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Research On The Causes Of Sea Ice Decline In The Arctic Ocean

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Abstract:
Background: *Global warming undoubtedly plays a crucial role in the decline of Arctic sea ice. However, the specific pathways leading to the decrease in sea ice remain controversial.*
Data and Methods: *This article uses remote sensing satellite data from 1982 to 2023 to analyze the sea ice area, sea surface temperature and air temperature in the Arctic Ocean.*
Conclusion: *It is found that air temperature affects sea surface temperature, and sea surface temperature determines sea ice area. In addition to the air temperature factor, the Pacific Water, the Atlantic Water, the Mackenzie River and the Lena River flowing into the Arctic Ocean will also cause changes in sea surface temperature, thus changing the size of sea ice area.*
Key Word: *sea ice area; sea surface temperature; Arctic Ocean; global warming.*

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I. Introduction

The Arctic Ocean is the smallest and shallowest ocean on Earth, consisting of the Arctic basin and marginal seas. Undersea mountains divide the Arctic Ocean into four basins: the Nansen Basin, the Amundsen Basin, the Makarov Basin, and the Canada Basin (**Figure 1**). The Arctic Ocean is surrounded by land and is nearly semi-enclosed. It is connected to the Atlantic Ocean through the Norwegian Sea, Greenland Sea and Baffin Bay, and to the Pacific Ocean through the narrow Bering Strait[1].

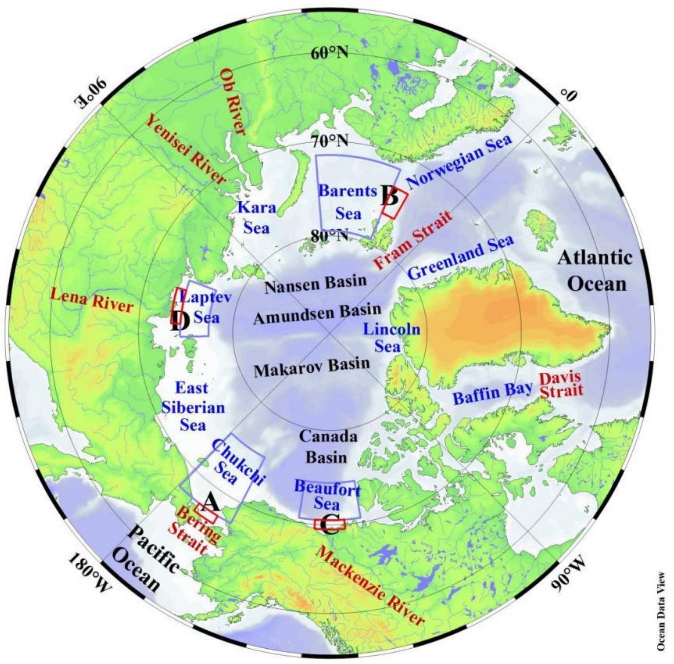

Figure 1 : Map Of The Arctic Ocean

In winter, the Arctic Ocean is almost entirely covered by sea ice, while in summer, a large amount of sea ice melts in the marginal sea of the Arctic Ocean[2]. In the context of global warming, the Arctic Ocean has undergone great changes. The Arctic surface is warming 2 to 3 times faster than the global average. The Arctic sea ice extent in September is decreasing at an average rate of 1.1% per year[3,4]. This has significantly changed the ecological environment of the Arctic, which in turn has an important impact on the weather and climate in the middle and low latitudes of the Northern Hemisphere[3].

The decrease in Arctic sea ice is not the result of changes in the natural internal climate system, but the greenhouse effect caused by human activities[5]. However, scientists have not yet reached a unanimous conclusion as to what exactly causes the decrease in Arctic sea ice. Possible direct reasons for the reduction of sea ice include: absorption of more solar radiation[6]; changes in atmospheric circulation[7,8]; changes in atmospheric temperature[9]; advection of sea ice[10]; release of heat from the near-surface temperature maximum[11,12]; water mass from the Pacific Ocean[13,14]; water mass from the Atlantic Ocean[15,16], etc.

