



Research Article

The Impacts of Warming Ocean Currents and Rivers on Arctic Sea Ice

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KEYWORDS

Arctic sea ice decline
ocean currents
river discharges
sea surface temperature
sea ice area

ABSTRACT

Global warming plays a central role in the decline of Arctic sea ice, but the mechanisms remain debated. Using satellite remote sensing data from 1982 to 2023, we investigate the relationship between Sea Ice Area (SIA) and Sea Surface Temperature (SST) in the Arctic Ocean. This study focuses on SIA across six marginal seas of the Arctic Ocean—the Barents, Kara, Laptev, East Siberian, Chukchi, and Beaufort Seas—and investigates SST in regions affected by oceanic inflows and riverine freshwater discharge. These regions encompass the Barents Sea Branch of Atlantic Water inflow, the Ob and Yenisei River mouths, the Lena River mouth, the Kolyma and Chaun River mouths, the Pacific Water inflow region, and the Mackenzie River mouth. Results indicate that SST is strongly associated with the reduction in SIA, with additional influences from Pacific and Atlantic water inflows, as well as riverine discharges, which are associated with higher SST and lower SIA. Lagged correlation analysis reveals that SST changes precede SIA changes by approximately 13 days, indicating that SST changes precede subsequent changes in SIA. The 13-day lag and the significant linear relationship between SIA and SST provide evidence for a strong temporal association between the two variables. This study elucidates the impact of warming ocean currents and freshwater influxes on Arctic sea ice dynamics, contributing to our understanding of the role of oceanic thermal conditions in Arctic sea-ice variability.

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ARTICLE INFO

Received: 17 April 2026 | Revised: 27 May 2026 | Accepted: 28 May 2026 | Published Online: 29 May 2026

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1. Introduction

The Arctic Ocean, Earth's smallest and shallowest ocean, comprises a central basin divided by undersea mountain ranges into four primary sub-basins: the Nansen, Amundsen, Makarov, and Canada Basins (Figure 1). Surrounding these are several marginal seas, including the Barents, Kara, Laptev, East Siberian, Chukchi, and Beaufort Seas. Nearly landlocked, the Arctic Ocean forms a semi-enclosed body of water, connected to the Atlantic Ocean through the Norwegian Sea, Greenland Sea, and Baffin Bay, and to the Pacific Ocean via the narrow Bering Strait.

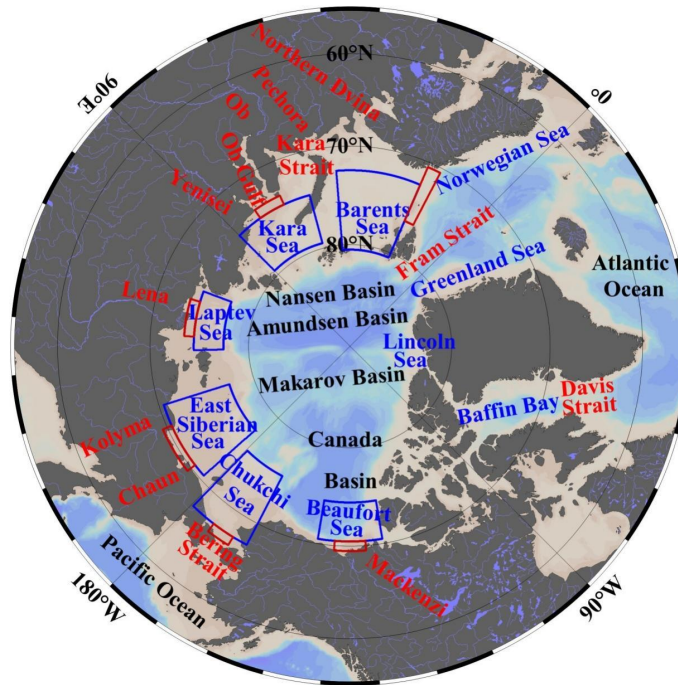


Figure 1. Map of the Arctic Ocean. The blue boxes represent distinct sea regions, while the red boxes delineate areas of ocean current flow and river discharge.

