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Effects of sea surface and air temperatures on inter-annual variations and trends of Arctic sea ice concentration in summer and autumn

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Abstract. We analyzed the Arctic atmosphere - sea ice - ocean relationships to reveal their intrinsic connections and the roles of the sea surface temperature (SST) and surface air temperature (SAT) on the interannual variations and trends of Arctic sea ice concentration (SIC) in July to October during 1951 to 2021. Both SST and SIC have significant impacts on Arctic SIC. SST affects both interannual variations and decadal trends of SIC, whereas SAT has more significant effects on interannual variations of SIC. In addition, SAT affects SIC trends with a seven-month lead time, which is due to the much stronger warming trend in winter than summer. Statistically SST explained 53% and SAT 35% of the detrended interannual variance of SIC. SIC trends will continue to decline in the future as SAT and SST continue to rise.

1 Introduction

Sea ice decline in the Arctic is reflected in the sea ice extent, area, concentration and thickness. A decreasing trend in sea ice extent is evident since late 1960s (Meier et al., 2012), and a weaker significant trend in sea ice area is detectable in most of the Arctic already since 1850 (Walsh et al., 2017; Cai et al., 2021). An estimated decrease of sea ice thickness near the end of the melt season is 2.0 m or some 66% (Kwok et al., 2018), with a remarkable regime shift from thicker and deformed to thinner and more uniform ice cover in 2007 (Sumata et al., 2023).

Numerous processes have affected the variations and trends in Arctic sea ice. The declining trend of September sea-ice area closely follows accumulated greenhouse gas concentrations (Notz and Stroeve, 2016), modulated by large internal variability (Swart et al, 2015) and decadal increases after major volcanic eruptions (Gagné et al., 2017). The large-scale atmospheric and oceanic drivers on sea ice include tropical teleconnections (Meehl et al., 2018) and poleward heat transport in the ocean (Arthum

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et al., 2012, 2019; Lien et al., 2017) and atmosphere (Graversen and Burtu, 2016; Wang et al., 2022; Liang et al., 2023). Synoptic-scale drivers affect sea ice on time scales of days but decadal and interannual variations in cyclone and anticyclone activity (Wickström et al., 2020) are important for sea ice variations on similar time scales (Ogi et al., 2010). The thermodynamic processes that directly contribute to surface melt of sea ice are the downward longwave radiation, enhanced by clouds, which is usually responsible for the spring onset of melt (Maksimovich and Vihma, 2012; Mortin et al., 2016), and the solar shortwave radiation, which is responsible for most of the summer melt (Perovich et al., 2007). Further, the turbulent flux of sensible heat is typically directed from air to ice (Persson et al., 2002), contributing to surface melt in summer and reduction of ice growth in winter. The basal melt/growth of ice is driven by the convergence/divergence of the heat flux at the ice bottom, which is sensitive to the ocean temperature, efficiency of turbulent mixing, and to the ice and snow thickness, which control the conductive heat flux upwards from the ice bottom (Lin et al., 2022).

Despite of increasing understanding of the above-mentioned processes, the relative importance of two essential climate variables, sea surface temperature (SST) and surface (2 m) air temperature (SAT), on trends and variations in Arctic SIC is not yet well quantified. Docquier et al. (2022) demonstrated their dominating role (together with ocean heat transport) but noted that regional patterns of the relationships require more attention. In this study we present statistical analyses on the relationships of SST, SAT and SIC on decadal and inter-annual time scales. We focus on the July – September season, when the Arctic sea ice decline has been strongest, and pay attention to both circumpolar means and regional patterns of trends and variations.

In this paper we explore the contributions of the direct drivers to Arctic sea ice, including Arctic Ocean SST and SAT, as well as sea-air heat flux and northward (v) wind component. The study focuses on the physical mechanisms of interannual changes and trends of Arctic sea ice.

2 Data and Methods

2.1 Data

We use Arctic sea ice concentration (SIC) and monthly mean SST information from the Hadley Center with a horizontal resolution of 1.0° × 1.0° (Rayner et al., 2003). Sea ice data cover all areas north of 65°N, including the Barents Sea, Greenland Sea, Kara Sea, Laptev Sea, Chukchi Sea, Beaufort Sea. Data from the fifth-generation atmospheric reanalysis from the European Center for Medium-Range Weather Forecasts (ERA5), including 2-m air temperature, 10-m meridional (v) wind component, and surface sensible heat flux (SH), are utilized at a horizontal resolution of 0.25° × 0.25°. All data are monthly means, unless otherwise declared, from the period 1951-2021. Data in the pre-satellite era have overall proven to be reliable as more conventional observations are assimilated and continually refined (Bell et al., 2021). We use such long-term data to enhance the robustness of our conclusions. Prior to analyses, we converted all the data into anomaly fields by removing the 1981–2010 mean of each month, to remove the seasonal cycles. We removed the linear effects of climate warming by removing linear trends.