In this paper, remote sensing satellite data from 1982 to 2023 are used to analyze sea ice area (SIA), sea surface temperature (SST) and air temperature (AT) in the Arctic Ocean, and to investigate whether there is any correlation between them. In Section II, the data and methods are presented. In Section III, the relationship between SIA, SST and AT in the Arctic Ocean is analyzed. In Section IV, sea ice changes in the marginal seas of the Arctic Ocean are studied. Section V is the conclusion.

II. Data And Methods

In this paper, Sea Ice Concentration (SIC, percentage of sea ice per unit area of ocean), SST and AT data from several remote sensing satellites are used for cross-comparison. Data sources are as follows:

1. SIC and SST from National Oceanic and Atmospheric Administration (NOAA) optimum interpolation high resolution datasets[17];
2. Monthly SIC and SST from Met Office Hadley Center observations datasets[18];
3. Monthly SIC and SST from the Japan Meteorological Agency's Centennial in situ Observation-Based Estimates (COBE)[19];
4. SIC from the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E)[20];
5. Monthly altitude 2m AT from the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP-NCAR) reanalysis[21];
6. Daily altitude 2m AT from National Oceanic and Atmospheric Administration (NOAA), the Cooperative Institute for Research in Environmental Sciences (CIRES), and the U.S. Department of Energy (DOE) 20th century reanalysis[22].

Based on data of remote sensing satellite, SIC of each grid can be obtained (SIC_i), and then multiplied by the area of each grid (S_i), to obtain the sea ice area of each grid[23], and then summed to get the total sea ice area (SIA_{Total}), i.e. Equation (1).

$$SIA_{Total} = \Sigma SIC_i S_i \tag{1}$$

Similarly, when calculating the mean SST and mean AT within the region, the temperature at each grid (T_i) multiplied by the area of the grid, then summed it up, and then divided by the total area to obtain the mean temperature within the region (T_{mean}), i.e., Equation (2).

$$T_{mean} = \Sigma T_i S_i / \Sigma S_i \tag{2}$$

Why not just average the temperature here? This is because the earth is a sphere, and each grid of remote sensing satellite data corresponds to a different area. If the temperature is directly averaged, the result obtained is not the accurate average temperature in this area.

III. Relationship Between SIA, SST And AT

In order to study the interannual variation of the Arctic Ocean from 1982 to 2023, spatially, within 70°N latitude was selected as the study area, which encompasses almost the entire Arctic Ocean. Temporally, September of each year was chosen because of the least sea ice in September[24]. In terms of data, monthly data from NOAA, Hadley, and COBE were used to calculate SIA and SST in the Arctic Ocean, while AT were derived from NCEP-NCAR monthly altitude 2m AT.

The interannual variation in SIA, SST and AT in the Arctic Ocean in September are shown in **Figure 2a**. The SIA is decreasing significantly for all three data, from about 6 million km^2 in the last century to about 4 million km^2 now, and the SIA reaching its lowest value in 2012. In order to compare with the SIA, the temperature axis was inverted. The SST is increasing for all three data, about 1°C since 1982. Moreover, SIA has a high correlation with SST, with a correlation coefficient of -0.883 for NOAA data, -0.924 for Hadley data and -0.965 for COBE data.

AT in the Arctic Ocean increased from about -5°C to about -2°C, with interannual variation almost identical to SST and a high negative correlation with SIA. The correlation coefficient between AT and SIA from NOAA data is -0.891, the correlation coefficient with SIA from Hadley data is -0.927, and the correlation coefficient with SIA from COBE data is -0.910. A more plausible explanation for such a high correlation between sea ice and temperature is that SST and AT determine sea ice conditions, i.e., higher temperatures cause sea ice to melt and lower temperatures cause sea ice to freeze.