In winter, the Arctic Ocean is almost entirely covered by sea ice, while in summer, a substantial portion of this ice melts, particularly in the marginal seas [1]. Under the influence of global warming, the Arctic region has experienced profound changes, with surface temperatures rising at a rate of 2 to 3 times faster than the worldwide average. Arctic sea ice extent in September has been decreasing at an average rate of 1.1% per year [2]. This decline has led to significant alterations in the Arctic's ecological environment, with far-reaching impacts on weather patterns and climate conditions across the middle and lower latitudes of the Northern Hemisphere [2].

The decline in Arctic sea ice is attributed not to natural variations within the climate system but to the greenhouse effect resulting from human activities [3]. However, there remains no consensus on the precise

mechanisms driving this decrease. Potential direct contributors to sea ice reduction include increased solar radiation absorption [4], shifts in atmospheric circulation [5,6], rising atmospheric temperatures [7], sea ice advection [8], and heat release from near-surface temperature maxima [9,10]. Additional influences include water mass influxes from the Pacific [11,12] and Atlantic Oceans [13,14], as well as increased river discharges [15,16].

However, the temporal relationship between Sea Surface Temperature (SST) and Sea Ice Area (SIA), particularly the time lag between SST changes and subsequent SIA changes, remains insufficiently quantified across the Arctic marginal seas. Therefore, this study investigates the relationship between SST and SIA using daily observations from 1982 to 2023. The main objectives are to determine the relationship between SST and SIA, identify the characteristic time lag between them, and examine whether similar relationships occur in marginal seas influenced by Atlantic Water, Pacific Water, and river discharge. We hypothesize that changes in SST precede subsequent changes in SIA and that the characteristic lag may differ among marginal seas because of differences in oceanic and riverine inflows. The main contribution of this study is to quantify these lagged SST–SIA relationships consistently across the Arctic Ocean and its major marginal seas.

2. Data and Methods

This study utilizes remote sensing satellite data from 1982 to 2023 to analyze the SIA and SST in the Arctic Ocean. The data, sourced from the National Oceanic and Atmospheric Administration (NOAA), provide a high-resolution blended analysis of daily SST and Sea Ice Concentration (SIC, defined as the percentage of sea ice per unit ocean area) on a global grid with a spatial resolution of 0.25° latitude by 0.25° longitude [17].

The SIC dataset served as the source for calculating SIA. SIA was calculated by summing the areas of grid cells, each multiplied by its respective SIC, including only cells with ice concentrations of at least 15% [18]. The calculation is expressed by the following formula:

$$SIA = \sum SIC_i S_i \quad (1)$$

Here SIA is sea ice area (km²), S_i is the area of the grid cell (km²), and SIC_i is sea ice concentration of the grid cell (%).

To calculate the mean SST within the region, the temperature at each grid cell was multiplied by the cell's area, summed across the region, and then divided by the total area to obtain the regional mean temperature [19]. The calculation is expressed by the following formula:

$$SST = \sum T_i S_i / \sum S_i \quad (2)$$

Here SST is sea surface temperature (°C), T_i is temperature in the grid cell (°C).

To examine SIA across different seas, the blue box in Figure 1 defines the study area, which includes the Barents Sea (72.5°N–80.5°N, 21.5°E–49.5°E), the Kara Sea (74.5°N–79.5°N, 60°E–90°E), the Laptev Sea (74.5°N–77.5°N, 114.5°E–136.5°E), the East Siberian Sea (70.5°N–77.5°N, 152.5°E–176.5°E), the Chukchi Sea (67.5°N–75.5°N, 162.5°W–179.5°W), and the Beaufort Sea (70.5°N–74.5°N, 125.5°W–144.5°W).