2.2 Methods

2.2.1 Pearson Correlation Analysis (Including Time-Lag Correlation Analysis)

The Pearson correlation coefficient, also known as Pearson's product-moment correlation coefficient, quantifies the proportion of the total variance in observed data that can be explained by a linear

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relationship between research variables (Benesty et al., 2009). This method will be used to explore the potential relationships between Arctic SIC and its influencing factors.

2.2.2 Empirical Orthogonal Function (EOF) Analysis

EOF analysis is a widely used technique in atmospheric and oceanographic sciences for identifying spatial patterns of variability in a given variable and understanding how these patterns change over time (Hannachi et al., 2007). In this study, EOF analysis will be employed to identify patterns of variability in Arctic SIC on both annual and seasonal scales.

2.2.3 Composite Analysis

Composite analysis, also known as superposed epoch analysis or conditional sampling, is a valuable tool for understanding the relationships between different phenomena and identifying the fundamental structural characteristics of meteorological or climatological events (Haurwitz and Brier, 1981; Laken and Čalogović, 2013). This method will be used to elucidate the connection between Arctic SIC and its drivers.

2.2.4 Singular Value Decomposition (SVD) Analysis

SVD is a mathematical technique used for factorizing a real or complex matrix (Kalman, 1996). SVD is related to polar decomposition and is utilized in meteorology to study the interactions between two fields. This analysis provides a more compact representation of correlations, particularly in multivariate datasets, and helps reveal spatial and temporal variations in the data. In this study, SVD analysis will be used to uncover the linkage between Arctic sea ice and other variables.

2.2.5 Dominance Analysis

Dominance analysis is used to compare the relative importance of predictors in multiple regression (Azen et al., 2003). It assesses the dominance of one predictor over another by comparing their contributions to the explained variance (R^2) across all subset models. This method will be employed to quantify the contributions of major factors influencing changes in Arctic sea ice.

3 Results

3.1 Arctic sea ice variability characteristics

Both the seasonal minimum of Arctic SIC and the maximum interannual variance of monthly mean SIC occur in July-October. In these months, hereafter referred to as summer-fall, the SIC trends over 1951-2021 were -4.3% per decade in July, -5.1% per decade in August, -5.0% per decade in September, and -4.5% per decade in October.

To objectively reflect the distribution characteristics of the spatial reduction rate of SIC, the annual circumpolar pattern of the reduction rate at 65°-90°N was calculated. Both the annual mean sea ice reduction rate (Figure 1a) and the summer-fall reduction rate (Figure 1b) show large spatial differences, and the reduction rates are larger for summer-fall. The maximum annual mean decreases occur in the Barents Sea and Greenland Sea in the Atlantic sector, where the reduction rates are approximately 3 to 7% per decade. However, the reduction rate of the Pacific sector is significantly lower, 3 to 5% per decade. The average reduction rate of the entire Arctic sea ice is 2.6 % per decade including multiyear ice. The results show that the reduction rate is mostly 6 to 10% per decade for summer and fall, and 4.9% per decade for the annual average excluding multiyear ice.

The spatial distributions of annual average and summer-fall Arctic sea ice coverage are shown in Figure 1(c,d). As the sea ice change is largest in summer and fall, this paper hereafter only focuses on these seasons.

