University of South Carolina, Columbia, SC 29208, USA

Corresponding author: Corinne B. Hall, corinnehall@universitysc.sc.edu

Abstract:

This paper aims to explore the correlation between satellite remote-sensing data of sea ice dynamics and polar meteorological conditions. Through the analysis of relevant satellite remote-sensing data and polar meteorological observation data, the characteristics of sea ice dynamic changes and the main elements of polar meteorological conditions are expounded. The mutual influence mechanism between the two is deeply discussed, and the significance of this correlation in climate change research, polar sea-route development, etc., is revealed. At the same time, the existing problems in current research and future research directions are also pointed out.

Keywords:

Sea ice dynamic satellites
Remote sensing
Polar regions
Meteorological conditions

Online publication: December 22, 2023

1. Introduction

The polar regions, as an important part of the Earth's climate system, the dynamic changes of sea ice in these regions have a profound impact on the global climate and environment. With the continuous development of satellite remote-sensing technology, it has become more convenient and accurate to obtain sea ice dynamic information, which provides strong support for studying the correlation between sea ice and polar meteorological conditions. An in-depth exploration of this correlation helps us better understand the changes in the polar climate system, improves the ability to predict global climate change, and also provides a scientific basis for the safe utilization of polar sea - routes and the development of polar resources.

2. Overview of satellite remote-sensing data of sea ice dynamics

2.1. Remote sensing of sea ice concentration

The rapid development of space-based remote-sensing technologies such as satellite remote sensing has made it possible to obtain continuous spatiotemporal data for sea ice monitoring and prediction. Satellite-based sea ice remote sensing has the advantages of convenient data acquisition, wide data coverage, and data collection not being restricted by special geographical environments. The use of satellite remote-sensing data can effectively and relatively accurately identify sea ice in the Bohai Sea. Remote-sensing technology is also increasingly applied in the field of sea ice disaster monitoring [1]. In the remote-sensing monitoring of sea ice concentration, electro-optical remote sensing and microwave remote sensing are the main technical means. Electro-optical remote sensing captures the reflection and radiation characteristics of sea ice through optical sensors and uses single-scattering and double-scattering models for inversion to determine the sea ice concentration. Sea ice in different states exhibits different optical characteristics under illumination. The sensor records this information and infers the sea ice concentration through algorithm models. Microwave remote sensing, on the other hand, takes advantage of its penetration power and sensitivity to sea ice changes, and performs sea ice concentration inversion through parameters such as brightness temperature, scattering coefficient, and polarization. Satellite sensors such as AMSR-E and AMSR2, with their high performance and reliable data collection, play a key role in the study of sea ice concentration, providing a solid guarantee for obtaining accurate sea ice data.

2.2. Remote sensing of sea ice thickness

In terms of remote-sensing detection of sea ice thickness, optical remote sensing estimates the thickness by obtaining the fine geometric information of the sea ice surface and combining optical models and algorithms. However, affected by atmospheric scattering, absorption, and sea ice impurities, the effective light signal attenuates, and the resolution limitation leads to insufficient accuracy [2]. In contrast, radar remote sensing uses the penetration power of radar waves. By analyzing the characteristics of radar echoes such as time delay, amplitude, and phase, and combining special inversion models, it can achieve high-precision sea ice thickness measurement, providing key data for the study of the physical structure of sea ice.

2.3. Monitoring of Sea ice Dynamic Changes

By systematically comparing and deeply analyzing multi-period satellite remote-sensing images, various change trends of sea ice can be comprehensively and dynamically monitored, including the ablation rate of ice sheets, the spatio-temporal evolution of ice thickness, and key dynamic indicators such as the drift trajectory and speed of sea ice. Many scientific research teams have long-term tracked the dynamic changes of sea ice in the Arctic region. Based on long-time-series satellite remote-sensing data, using advanced image registration, feature extraction, and change-detection algorithms, it has been accurately revealed that the sea ice coverage in the Arctic shows a statistically significant decreasing trend year by year. This discovery not only provides key empirical evidence for the study of the evolution of the Arctic ecosystem but also alerts scientific researchers to further explore the deep-seated driving factors behind it, as it is crucial for understanding the response mechanism of sea ice under the background of global climate change.

3. Main elements of polar meteorological conditions

3.1. Air temperature

The polar regions exhibit significant low-temperature characteristics, with a considerable annual temperature range. Taking the Arctic region as an example, the average air temperature often drops below - 30 ℃ in winter, presenting an extremely cold climate environment. In summer, the average air temperature only remains at a relatively low level of around 0 ℃. Air temperature, as a key environmental variable, is closely intertwined with the life cycle of sea ice. Its dynamic change process directly affects the formation process, ablation rate, and growth trend of sea ice, and is one of the core factors driving the dynamic evolution of sea ice [3]. From the perspective of thermodynamics, a low-temperature environment causes the seawater to lose heat, strengthens the interaction between water molecules, and then triggers the formation of ice crystals, initiating the condensation process of sea ice. Conversely, when the air temperature rises, sea ice absorbs external heat, the stability of the internal lattice structure is damaged, and the melting and decomposition are accelerated, resulting in significant changes in the sea ice coverage and physical form.