To analyze the temperatures associated with various currents and rivers, the red boxes in Figure 1 indicate the regions where these currents and rivers flow into the Arctic seas. These regions include the Barents Sea Branch of Atlantic Water inflow region (70.5°N–76.5°N, 17.5°E–21.5°E), the mouths of the Ob Gulf and Yenisei River (73.5°N–74.5°N, 70°E–80°E), the mouth of the Lena River (73.5°N–74.5°N, 118.5°E–131.5°E), the mouths of the Kolyma and Chaun Rivers (69.5°N–70.5°N, 159°E–172.5°E), the Pacific Water inflow region (66.5°N–67.5°N, 166.5°W–172.5°W), and the mouth of the Mackenzie River (69.5°N–70.5°N, 130.5°W–139.5°W).

To investigate the underlying cause of the observed linear relationship, the heat content of seawater is analyzed. The change in heat is defined as the difference between heat input and heat output, i.e.,

$$\Delta Q = Q_{in} - Q_{out}$$

ΔQ represents the change in heat within the sea surface mixed layer from the initial time. When heat is added to seawater, it typically increases in temperature. It is assumed that a certain proportion of the input heat is used to raise the temperature of the water body, such that $\Delta Q = Q_{in} / R$ ($R > 1$), Substituting this relationship, we obtain:

$$(R-1)\Delta Q = Q_{out}$$

Substituting the equation for the change in heat energy of a given mass of water, we obtain:

$$(R-1)m_{water}c_p(SST-SST_0)=Q_{out}$$

Where m_{water} is the mass of the given water in the mixed layer, c_p is the specific heat of seawater, and SST_0 is the initial temperature.

Assuming that the primary use of heat released by seawater is for melting sea ice, this relationship can be incorporated into the latent heat equation:

$$(R-1)m_{water}c_p(SST-SST_0)=L\rho_{ice}(H_0SIA_0-HSIA)$$

Where L is the latent heat coefficient, ρ_{ice} is the density of ice, and H is the sea ice thickness. The parameters H_0 and SIA_0 represent the initial values of sea ice thickness and area, respectively. Expressed as a linear relationship, this becomes:

$$SIA = \frac{H_0SIA_0}{H} + \frac{(R-1)m_{water}c_pSST_0}{HL\rho_{ice}} - \frac{(R-1)m_{water}c_p}{HL\rho_{ice}}SST \quad (3)$$

During the process of sea ice melting, a linear relationship exists between SST and SIA. Under freezing conditions, we assume that a portion of the heat output is used to cool the water, expressed as $\Delta Q = -Q_{out} / R$ ($R > 1$). The derivation process is similar to that of melting ice, and the same formula (3) is obtained. This shows that whether it is freezing or melting ice, there is a linear relationship between SST and SIA. The formulation is used here as a simplified physical framework for interpreting the observed SST–SIA relationship, rather than as a complete ocean heat-budget calculation.

3. Results

The interannual variation of the Arctic Ocean from 1982 to 2023 was analyzed within the region north of 70°N, encompassing nearly the entire Arctic Ocean. Figure 2a shows the interannual variation in annual mean SIA and SST for this region. To facilitate comparison with SIA, the temperature axis was inverted. Over the past 40 years, SIA has generally declined, while SST has shown a corresponding increase. SIA and SST demonstrate an inverse relationship, with a correlation coefficient of -0.78, indicating that higher SSTs are associated with lower SIA and vice versa.

The analysis of specific Arctic waters is detailed below. Atlantic Water enters the Arctic Ocean through either the Fram Strait or the Barents Sea, with these water masses merging in the northern Kara Sea and then flowing counterclockwise along the Arctic basin's periphery [20,21]. In the Barents Sea, Atlantic Water significantly influences the regional climate and ecosystem and is closely linked to sea ice dynamics [22]. Figure 2b illustrates the interannual variation of SIA in the Barents Sea and SST of the Barents Sea Branch of Atlantic Water, which show similar interannual variations, with a correlation coefficient of -0.79. In addition to Atlantic Water, the Northern Dvina and Pechora Rivers also play a significant role, particularly in spring when large amounts of freshwater enter the Barents Sea as snow and ice melt, influencing seasonal ice cover in the region.