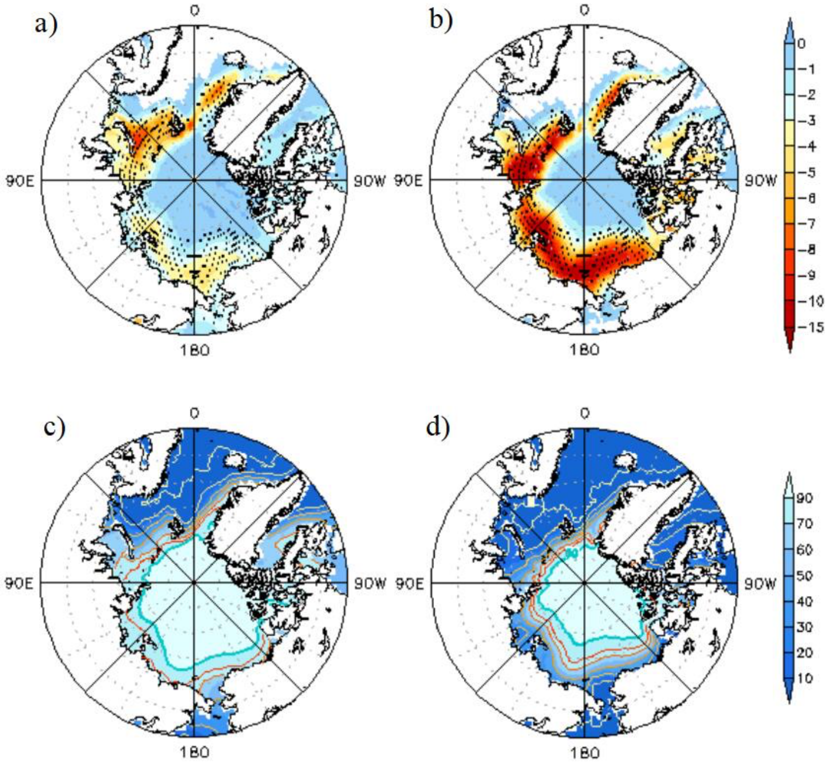

Figure 1: Arctic SIC trend for (a) annual average; (b) summer-autumn average. The dotted area is statistically significant above a 99.9% confidence level. Unit: %, (c) the annual distribution of Arctic SIC averaged over 1951-2021, and (d) the summer-autumn average. The green line surrounds the area of multi-year ice.

To analyze and explore the long-term change characteristics of Arctic sea ice, the long-term SIC change was calculated for the circumpolar region north of 65°N. The time series of annual mean and summer-fall SIC anomalies show interannual variations superimposed to the decreasing trend (Figure 2). The amplitude of the variations is larger in summer-fall than for the annual mean, especially since 2007, when the rapid decrease of sea ice in summer and fall occurred.

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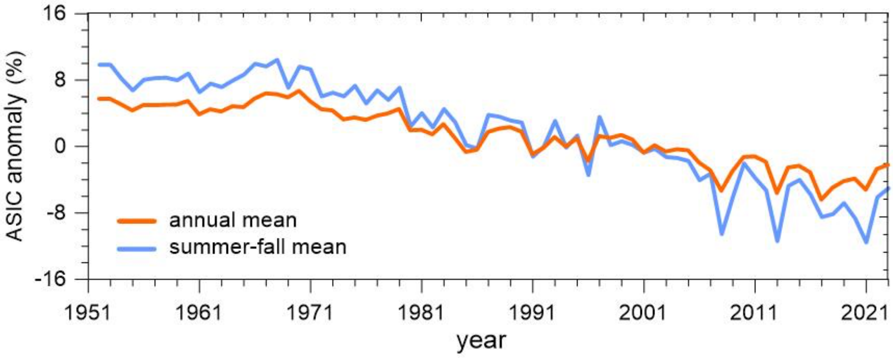

Figure 2: Time series of the annual and summer-autumn Arctic SIC for 1951 to 2021.

3.2 Contribution of SST to Arctic sea ice variations

To investigate the contribution of Arctic SST, SAT, and SH and v-wind component to the trend and interannual variability of Arctic SIC, the dominance analysis (Budescu and David, 1993; Azen et al., 2003) was adopted. The results showed that the main statistical contributor to Arctic SIC variability is Arctic SST, followed by SAT, while SH and V-wind components are clearly weaker. Their contributions to detrended Arctic SIC interannual variance are 53.0%, 35.1%, 9.8% and 2.0%, respectively. Hereafter we only focus on SST and SAT, which have significant contributions to summer-fall Arctic sea ice.

On the basis of the long-term time series of Arctic SIC and SST, it is evident that Arctic SST and SIC anomalies are in inverse phase (Figure 3a), which is the case also for the detrended data (Figure 3b). A time-lag correlation analysis revealed that SST starts to influence sea ice with a four-month lead time, and the most significant influence occurs when Arctic SST anomalies and SIC anomalies appear simultaneously, independent of detrending. The correlation coefficient (r) is as high as -0.90 and -0.51 for the original and detrended data, respectively (sample size n = 852), far exceeding the 99.9% confidence level.