3.2. Wind speed

The atmospheric circulation pattern in the polar regions creates a high-wind-speed environment, and the wind direction is highly variable. Strong winds play a key dynamic role in the interaction system between the polar ocean and sea ice. The horizontal force exerted can cause the displacement of sea ice, leading to drift phenomena, resulting in the redistribution of sea ice on the ocean surface. At the same time, the continuous impact of wind increases the uneven stress distribution inside the sea ice, causing the ice to break, and then forming fragmented ice-accumulation areas of various shapes. Moreover, the frequent friction and collision between the wind and the sea ice surface profoundly affect the heat exchange efficiency between the sea ice and the surrounding atmosphere, as well as the water vapor transfer flux, breaking the original energy and material balance state, and inducing adaptive adjustments in the physical properties of sea ice, such as changing the microstructure parameters of sea ice, such as density and porosity, and then reshaping the macroscopic distribution pattern of sea ice in the ocean [4].

3.3. Air pressure

The unique air-pressure system structure in the polar regions has a non-negligible impact on the dynamic changes of sea ice. Specifically, the polar high-pressure and sub-polar low-pressure, as the dominant air-pressure systems in this region, the spatial distribution pattern and periodic change characteristics of the two jointly drive the complex evolution of the atmospheric circulation. The atmospheric circulation, as the macro-background field of sea ice movement, the dynamic adjustment of its flow direction and velocity is directly reflected in the changes of the movement trajectory and speed of sea ice. For example, during the strong stage of the polar high-pressure, driven by the pressure-gradient force, the cold air mass accelerates the advance of sea ice to low-latitude regions, expanding the sea ice distribution boundary. When the sub-polar low-pressure system deepens, the surrounding warm and humid air currents pour in, causing the sea ice to converge towards high-latitude sea areas under the complex air-flow disturbances, reshaping the sea ice distribution situation and profoundly affecting the material cycle and energy flow processes of the polar marine ecosystem [5].

3.4. Precipitation

The precipitation mode in the polar regions is mainly snowfall, and the amount of snowfall plays a key regulatory role in the evolution process of sea ice. The newly fallen snow covering the sea ice surface significantly changes the original albedo characteristics of the sea ice from the perspective of radiant energy balance. Pure sea ice usually has a high albedo and can reflect a large amount of incident solar radiation, maintaining the low-temperature environment in the polar regions. However, the snow cover reduces the overall surface albedo, increasing the share of solar-radiation energy absorbed by the sea ice, breaking the original energy-income and expenditure balance, and accelerating the melting process of sea ice. At the same time, the accumulated snow-depth, as a key physical parameter, not only increases the surface load of the sea ice, challenges the mechanical stability of the internal structure of the sea ice, and induces deformation phenomena such as cracks and collapses, but also the deep snow-layer can block the heat - exchange paths between the sea ice and the external atmosphere and seawater, further disturbing the energy balance of the sea ice and profoundly reshaping the evolution trajectory of sea ice in the polar marine ecosystem.

4. Mutual influence mechanisms between sea ice dynamics and polar meteorological conditions

4.1. Influence of polar meteorological conditions on sea ice dynamics

The increase in air temperature has a direct impact on the melting of sea ice. Research shows that in the Arctic region, for every 1 ℃ increase in air temperature, the melting speed of sea ice increases by approximately 10–15%. The high temperature in summer is particularly significant, which can quickly melt the edges of sea ice, leading to a reduction in the coverage area. At the same time, wind speed is a key factor in promoting the movement of sea ice. Strong winds can significantly accelerate the drift speed of sea ice. When the wind speed exceeds 10 m/s, the drift speed of sea ice can exceed 10 kilometers per day [6]. The change in wind direction is also important because it determines the distribution pattern of sea ice in the ocean. In addition, the change in the air-pressure system cannot be ignored. The enhancement of the polar high pressure and the deepening of the sub-polar low pressure will both affect the distribution of sea ice, causing sea ice to drift to different latitudes. This not only changes the distribution range of sea ice but also affects its thickness, having a profound impact on the polar marine ecosystem and climate environment. Finally, precipitation, especially snowfall, also affects the properties of sea ice. The increased snow depth will reduce the albedo of the sea ice surface, making it absorb more solar radiation and accelerating the melting process. At the same time, the weight of the snow may also cause deformation and cracking of the sea ice structure.

