Analysis of Sea Ice Area Variation in the Arctic Ocean

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Abstract. Against the backdrop of global warming, the changing area of Arctic sea ice is constantly shrinking, and the fluctuation of the Arctic sea ice area is the outcome of multiple factors. This paper mainly studies the volatility, periodicity, trend and related climate factors of Arctic sea ice area variation. It is found that the period of Arctic sea ice area variation T is equal to 3.468 years by establishing a sea ice area change model, and there is a strong negative correlation between the time series of the deseasonalized temperature and the sea ice area through the correlation analysis, with a Pearson coefficient of -0.711. In addition, the Bruun rule leads to the conclusion that for every 1cm increase in sea level, the coastline will retreat by 0.5-1m, which indirectly indicates that without considering other conditions, the continental area will decrease as the sea ice area decreases. Finally, the conclusion obtained is that the CO_2 level has the highest correlation degree by establishing a grey correlation degree model for each factor. Based on this, various measures are proposed to find solutions to the relevant factors and change existing policies to minimize the harm of the warming climate.

1 Introduction

The fluctuation of the Arctic sea ice area can reflect climate change. As various activities on Earth have significantly increased carbon dioxide, the temperature is going up. Studying the area fluctuation data of Arctic sea ice not only reveals the driving forces of climate change, but also explores the greenhouse effect and quantitatively studies the harm of adverse factors of climate change.Nowadays,There are two main methods to study the area of sea ice cover in the Arctic Ocean:satellite observations and numerical simulations.Satellite observations are passive monitoring methods that utilize images captured by satellites to acquire the coverage and distribution of sea ice. Besides,Numerical simulations are active monitoring methods that use numerical simulation software to model the flow and movement of sea ice.

Using this two methods,many researchers have carried out different aspects of research in the study on the area of the Arctic Ocean covered by sea ice. In satellite observations field,aiming at getting correlation between sea ice area and temperature, Ren et al.[1] ,found that there is consistency in the impact of temperature changes on sea ice and snow cover, but there are differences in the response time of snow cover and sea ice to temperature, indicating spatial variability.As for the climate change,Xue et al.[2] found that the increase in CO_2 concentration in the atmosphere affects climate change factors, including temperature, leading to the retreat of Arctic sea ice.Additionally,to sum up the seasonal rule,Liu[3] analyzed the spatial variation trends of long-term ice and seasonal sea ice by performing map algebra operations on the density data within the edge line range of these two types of ice.In numerical simulations field, Liu et al.[4-5] pointed out a relationship between sea ice area variation and ice density in the North and South Poles. Wang et al.[6-8] believed that the reduction of sea ice cover significantly increases the impact of atmospheric heat transfer, while Han et al.[9-10] put forward other perspectives for analyzing changes in the Arctic Ocean sea ice area.H.Yu Models[11] changes in coastal erosion and sedimentation under wave action to search for the effect of the reduction of sea ice area. Additionally,Aldenhoff[12-13] offered other efficient methods to analysis the variation of sea ice area.

Although there has been a lot of research,there is still a vacany in the study of sea ice area characteristics and related quantitative analysis.Thus,this paper mainly studies the volatility, periodicity, trend and related climate factors of changes in Arctic sea ice area as well as the interrelationship between sea ice area variation and climate change, and presents the impact of Arctic sea ice change on the regional area of the Earth. A mathematical model is established through given indicators to minimize the harm of climate change by changing existing policies. The main contributions are as follows:

1. By establishing a model of sea ice area variation, it is determined that the period of sea ice area variation in the Arctic Ocean T is equal to 3.468 years.

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2. There is a strong negative correlation between the time series of the deseasonalized temperature and the sea ice area through the correlation analysis, with a Pearson coefficient of -0.711.Besides,the area change of Arctic sea ice lags behind the temperature from 1 to 2 months.

3. According to Bruun's conclusion that for every 1cm increase in sea level, the coastline will retreat by 0.5-1m, which indirectly indicates that without considering other conditions, the continental area will decrease as the sea ice area decreases.

4. The conclusion obtained is that the CO_2 level has the highest correlation degree by establishing a grey correlation degree model for each factor, so various measures are proposed to find solutions to the relevant factors and change existing policies to minimize the harm of the warming climate.