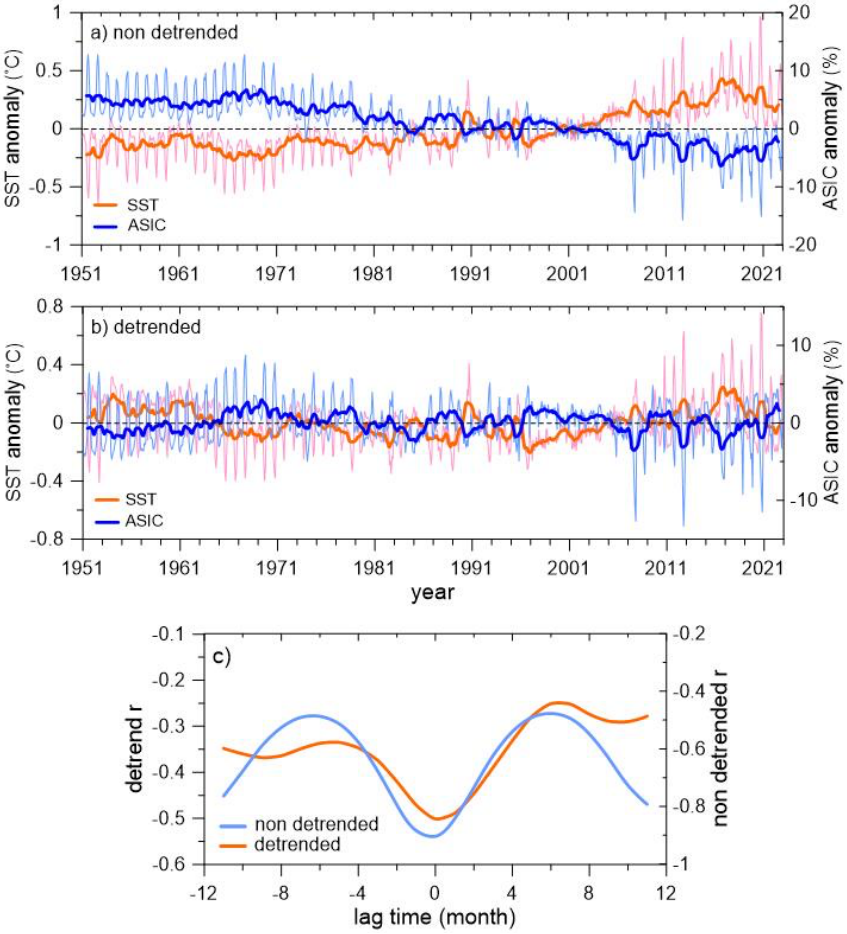

Figure 3: (a) Original and (b) detrended long-term time series of monthly SIC and SST anomalies. The blue and red solid lines are the 11-month running means of the SIC and SST anomalies, respectively: c) time-lagged correlation between SIC and SST anomalies for the original and detrended data. Negative values of the horizontal coordinate indicate months of SST anomalies leading SIC anomalies, whereas positive values indicate months of SST anomalies lagging SIC anomalies.

To better understand the interannual relationship between summer-fall Arctic SIC variability and the SST field, we performed SVD analysis. Figure 4 shows the first mode of the SVD analysis of the detrended Arctic SST and SIC data. The variance contribution of the first mode is 34.4%. The SST variations in most of the Arctic are in the opposite phase with those in the Greenland Sea and regions north of Svalbard (Figure 4a). The corresponding SIC field (Figure 4b) shows spatial patterns opposite to those of the SAT field, i.e., when the Arctic SST is high, the SIC is low, and vice versa. The temporal coefficients of the Arctic SAT and SIC fields (Figure 4c) show an obvious inverse phase relationship (r = -0.90). This analysis shows that the SST has a greater impact on the SIC than the SAT.