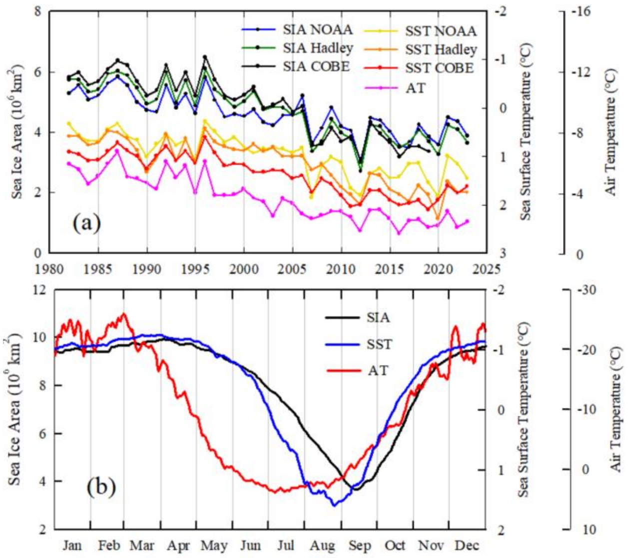

Figure 2 : (a) Interannual Variation Of SIA, SST And AT In The Arctic Ocean In September, (b) Changes Of SIA, SST And AT Over Time In The Arctic Ocean In 2010

However, it could also be the opposite. Sea ice conditions determining the temperature, i.e., more sea ice resulting in lower temperatures and less sea ice resulting in higher temperatures. Why is this so? This is due to the fact that the albedo of solar radiation is much higher in areas covered by sea ice (about 85%) than in seawater (about 7%). The reduction of sea ice will cause more solar radiation being absorbed, which will result in higher SST and AT, as well as greater sea ice melting, i.e., ice–albedo feedback[6,25].

So which happened first, the decrease in sea ice causing the increase in temperature or the increase in temperature causing the decrease in sea ice? We have analyzed the daily NOAA data in 2010. The changes in SIA, SST and AT over time in the Arctic Ocean in 2010 are shown in **Figure 2b**. The three have similar seasonal change patterns, and there is an obvious lagging relationship. AT reaches its maximum in July, SST is highest in August, and SIA is smallest in September.

The correlation between AT and SST with a lag of 33 days is the highest, with a correlation coefficient of -0.877. The correlation between SST and SIA with a lag of 16 days is the highest, with a correlation coefficient of -0.993. This shows that AT changes earlier than SST, and AT can affect SST. The correlation between SST and SIA is higher and closer in time.

Not only 2010, but also other years have the same lagged relationship, as shown in **Table 1**. From 1982 to 2023, changes in SIA lag behind SST, with an average lag of 12.4 days, and an average correlation coefficient of -0.989. This means that after the SST changes, the SIA changes. There is a very strong correlation between the two, that is, the SST determines the SIA.

Table 1 : Lagging Relationship Between SIA And SST

Years	Lag days	Correlation coefficient
1982	13	- 0.989
1983	9	- 0.994
1984	15	- 0.987
1985	11	- 0.989
1986	13	- 0.994
1987	11	- 0.994
1988	9	- 0.990
1989	12	- 0.993
1990	9	- 0.989
1991	12	- 0.987
1992	8	- 0.995
1993	11	- 0.995
1994	10	- 0.995
1995	8	- 0.990
1996	12	- 0.989
1997	9	- 0.988
1998	13	- 0.989
1999	12	- 0.989
2000	11	- 0.990

2001	8	- 0.995
2002	13	- 0.995
2003	13	- 0.989

Table 1 : Lagging Relationship Between SIA And SST (Continue)

Years	Lag days	Correlation coefficient
2004	13	- 0.994
2005	16	- 0.990
2006	12	- 0.989
2007	13	- 0.985
2008	14	- 0.994
2009	18	- 0.971
2010	16	- 0.993
2011	14	- 0.994
2012	16	- 0.993
2013	14	- 0.990
2014	17	- 0.989
2015	16	- 0.990
2016	18	- 0.992
2017	11	- 0.986
2018	13	- 0.979
2019	12	- 0.974
2020	13	- 0.975
2021	8	- 0.979
2022	14	- 0.975
2023	12	- 0.983

IV. Sea Ice Changes In The Marginal Seas Of The Arctic Ocean

After analyzing the temporal changes of Arctic sea ice, we then analyzed the spatial distribution of sea ice. The SIC data from AMSR-E in August 2010 were selected to plot the interpolated map of sea ice distribution (**Figure 3a**). It can be clearly seen that the Arctic basin has a higher SIC, indicating that it is mostly sea ice, while the marginal sea has a lower SIC, indicating that it is mostly seawater. The melting of sea ice is particularly significant in the Barents, Kara, Laptev, Chukchi and Beaufort Seas.