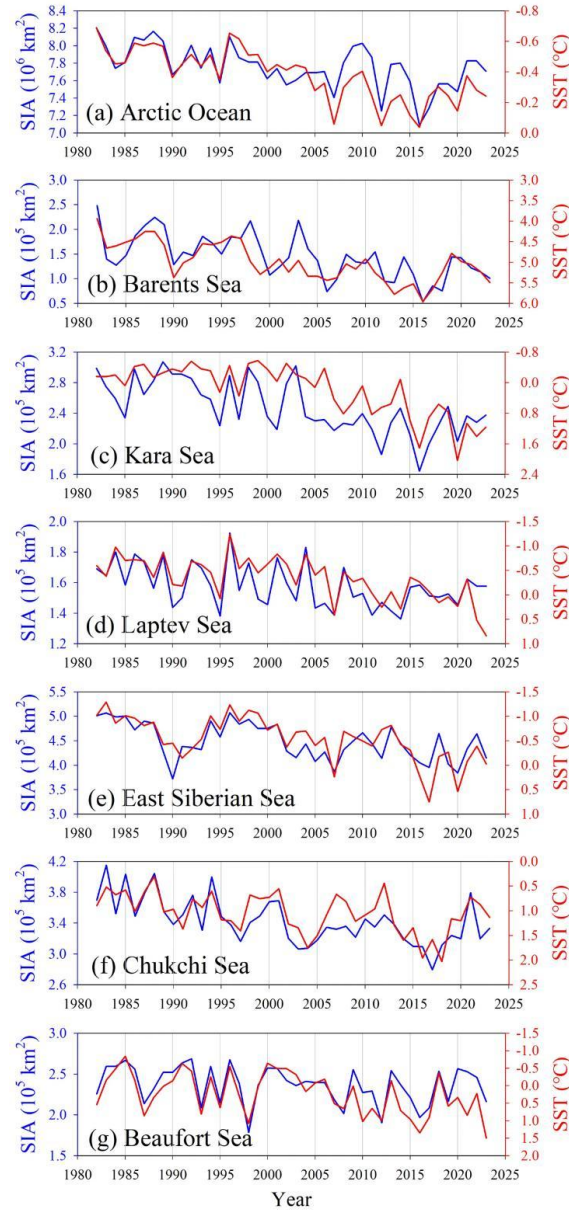


Figure 2. (a) Interannual variation of SIA and SST between 70°N and 90°N in the Arctic Ocean. (b–g) Interannual variation of SIA in various seas and SST from different sources.

The Ob River, extends 3,650 kilometers across Western Siberia, eventually draining into the Kara Sea via the Gulf of Ob. The Yenisei River, the fifth-longest river system in the world, is the largest river discharging into the Arctic Ocean. Significant increases in both the discharge volume and heat flux of the Ob and Yenisei rivers, accompanied by reductions in sea ice extent in the Kara Sea, have been observed in recent years [15]. Figure 2c illustrates the interannual variations in SIA in the Kara Sea and SST at the mouths of the Ob Gulf and Yenisei River. These variables display negative correlations, with a correlation coefficient of -0.75, indicating a close statistical association between SST at the river-influenced region and SIA variability. Additionally, the influence of water inflow through the Kara Strait into the Kara Sea must be considered. The Kara Strait, a narrow passage connecting the Barents Sea and the Kara Sea, plays a critical role in the seasonal melting of sea ice, especially during warmer months.