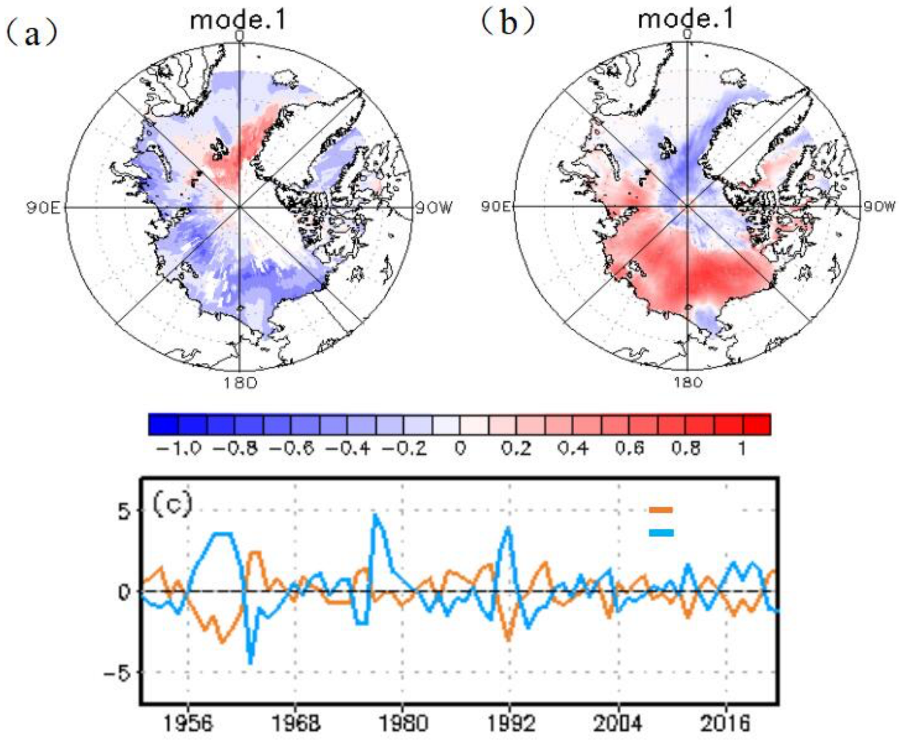

Figure 4: The leading SVD spatial patterns of (a) the Arctic SST and (b) SIC, as well as (c) the time coefficients corresponding to the first modes of SST and SIC. The correlation between the time coefficients of SST and SIC is -0.91, which far exceeds the 99.9% confidence level test. The variance contribution of the first mode is 34.2%. All analyses are for detrended SST and SIC in summer-fall.

3.3 Contribution of the surface air temperature to Arctic sea ice

The time series of Arctic SAT and SIC show an inverse phase relationship for both the trend (Figure 5a) and interannual variability (Figure 5b). In the original data the most significant effects on Arctic sea ice occur when SAT leads SIC by 7 months (r = -0.74) or SAT lags SIC by 4 months (r = -0.74), whereas for detrended data the most significant influence occurs simultaneously (r = -0.48).