Data of NOAA for the same time period were used to plot an interpolated map of the SST distribution (**Figure 3b**). SST were found to be lower in the Arctic basin and higher in the marginal seas. In particular, the SST is significantly higher at the mouths of rivers and in the region where Pacific and Atlantic waters converge into the Arctic Ocean. Moreover, the SST distribution and the SIC distribution are consistent in space. Where the SST is high, the sea ice has melted significantly.

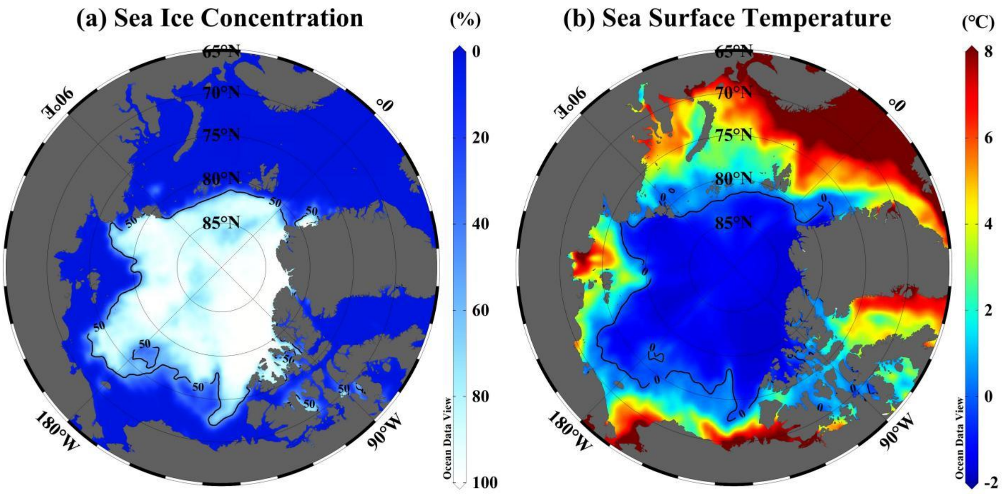

Figure 3 : Interpolation Of (a) SIC And (b) SST In The Arctic Ocean In August 2010

The following is an analysis of the specific waters of the Arctic Ocean. The Pacific Water passes through the Bering Strait and flows through the Chukchi Sea into the Arctic basin. Due to the seasons, Pacific Water is divided into Pacific Summer Water, which is warmer and less saline, and Pacific Winter Water, which is cooler and more saline[26]. In recent years, the temperature and flux of Pacific Summer Water have continued to increase. The temperature has been 2 to 4°C higher than in the 1990s, and the water flow has increased by an average of 0.01Sv per year[27]. In the Chukchi Sea, the SIA has a high correlation with the heat flux of the water mass, and significant melting of sea ice occurs along the flow path of the water mass[23,27].

The interannual variation of SIA in the Chukchi Sea and SST of the Pacific Water are shown in **Figure 4a**. The area corresponding to the SIA is the blue box A in Figure 1 (latitude 67.5°N~75.5°N, longitude 162.5 °W~179.5°W), the area corresponding to the SST is the red box A in Figure 1 (latitude 66.5°N~67.5°N, longitude 166.5°W~172.5°W). To avoid the influence of lag effects, the data were averaged over a full year. The SIA in the Chukchi Sea has a high correlation with the SST of the Pacific Water, with correlation coefficients of -0.856 for NOAA data, -0.888 for Hadley data, and -0.909 for COBE data.