For the organizational structure below, the third paragraph mainly focuses on the model of sea ice area change and mainly analyzes the correlation between the time series of the deseasonalized temperature and the sea ice area, the fourth paragraph mainly introduces the impact of Arctic sea ice variation on the regional area of the Earth, and the fifth paragraph mainly discusses the correlation coefficients and relevant measures between various data and temperature values, while the conclusion and discussion are narrated in the sixth paragraph.

2 Methods

2.1. Sea Ice Area Change Model

2.1.1 Construction of Sea Ice Change Model:

The years of changes in sea ice reflect the characteristics of the climate changes in the Arctic Ocean over the years. At present, research on the mechanism of sea level changes in the Arctic Ocean is not systematic. Essentially, sea level change is the sum of changes in the specific volume and mass of seawater. The change in specific volume comes from changes in temperature and salinity of seawater, which is actually the rise and fall of sea level caused by changes in seawater density and volume. In this section, a sea ice area change model from volatility, periodicity and trend will be built based on the sea ice area data provided by the National Snow and Ice Data Center of the United States from 1979 to 2020.

After standardizing and normalizing the data for each month, the standard deviation is used as the volatility value to measure each region. Table 1 shows the volatility analysis of representative regions:

Table 1: Fluctuation of Sea Ice Area in the St. Lawrence Area

Corresponding Year	Fluctuation Value (Standard Deviation)
1980	0.316
1990	0.878
2000	0.961
2010	1.235
2020	1.457

The sea ice area in the Saint Lawrence area is relatively low and will drop to 0 in August and September. Although the Arctic center, Eastern Siberia and the Bering Strait boast the largest sea ice area, the sea ice area continues to decrease over time due to global temperature rise. Overall, the sea ice area in the Arctic region reaches its maximum in March and its minimum in September, and the fluctuation of temperature changes increases with age.

2.1.2 Periodic Trend of Sea Ice Area Over Time in Various Regions:

Although the sea ice area varies in different regions due to different dimensions and geographical conditions, the periodicity of sea ice area variation can still be predicted. As shown in Table 2, the periodic statistical data of sea ice area variation in representative Arctic regions:

Table 2: Periodic Variation of Sea Ice Area on Baffin Island

Peak Year	The Period Recent Peak
1981	2 years
1987	5 years
1991	4 years
1993	2 years
1997	4 years
2000	3 years
2005	5 years
2010	5 years
2014	4 years
2017	3 years
2019	2 years

After analysis, regions with higher dimensions have a slower variation period. The common periodic sequence at the North Pole reaches 7 years, while for places with lower dimensions, such as St. Lawrence, the average periodic sequence is only 3 years. By analyzing the data in the above table and averaging the peak period values of 14 regions, the average sea ice area variation period for the 14 regions T equals 3.468 years.

Based on the analysis of the variation trend of sea ice area in the Arctic regions, the average variation trend in Baffin Island, Barents Sea, Eastern Siberia, Greenland, Hudson Bay, Laptev Sea, Sea of Okhotsk and other places is -3,246 square kilometers per year, while the trend of the Arctic midpoint is 22,780 square kilometers per year. On top of that, the sea ice area growth in other Arctic regions is also negative. In general, the sea ice area in various regions of the Arctic is decreasing year by year.

The following factors may affect changes in sea ice area:

1. The dimension; 2. The cold and warm currents; 3. The greenhouse gases; 4. The seawater salinity; 5. The direction of the sea breeze; 6. Other factors.

The variation trends and reasons in some regions of the Arctic are specifically explained below:

▶Although Greenland is affected by warm currents, the trend of change is relatively small due to its higher dimensions.

▶ Although the dimension of the Barents Sea is higher than that of the St. Lawrence Sea, the Barents Sea is affected by the North Atlantic warm current, while St. Lawrence is affected by the cold current, so their sea ice area changes are different.

▶ Although Eastern Siberia is affected by the cold current and its dimension is not low, the sea ice is still falling fast due to the excessive greenhouse gas emissions from production.

2.2 The Correlation Analysis on the Time Series of the Deseasonalized temperature and the Sea Ice Area

The changes in sea ice areas are mainly directly related to temperature. This section mainly analyzes the reasons for sea ice area variation from three aspects: the characteristics of changes within the year, deseasonalized analysis as well as the relationship between sea ice area and temperature changes.

2.2.1 Characteristics of Changes Within the Year:

The Arctic sea ice area and temperature for years are averaged by month, and both average monthly values can be obtained.