The Lena River, Russia's second-largest river, traverses Siberia and discharges into the Laptev Sea in the Arctic Ocean. Recent data indicate a substantial increase in the heat content of the Lena River, which has contributed to reductions in sea ice in the Laptev Sea during spring and summer [15,23]. Figure 2d presents the interannual variations in SIA in the Laptev Sea and SST at the mouth of the Lena River, which also show correlation, with a coefficient of -0.72, indicating a strong statistical association between SST near the river mouth and local sea-ice variability.

The Kolyma River, located in northeastern Siberia, exerts a significant influence on the East Siberian Sea. The river remains frozen to depths of several meters for approximately 250 days each year, becoming ice-free only from early June to October. The Chaun River, also in northeastern Siberia, provides an inflow of freshwater into the East Siberian Sea. Ice melt in late spring and summer represents a critical source of freshwater, supplementing the discharge from these rivers [16]. Figure 2e illustrates the interannual variations in SIA in the East Siberian Sea and SST at the mouths of the Kolyma and Chaun rivers. The two variables exhibit similar interannual patterns, with a correlation coefficient of -0.79, indicating a strong statistical association between river-mouth SST and sea-ice variability.

Pacific Water flows through the Bering Strait into the Chukchi Sea and subsequently enters the Arctic basin. Seasonal variations lead to the division of Pacific Water into two distinct types: Pacific Summer Water, which is warmer and less saline, and Pacific Winter Water, which is cooler and more saline [24]. In recent years, both the temperature and flux of Pacific Summer Water have been observed to increase [25]. In the Chukchi Sea, SIA is strongly correlated with the heat flux of the water mass, with significant melting of sea ice occurring along its flow path [25,26]. Figure 2f illustrates the interannual variations in SIA in the Chukchi Sea and SST of Pacific Water. The two variables exhibit similar interannual patterns, with a correlation coefficient of -0.76.

The Mackenzie River, the second-longest river in North America, flows through northwestern Canada and discharges into the Beaufort Sea in the Arctic Ocean. Each spring, the melting river ice transports significant amounts of heat northward, contributing to the melting of sea ice in the Beaufort Sea [27]. Figure 2g presents the interannual variations in SIA in the Beaufort Sea and SST at the mouth of the Mackenzie River. The two variables exhibit a strong negative correlation, with a correlation coefficient of -0.82.

A plausible explanation for the strong correlation between sea ice and temperature is that SST may influence SIA: higher temperatures are associated with sea-ice melting, while lower temperatures are associated with sea-ice formation. However, the relationship could also be reversed, with sea ice conditions influencing temperature. In this scenario, increased sea ice cover leads to lower temperatures, while reduced sea ice cover results in higher temperatures. This occurs due to the difference in albedo between sea ice and seawater. The albedo of sea ice is much higher (approximately 85%) compared to that of seawater (about 7%), meaning that areas covered by sea ice reflect most solar radiation. As sea ice decreases, more solar radiation is absorbed by the ocean, leading to an increase in SST, which further accelerates sea ice melt in a positive feedback loop known as the ice-albedo feedback [4]. This raises the question: which process occurs first—does the decrease in sea ice lead to an increase in temperature, or does the increase in temperature drive the reduction in sea ice?

Daily SIA and SST in the Arctic Ocean from 1982 to 2023 were analyzed. A significant negative correlation was observed between the two variables. When changes in SIA are lagged relative to SST, the correlation coefficient increases, as depicted in Figure 3. The highest correlation, with a lag of 13 days, yields a correlation coefficient of -0.98. This indicates that SST changes systematically precede subsequent changes in SIA, suggesting a strong lagged statistical relationship between the two variables. Figure 3 also illustrates the lagged relationships between SIA in various seas and SST from different sources.