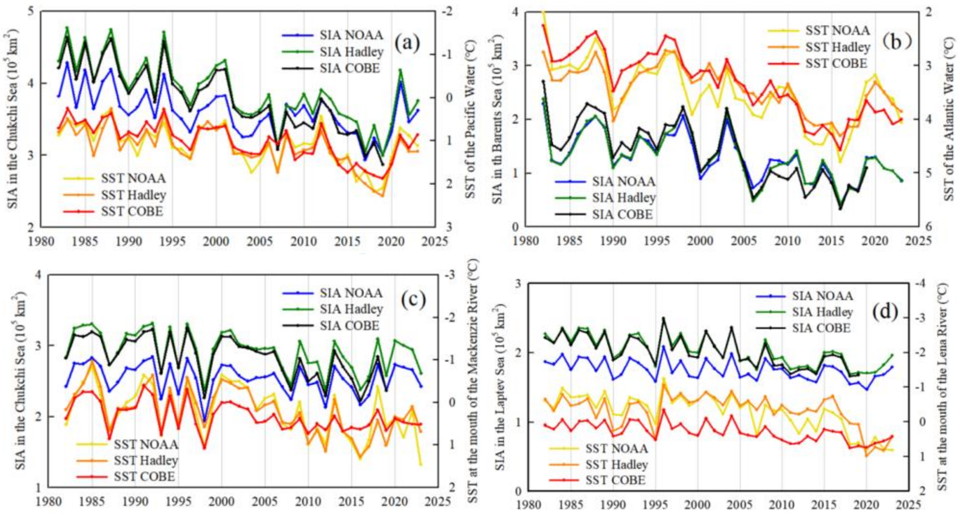

Figure 4 : Interannual Variation of SIA In Various Seas And SST From Different Sources In Annual Mean

The Atlantic water enters the Arctic Ocean through the Fram Strait or the Barents Sea. The two water masses merge in the northern Kara Sea and then flow counterclockwise along the edge of the Arctic basin[28,29]. For the Barents Sea, The Atlantic Water not only affects the climate and ecosystem, but also has a close relationship with sea ice[30]. The interannual variation of SIA in the Barents Sea (blue box B in Figure 1, latitude 71.5°N~79.5°N, longitude 21.5°E~49.5°E) and SST of the Atlantic Water (red box B in Figure 1, latitude 73.5°N~76.5°N, longitude 15.5°E~21.5°E) are shown in **Figure 4b**. The two have a high correlation, with correlation coefficients of -0.817 for NOAA -0.788 for Hadley, and -0.883 for COBE data.

The Mackenzie River is the second longest river in the North America, flowing through the northwestern Canada, and discharging into the Beaufort Sea of the Arctic Ocean. Every spring, the river ice begins to melt, transporting a large amount of heat northward and melting the sea ice in the Beaufort Sea of the Arctic Ocean[31]. The interannual variation of SIA in the Beaufort Sea (blue box C in Figure 1, latitude 70.5°N~74.5°N, longitude 125.5°W~144.5°W) and SST at the mouth of the Mackenzie River (red box C in Figure 1, latitude 69.5°N~70.5°N, longitude 130.5°W~139.5°W) are shown in **Figure 4c**. The two have a high correlation, with correlation coefficients of -0.799 for NOAA data, -0.868 for Hadley data, and -0.881 for COBE data.

The Lena River is the second largest river in Russia, flowing through Siberian and discharging into the Laptev Sea of the Arctic Ocean. In recent years, the heat of the Lena River has increased significantly, affecting the sea ice in the Laptev Sea during spring and summer[32,33]. The interannual variation of SIA in the Laptev Sea (blue box D in Figure 1, latitude 74.5°N~77.5°N, longitude 114.5°E~136.5°E) and SST at the mouth of the Lena River (red box D in Figure 1, latitude 73.5°N ~74.5°N, longitude 118.5°E~131.5°E) are shown in **Figure 4d**. The two have a high correlation, with correlation coefficients of -0.750 for NOAA data, -0.687 for Hadley data, and -0.969 for COBE data.

Through the interannual variation, it is found that the water temperature into the Chukchi Sea, the Barents Sea, the Beaufort Sea and the Laptev Sea is increasing, while the SIA is decreasing. There is an obvious negative correlation between them. This suggests that after the Pacific Water, Atlantic Water, Mackenzie River and Lena River merge into the Arctic Ocean, the temperature of the marginal sea of the Arctic Ocean increases, resulting in a significant reduction in sea ice.

V. Conclusion

As results of global warming, rivers flowing into the Arctic Ocean are warming, water from the Pacific and Atlantic is warming, and the atmospheric temperature in the Arctic Ocean is warming. These factors lead to rising water temperature of the Arctic Ocean, which in turn lead to the sea ice reduction. If global warming continues, water temperature will continue to rise, and the Arctic Ocean will become ice-free in summer.

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