4.2. Feedback of sea ice dynamics on polar meteorological conditions

Sea ice plays a crucial role in the polar regions. Its high-albedo property enables it to reflect a large amount of solar radiation, maintaining the energy balance in the polar regions. However, with the reduction of sea ice coverage, the amount of reflected solar radiation decreases, and the ocean absorbs more radiant energy, resulting in an increase in seawater temperature. This change not only directly affects the seawater temperature but also indirectly affects the atmospheric circulation and the entire climate system. It is estimated that for every 10% reduction in the Arctic sea ice area, the air temperature in this region may rise by 0.5–1 °C. At the same time, during the melting and freezing processes of sea ice, a large amount of latent heat is released or absorbed, and this change in thermal properties has a significant impact on the heat balance in the polar regions [7]. The latent heat released during the melting of sea ice will increase the atmospheric temperature and enhance the atmospheric convective movement, while the latent heat absorbed during the formation of sea ice may lead to a decrease in the atmospheric temperature and inhibit convection. In addition, the surface roughness of sea ice is also an important factor affecting the polar climate. Broken sea ice increases the surface roughness, thus enhancing the turbulent movement in the atmospheric boundary layer and promoting the heat, water vapor, and momentum exchange between the atmosphere and the ocean. These processes jointly act on the polar meteorological conditions and climate system, making them more complex.

5. Significance of correlation research

5.1. Significance for climate change research

In-depth exploration of the correlation between sea ice dynamics and polar meteorological conditions is crucial for improving the accuracy of climate prediction. Such research not only promotes the understanding of the role and mechanism of the polar regions in the global climate system but also, through the establishment of sea ice-meteorology coupling models, can more accurately simulate and predict global climate change, providing a solid scientific basis for addressing climate change [8]. The interaction between sea ice and meteorological conditions is a key process in the climate system. Studying this feedback mechanism is of great importance for understanding the complexity and uncertainty of the climate system and provides a valuable reference for the optimization of climate models.

5.2. Significance for polar sea-route development

Mastering the correlation between sea ice dynamics and meteorological conditions is of vital importance for ensuring the safety of polar sea - routes. This understanding not only provides accurate sea ice information and weather forecasts for route planning and navigation but also enables ships to select safe routes based on the distribution and changes of sea ice, effectively avoiding sea ice-dense areas and bad weather to ensure navigation safety. Long-term monitoring and analysis of sea ice dynamics and meteorological conditions help to reveal the navigation laws and seasonal changes of polar sea-routes, providing a scientific basis for reasonably arranging ship navigation times and improving the utilization rate of sea-routes.

6. Problems and challenges in research

6.1. Data acquisition and quality issues

Satellite remote-sensing technology has significantly improved the monitoring ability of sea ice dynamics in vast sea areas, but the spatio-temporal resolution of existing satellite data still has deficiencies. For example, the revisit period of some optical remote-sensing satellites is relatively long, limiting the ability to monitor the rapid changes of sea ice in real-time. In addition, during the acquisition and processing of satellite data, affected by factors such as atmospheric correction and sensor accuracy, data errors and uncertainties may occur, affecting the accurate analysis of the correlation between sea ice dynamics and meteorological conditions. Therefore, improving the spatio-temporal resolution of data and reducing data errors are crucial for improving the accuracy of sea ice monitoring and climate research.

6.2. Difficulties in model simulation and verification

In the study of the interaction between sea ice dynamics and polar meteorological conditions, there are challenges in simulating complex physical processes, which involve the exchange of heat, momentum, and matter between the ocean, sea ice, and the atmosphere. Existing climate models and sea ice models have limitations in accurately simulating these interactions and are difficult to fully and accurately reflect the actual situation. At the same time, there are few observation stations in the polar regions, and field-observation data are limited, making the model-verification work difficult. The lack of verification data not only affects the reliability and accuracy of the model but also restricts the in-depth study of the correlation between sea ice dynamics and meteorological conditions. Therefore, improving the simulation accuracy of models for complex physical processes and increasing the observation data in the polar regions are crucial for advancing research in this field.

7. Conclusion

This paper explores the connection between satellite remote-sensing data of sea ice dynamics and polar meteorological conditions, introduces monitoring methods, and key meteorological elements, and analyzes the interaction between the two. The research is of great significance for climate change and polar sea - route development. Despite challenges such as data acquisition and model verification, with the development of remote-sensing technology and observation methods, as well as the optimization of climate models, future research on the relationship between sea ice and polar meteorology will be more in-depth, providing solid scientific support for global climate change and polar sustainable development.

Disclosure statement

The author declares no conflict of interest.

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