2.2.2 Deseasonalized Analysis

Owning to the significant seasonal changes in the Arctic sea ice area, in order to remove the impact of seasonal fluctuations, it is necessary to deseasonalize the time series of the Arctic sea ice area to remove periodicity. Assume a time series X_{ijk} to represent the Arctic sea ice temperature on the k^{th} day of the j^{th} month in the i^{th} year. Consider a time series X_{ij} to represent the Arctic sea ice area in the j^{th} month of the i^{th} year, and the following formula can be obtained from the average Arctic sea ice area in the j^{th} month of the i^{th} year:

$$X_{ij} = \frac{\sum_k X_{ij}}{m} \tag{1}$$

The average temperature for years is:

$$\overline{X_{ij}} = \frac{\sum_k X_{ij}}{m} (i = 1,2,3 \ldots n; j = 1,2 \ldots 12) \tag{2}$$

The time series excluding seasonal fluctuations is:

$$Y_{ij} = X_{ij} - \overline{X_i} \tag{3}$$

By performing deseasonalized analysis on the Arctic temperature, Z_{ij}, Z_{ij} can be obtained that represents the Arctic temperature in the j^{th} month of the i^{th} year without seasonal fluctuations.

2.2.3 Relationship Between Sea Ice Area and Temperature Changes:

With the improvement of production capacity in each country, greenhouse gas emissions have increased, leading to global warming and a significant increase in global temperatures.

The correlation analysis between Arctic sea ice area variation and climate change can indicate the extent of their inherent interrelationships, which can be achieved by calculating correlation coefficients. Calculation of correlation coefficients between the Arctic sea ice area and Arctic temperature without seasonal fluctuations:

$$r_{xy} = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \overline{x})^2 (y_i - \overline{y})^2}} \tag{4}$$

Among them, x_i is the Arctic sea ice area and y_i is the corresponding temperature in the Arctic. The magnitude of correlation coefficients and positive or negative correlation coefficients can explain the relationship between the Arctic sea ice area variation and temperature. When r is larger than 0, the Arctic sea ice area is positively correlated with temperature. When r is less than 0, the Arctic sea ice area is negatively correlated with temperature. The closer r is to 1 or -1, the closer the relationship between the Arctic sea ice area and temperature is. If r tends to be 0, the smaller the relationship between the Arctic sea ice area and temperature is.

The least square method is used to fit the sea ice area and temperature, and the relationship between the sea ice area and temperature is obtained as follows:

$$\text{area} = -0.3346\text{t} + 12.22 \tag{5}$$

There is a significant negative correlation between the average temperature and the corresponding sea ice area in terms of variation. Based on the variation pattern of the sea ice area during a year, it is divided into two parts, namely the sea ice melting period from March to August and the sea ice accumulation period from September to February of the following year, with 6 months of the melting period and accumulation period respectively. There are two different relationships between the sea ice area and temperature at different periods. The slope of the accumulation period is greater than that of the melting period, indicating that when sea ice is in the accumulation period, the decrease in the sea ice area caused by temperature rise is greater than that of the melting period, which shows that the relationship between the sea ice area and temperature is a typical loop curve.

The lag correlation analysis on the time series of the deseasonalized temperature and Arctic sea ice area is performed to get the correlation coefficient between the two at different times:

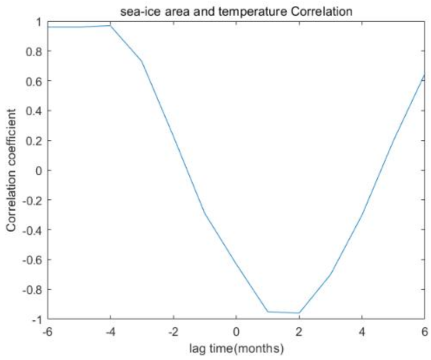

Figure 1: Seasonal Variation Curve of Temperature-Sea Ice Area

From the information in Figure 1, it can be seen that when the lag time is between January and February, the correlation coefficient between the sea ice area and the temperature reaches its maximum negative correlation, suggesting that the area change of Arctic sea ice lags behind the temperature from 1 to 2 months.

2.3 The Sea Ice Area-Land Area Model

It is difficult to obtain data on changes in the regional area of the Earth, so an indirect search for relationships is used. Firstly, the correlation coefficient model of the sea ice area and sea level rise is constructed, and then the relational model of the sea level rise and coastline is built to obtain the relational model of the sea ice area and coastline variation. Next, the influence of natural and human factors on this model is considered, so as to comprehensively analyze and discuss the impact of sea ice area changes on the land area.