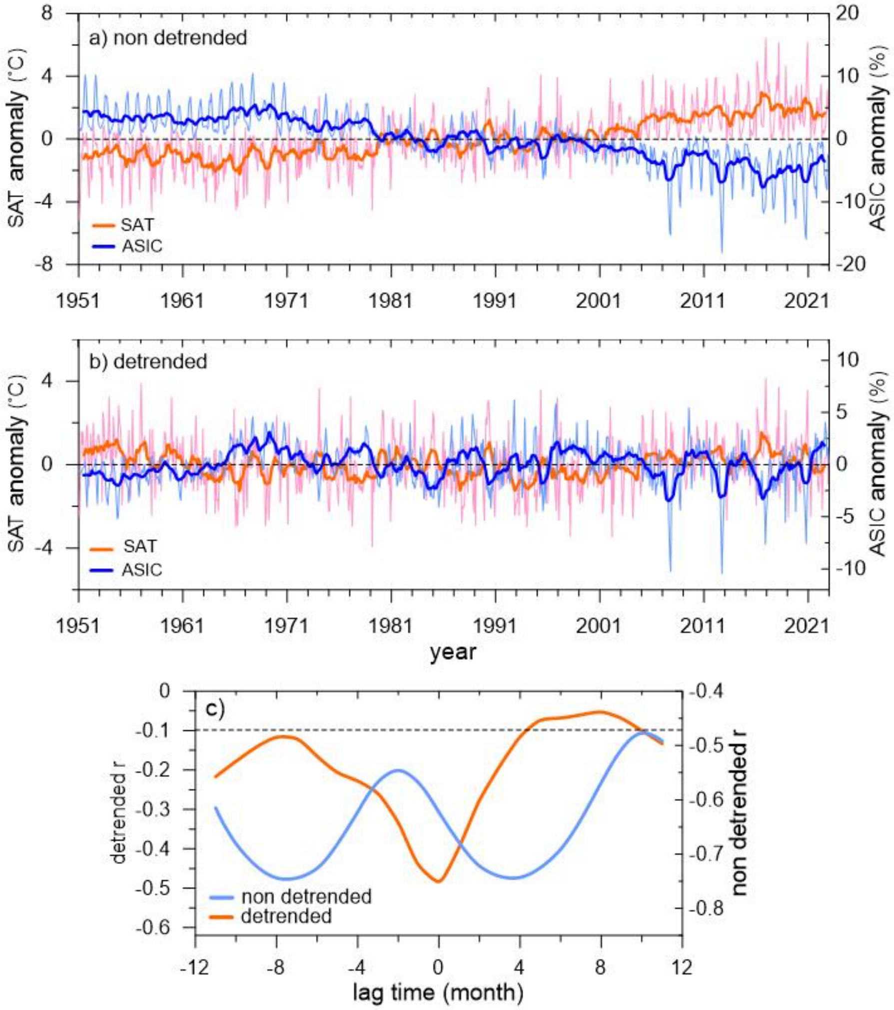

Figure 5: (a) Original and (b) detrended time series of monthly SIC and SAT anomalies. The blue and red solid lines show the 11-month running means of the SIC and SAT anomalies, respectively. (c) time-lagged correlation between SIC and SAT anomalies for the original and detrended data. Negative values of the horizontal coordinate indicate months of SAT anomalies leading SIC anomalies, whereas positive values indicate months of SAT anomalies lagging SIC anomalies. The dashed line shows the 99.9% confidence level. All analyses are for summer-fall.

Also, the SVD analysis shows a close relationship between detrended summer-fall SIC and SAT (Figure 6), with a first-mode variance contribution of 56.1%. In the SAT field (Figure 6a), the spatial distribution over the circumpolar Arctic appears to have a consistent pattern, which is more significant in the East Siberian Sea and the Laptev Sea and weaker in the Greenland Sea and the Barents Sea. The corresponding SIC field (Figure 6b) shows an opposite distribution characteristic to the SAT field, which

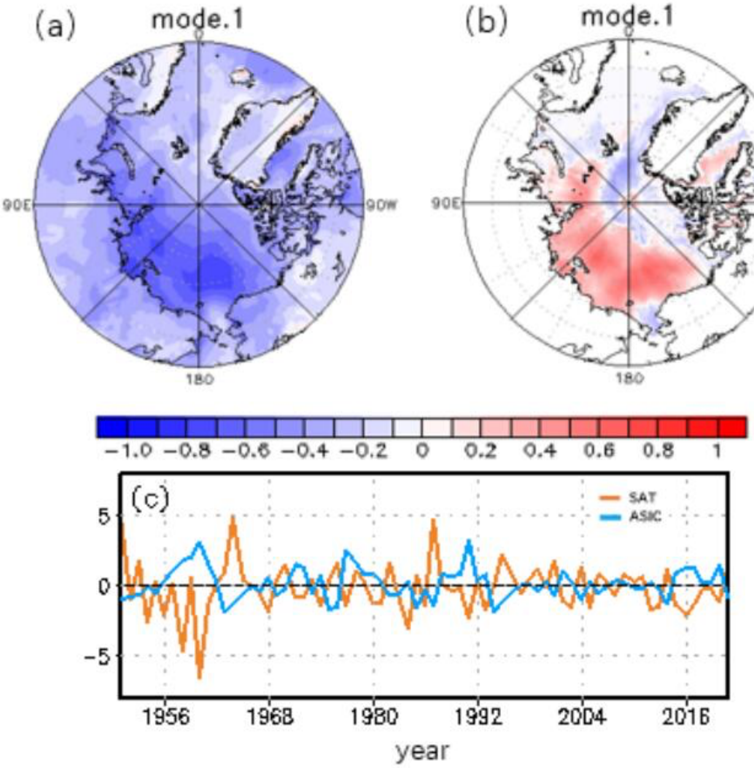

Figure 6: The leading SVD decomposition modes of (a) the Arctic SAT and (b) SIC, as well as (c) the time series corresponding to the first modes of detrended SAT and SIC. The correlation coefficient between the time coefficients of the two fields is -0.75, which far exceeds the 99.9% confidence level test. The variance contribution of the first mode is 56.1%.

indicates that when the SAT is high, SIC is low and vice versa. The temporal coefficients of the SAT and SIC fields (Fig 6 c) show a clear inverse phase relationship with a correlation coefficient of -0.75. This analysis indicates that Arctic sea ice variability is also closely related to Arctic SAT but the relationship is weaker than that between SIC and SST.