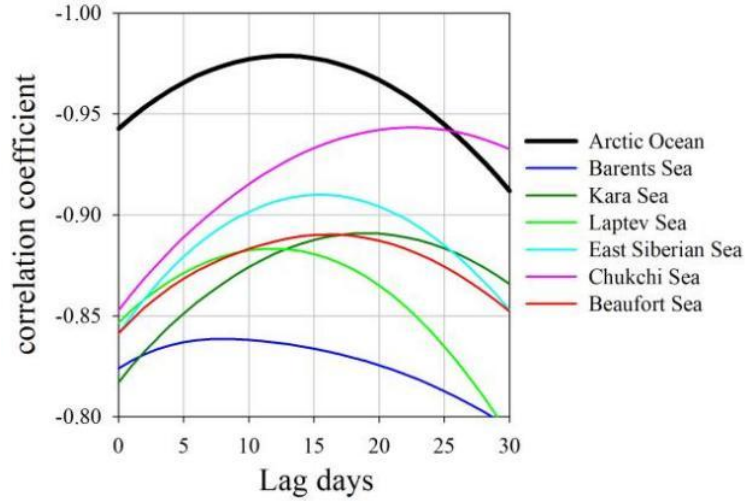


Figure 3. Temporal lag relationship between SIA and SST.

- Barents Sea: The highest correlation between SST of the Barents Sea Branch of Atlantic Water and SIA in the Barents Sea occurs with an 8-day lag, yielding a correlation coefficient of -0.84.
- Kara Sea: The highest correlation between SST at the mouth of the Ob Gulf and Yenisei River and SIA in the Kara Sea is observed with a 19-day lag, resulting in a correlation coefficient of -0.89.
- Laptev Sea: The highest correlation between SST at the mouth of the Lena River and SIA in the Laptev Sea occurs with an 11-day lag, producing a correlation coefficient of -0.88.
- East Siberian Sea: The highest correlation between SST at the mouth of the Kolyma and Chaun Rivers and SIA in the East Siberian Sea is found with a 15-day lag, yielding a correlation coefficient of -0.91.
- Chukchi Sea: The highest correlation between SST of the Pacific Water and SIA in the Chukchi Sea is observed with a 22-day lag, resulting in a correlation coefficient of -0.94.
- Beaufort Sea: The highest correlation between SST at the mouth of the Mackenzie River and SIA in the Beaufort Sea occurs with a 16-day lag, yielding a correlation coefficient of -0.89.

Analysis of interannual variations and lagged correlations reveals an increasing trend in water temperature in the Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea, Chukchi Sea, and Beaufort Sea, accompanied by a concurrent decrease in SIA. A significant negative correlation is observed between these variables. This indicates that, the warming of marginal-sea waters associated with Pacific Water, Atlantic Water, and river-influenced regions is accompanied by a notable reduction in SIA.

Given that SIA in the Arctic Ocean lags behind the SST by 13 days, the relationship between SIA and SST from 13 days prior SST_{13} is shown in Figure 4. A linear statistical relationship is observed between SIA and SST 13 days prior, as expressed by the following equation:

$$SIA = 7.003 \times 10^6 - 1.963 \times 10^6 \times SST_{13} \quad (4)$$

Here SIA is expressed in km^2 and SST_{13} is expressed in $^{\circ}\text{C}$; consequently, the regression slope has units of $\text{km}^2 \text{ } ^{\circ}\text{C}^{-1}$.

The empirical relationship fitted from the observational data (formula 4) is similar to the relationship derived under idealized conditions (formula 3), with both indicating a linear negative relationship between SST and SIA. The observed lagged correlation between SST and SIA is physically consistent with heat-transfer processes between seawater and sea ice. However, the present analysis does not independently quantify atmospheric forcing, radiative processes, or ice–albedo feedback; therefore, the effects of other processes on sea ice cannot be neglected.