2.3.1 Construct a Correlation Coefficient Model Between the Sea Ice Area and Sea Level Rise:

$$r_{xs} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(s_i-\bar{s})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2(s_i-s)^2}} \quad (6)$$

Among them, x_i represents the Arctic sea ice area, and x_i the rising value of sea level. The relationship between the Arctic sea ice area variation and the rising value of sea level can be explained by the magnitude of correlation coefficients and positive or negative correlation coefficients. When r is larger than 0, the Arctic sea ice area is positively correlated with the rising value of sea level. When r is less than 0, the Arctic sea ice area is negatively correlated with the rising value of sea level. The closer r is to 1 or -1, the closer the relationship between the Arctic sea ice area and the rising value of sea level is. If r tends to be 0, the smaller the relationship between the Arctic sea ice area and the rising value of sea level is.

2.3.2 Build a Relational Model Between the Sea Level Rise and Coastline:

According to the Bruun rule in the United States,

$$R = SL_*(B + h_*)^{-1} \quad (7)$$

In the formula, R is the distance of shoreline erosion, S is the rising value of sea level, L∗ and h∗ are the width and thickness of beach sand movement in the wave field; B is the vertical height of eroded sand dunes.

By simplifying the above equation, R=50-100S can be obtained, which is usually used as a rough value for the shoreline retreat caused by sea level rise, i.e. if the sea level rises by 1cm, the shoreline will retreat by 0.5-1m.

Due to the difficulty of directly finding land area, indirect analysis of the rising value of sea level and coastline retreat values is used to analyze the impact of changes in sea ice area on land area variation.

As rising sea levels will inevitably lead to the retreat of continental coastlines, there is a strong positive correlation between the two. However, the retreat of the coastline will result in a decrease in the land area, so the land area will also decrease with the decreasing sea ice area.

Changes will happen in surface water and other factors as the sea ice area change, with green and blue indicating areas where surface water changes have occurred in the past thirty years. Green pixels represent the location where surface water becomes land (absorption, land reclamation and drought), while blue pixels display the location where land becomes surface water (erosion and waterfront construction). In the past thirty years, 173,000 km^2 of land and 115,000 km^2 of water resources have been increased on the Earth's surface.

From this, it can be seen that the land area is constantly increasing under the influence of natural factors. Furthermore, human factors such as sea reclamation, reclamation of usable sea areas and reclamation of lakes and fields have also led to an increase in land area. Therefore, in the current situation, although the reduction of the Arctic sea ice area will lead to a decrease in land area, more natural and human factors have brought about an increase in the total land area instead of a decrease.

2.4 Establishment of the Grey Correlation Degree Model for Various Factors

For the fluctuation of the Arctic sea ice area mentioned above, a grey correlation analysis model is used to construct indicators and propose corresponding suggestions in this section.

2.4.1 Grey Correlation Analysis Model:

1. Determine the analysis sequence:

Parent sequence (parent indicator): A data sequence that reflects the behavioral characteristics of a system and is similar to the dependent variable, which refers to the temperature value here. Subsequence (sub-indicators): data series composed of factors influencing system behavior, which is similar to the independent variable and refers to the factor set U=(forest area, CO_2 emissions, CO_2 level, sea ice area and world population) here.

2. Definition of correlation matrix:

Assume there is a set of reference and comparison sequences as follows:

$$X_j = (X_j(1), X_j(2), X_j(3)\ldots\ldots X_j(n))\ j = 1,2,3\ldots s \quad (8)$$

$$X_i = (X_i(1), X_i(2), X_i(3)\ldots\ldots X_i(n))\ i = 1,2,3\ldots t \quad (9)$$

Based on the above two sequences, the correlation matrix is defined as follows:

$$\delta_{ij}(k) = \frac{minmin\,|\,x_j(k)-x_i(k)|+\rho\,maxmax\,|\,x_j(k)-x_i(k)|}{|x_j(k)-x_i(k)|+\rho\,maxmax\,|\,x_j(k)-x_i(k)|} \quad (10)$$

Among them, δji (k) represents the correlation coefficient between the i[th] comparative sequence and the k[th] sample of the j[th] reference sequence, and $minmin\,|\,x_j(k) - x_i(k)|$ as well as $max\,max\,|\,x_j(k) - x_i(k)|$ show the minimum and maximum values after the difference between the reference sequence matrix and the comparison sequence matrix values.