To further explore the intrinsic link between the summer-fall anomalies in Arctic SIC, SST, and SAT, four years each of significantly negative (1995, 2007, 2012, 2016) and positive (1970, 1978, 1992, 1996) anomalies in Arctic SIC were selected for composite analysis. Significant SIC anomalies, exceeding the 99.9% confidence level, occur in the Barents, Kara and Greenland seas in the Atlantic and in the Beaufort, Chukchi, and East Siberian seas in the Pacific sector both in years of negative (Figure 7a) and positive (Figure 7b) anomalies.

Considering SST fields, a consistent positive anomaly distribution (Figure 7c) is present in the four years of negative SIC anomalies. The regions with largest SST anomalies consist of the almost entire Atlantic sector, in particular the Barents and Kara seas, as well as the Beaufort, Chukchi, and East Siberian seas in the Pacific sector. The years with positive SIC anomalies correspond to a negative SST anomaly pattern for the whole Arctic-Atlantic sector (Figure 7d). The regions where the correlation reaches 99.9% confidence are the Norwegian Sea, the Barents Sea and the Kara Sea in the Atlantic sector. Based on the above analysis, rising SST in these regions is one of the critical reasons for the rapid decrease in Arctic sea ice.

The composite analysis on the relationship between SIC and SAT shows that negative SIC anomalies (Figure 7a) are associated with positive SAT anomalies (Figure 7e). The relationship is strongest in the Barents and Kara seas, and weaker in the Pacific sector, where the positive SAT anomalies are smaller. The eastern Beaufort Sea and regions north of Greenland show negative SAT anomalies but weak if any SIC anomalies. Positive SIC anomalies (Figure 7b) are associated with negative SAT anomalies, above all in the Barents and Kara seas (Figure 7f).Positive SAT anomalies occur in parts of the Bering and Chukchi seas, approximately collocated with local negative SIC anomalies.