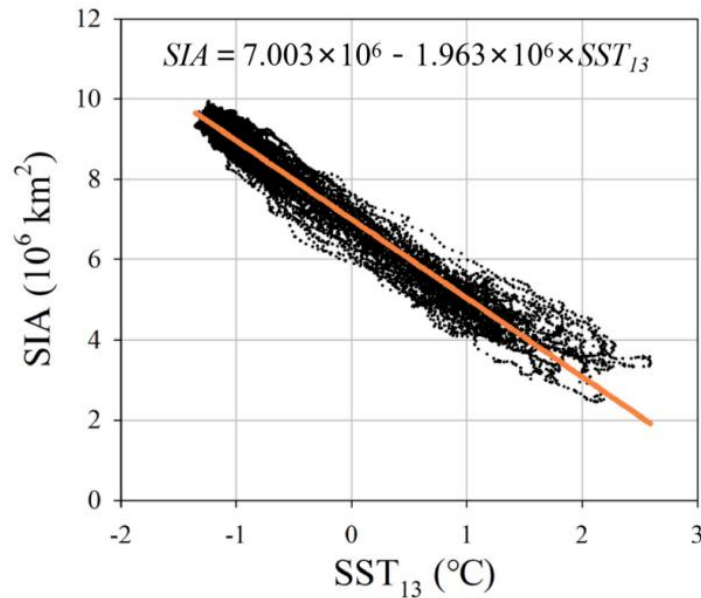


Figure 4. Relationship between SIA and SST from 13 days prior in the Arctic Ocean. The orange line represents the linear regression fit.

4. Summary

This study investigates the relationship between Sea Surface Temperature (SST) and Arctic Sea Ice Area (SIA), with emphasis on regions influenced by Pacific Water, Atlantic Water, and river discharge into the Arctic Ocean. Using satellite remote sensing data from 1982 to 2023, the study identifies a strong inverse relationship between SST and SIA, with SST changes preceding SIA changes by approximately 13 days in the Arctic Ocean. The analysis highlights that Pacific Water, Atlantic Water, and river discharges, raise SSTs in marginal seas, potentially contributing to regional sea-ice variability through oceanic thermal processes. The potential impact of ocean currents and river inflows on sea ice dynamics in the Arctic basin requires further investigation. However, the correlation and lagged-correlation analysis cannot by itself establish causality or exclude the influence of other atmospheric, radiative, and cryospheric processes.

Author's Contributions

Xue-Long Song and Sheng-Qi Zhou conceptualized the study and developed the initial research framework. Sheng-Qi Zhou and Ling Qu conducted data collection and processing, including the analysis of satellite remote sensing data. Sheng-Qi Zhou and Yuan-Zheng Lu performed the correlation and lagged analyses of SST and SIA. Qun-Hui Gao and Lu-Dan Pan prepared the figures and visualized the key results. Xue-Long Song and Qun-Hui Gao wrote the manuscript. All authors reviewed and approved the final manuscript..

Funding

This study is supported by the National Key Research and Development Program of China (2021YFC3101300, 2021YFC3101303), the National Natural Science Foundation of China (42006196, 91952106), the Hainan Province Science and Technology Special Fund (ZDYF2021GXJS217), the Guangdong Basic and Applied Basic Research Foundation (2021A1515110839), the Key Special Project for Introduced Talents Team of Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou) (GML2019ZD0304; SMSEGL20SC01), the

Institution of South China Sea Ecology and Environmental Engineering, Chinese Academy of Sciences (ISEE2021PY01), Hubei Provincial Natural Science Foundation of China (2022CFB334), and the LTO Research Project (LTOZZ2001).

Data Availability

NOAA OI SST V2 High Resolution Dataset data provided by the NOAA PSL, Boulder, Colorado, USA, from their website at <https://psl.noaa.gov>

Conflict of Interest

The authors of this work declare that they have no conflicts of interest.

Declarations Ethics

This study used publicly available satellite remote sensing datasets and did not involve human participants, animals, or biological specimens; therefore, ethics approval was not applicable.

Acknowledgements

The remote sensing satellite data provided by NOAA is gratefully appreciated.

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