The equation $|x_j(k) - x_i(k)|$ is called the Hamming distance, and its reciprocal is called the inverse reciprocal distance. The essence of the grey correlation degree is to determine the degree of correlation by the size of the inverse reciprocal.

3. Define sequence correlation

$$z^{(1)}(k) = \frac{x^{(1)}(k)+x^{(1)}(k-1)}{2} \quad (11)$$

Then the new sequence $z^{(1)} = (z^{(1)}(2)z^{(1)}(3)\ldots z^{(1)}(n))$ is the nearest neighbor mean sequence of $x^{(1)}$.

4. Define the grey differential equation of GM (1,1) δji (k), which needs to be integrated, can only reflect the correlation between points and is scattered in the correlation information, making it difficult to characterize the correlation between sequences, thus the correlation is defined here:

$$r_{ij} = \frac{\sum_{k=1}^{n} q_{ij}(k)}{n} \quad (12)$$

Based on this matrix, we can clearly conclude that the effect of the comparison sequence can be seen from the column, and the degree of influence of the reference sequence can be seen from the row, while which sequence plays the main role in the comparison sequence matrix can be analyzed on the basis of the numerical size of the matrix. For example, if the numerical value of a certain column is significantly larger than that of other columns, such a sequence is called the advantage sub-factor, and vice versa is the disadvantage sub-factor; if the value of a certain row is significantly larger than that of other rows, it is called the dominant parent factor, which is relatively sensitive and easily influenced by the driving force of sub factors.

2.4.2 Result Analysis:

The Figure 2 shows the correlation coefficients of the five factors:

Step 1: Perform dimensionless processing on the data.

Step 2: Solve the grey correlation coefficient value between the parent sequence and the feature sequence.

Step 3: Solve the grey correlation value.

Step 4: Sort the grey correlation value and draw a conclusion.

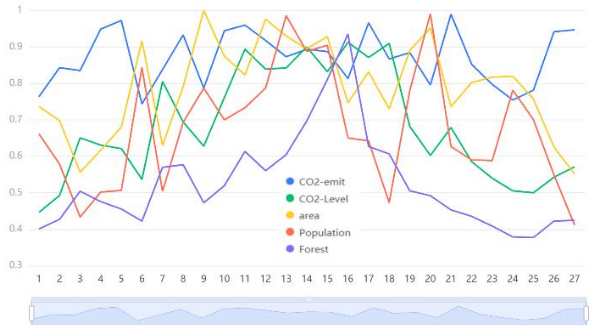

Figure 2: Correlation Coefficient Diagram of Five Factors

The correlation analysis of five-factor sets on temperature are as follows in Table 3:

Table 3. five-factor sets on temperature

Evaluative items	Correlation	Ranking
CO_2 level	0.871	1
Forest area	0.789	2
population	0.684	3
Sea ice area	0.678	4
CO_2 emission	0.525	5

Correlation values are obtained after combining the above correlation coefficients for weighted processing, and they are used to evaluate and sort the five factors. The larger the correlation value, the stronger the correlation between the two. From the above table, it can be seen that for evaluation items in this analysis, the CO_2 level correlation is the highest at 0.871, followed by forest area at 0.789.

3 Conclusion and Discussion

3.1. Conclusion:

This paper studies the overall trend of the Arctic sea ice area variation and provides a spatial analysis of the changes in long-term and seasonal ice, reflecting the changing characteristics of the Arctic sea ice. At the same time, the paper also discusses the relationship between the sea ice area variation and climate change, providing the impact of the Arctic sea ice variation on the regional area of the Earth and establishing mathematical models by providing indicators to minimize the harm of climate change by changing existing policies.

3.2. Discussion:

To clarify the effect Sea Ice Area Variation and obtain the effective scheme,we performed the Correlation model.Various suggestions based on the strength of model correlation are proposed:

1. Reduce the air value level of CO_2, regulate and formulate relevant laws to control the massive production of CO_2 and pursue the idea of carbon neutrality.2. Make efforts to increase afforestation projects and construct projects to protect the natural environment, such as the Three-North Shelterbelt Program Project, which will indirectly affect the air concentration of CO_2, so as to slow down the process of global warming.3. Reasonably control the World population.4. Reduce CO_2 emissions by reducing high-polluting enterprises to weaken the greenhouse effect.

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