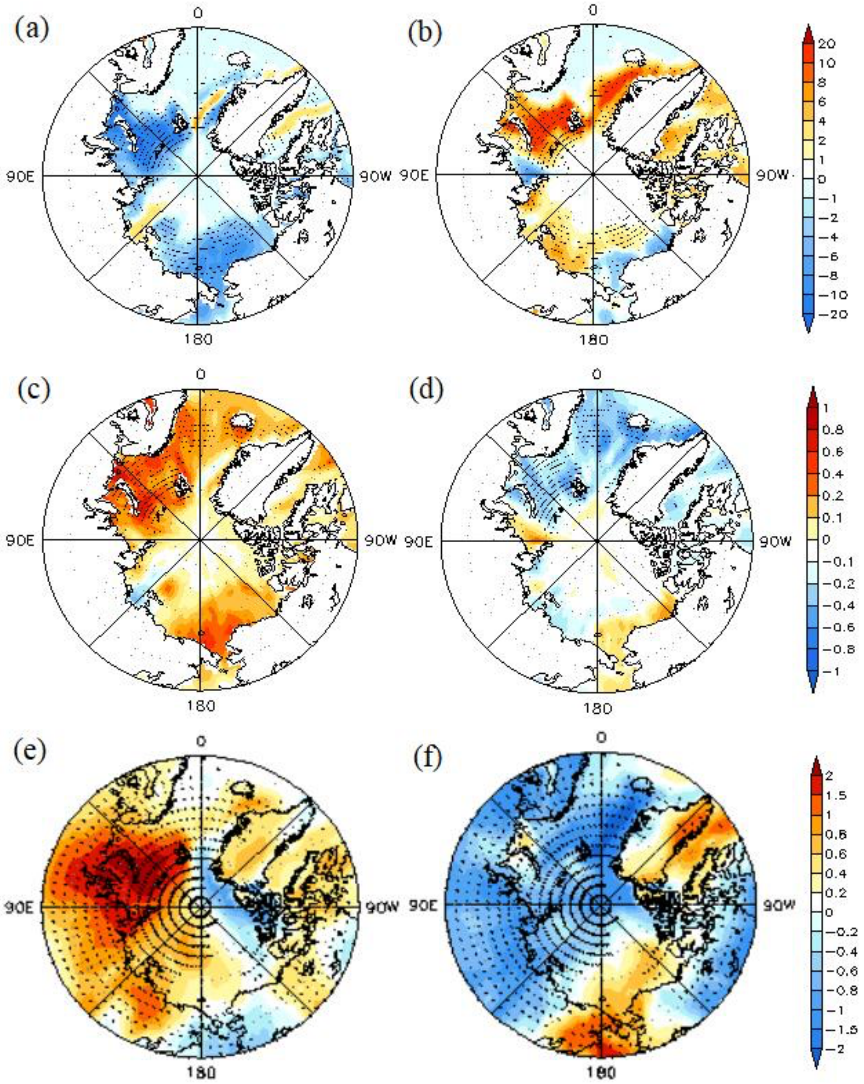

Figure 7: Composites of four summer-fall seasons with (a) negative (1995, 2007, 2012, 2016) and (b) positive (1970, 1978, 1992, 1996) anomalies in SIC. Plots (c) and (d) show SST composites corresponding to the years of anomalously low and high SIC, respectively. Plots (e) and (f) show SAT composites corresponding to the years of anomalously low and high Arctic sea ice, respectively. The dotted areas indicate the 99.9% significance level of the two-sided t test.

4 Discussion and Conclusions

Our results can be summarized as follows.

1) According to our study, the reduction rates of Arctic (65-90ºN) SIC during 1951-2021 were 4.3% per decade for July, 5.1% per decade for August, 5.0% per decade for September, and 4.5% per decade for October, which are the months of the fastest sea ice decline. Previous studies have shown that the Arctic (70°-90°N) summer (July-September) sea ice area decreased at a rate of 2.6% per decade from 1948-2017 (Cai et al., 2021); and the Arctic (55°-90°N) annual sea ice extent decreased at a rate of 4.7% per decade during 1979-2019 (Yadav et al., 2020). The major difference between our results and those by Cai et al. (2021) originates from the different southern border of the study area, as the sea ice decline has been fastest in the marginal seas.

2) There is a dipole mode in the Arctic SIC anomaly, i.e., the Atlantic sector and the Pacific sector have opposite variation characteristics. When the sea ice in the Atlantic sector is lower, the sea ice in the Pacific sector is higher and vice versa. This is in line with the findings of Wu et al. (2006), who attributed sea ice anomalies to a dipole anomaly in sea-level pressure patterns over the Arctic Ocean. Although Wu et al. (2006) focused on the winter season (October to March), Wang et al. (2009) demonstrated the strong impacts of the dipole anomaly on the trend in summer seas ice extent. Our study demonstrated that the dipole mode in SIC anomaly is also strongly related to interannual variations of regional SIC.

3) There are obvious spatial distribution characteristics of the annual average reduction rate of Arctic sea ice, i.e., there are large differences in different sectors, and the whole Arctic sea ice shows a decreasing trend. The average annual reduction rate is basically zonally distributed except from the North American continent to Greenland, where the rate is maintained at 3-5% per decade, while the maximum reduction rate is in the Barents Sea and Greenland Sea, and the average reduction rate of the whole Arctic is 2.6% per decade. The spatial distribution of the mean Arctic sea ice decreases in summer and fall (July-October) is generally consistent with the annual mean distribution excluding multiyear ice, where the maximum decreases are in the range of 6-10% per decade, and the mean decreases are 4.9% per decade for the whole Arctic. These findings are generally similar to a number of studies, which to some extent also strengthens the robustness of our conclusions, given the differences in the data sources, time spans, regional scope and seasons of the studies (Wang et al., 2023; Parkinson 2022). For example, Wang et al (2023) shows an overall spatial distribution of SIC decline similar to ours, but also found that in the coastal regions of Siberia and Alaska SIC decreased at a rate of more than 5% per decade during the June-August period from 1979 to 2020. This difference in the spatial distribution of Arctic sea ice decrease may be related to local oceanic and atmospheric circulation.

4) Both SST and SAT have significant impacts on Arctic SIC. The most significant effects of SST on Arctic SIC are contemporaneous, regardless of detrending the time series or not. However, the most significant effects of SAT on Arctic sea ice are contemporaneous only for detrended time series but occur with a lead time of seven months for the original time series. This is probably due to the fact that SAT over Arctic sea ice in July and August has had minor or no trend (Vihma et al, 2008; Przybylak and Wyszyński, 2020; Räisänen, 2021), and therefore cannot explain the strong decreasing trend in contemporaneous SIC. On the contrary, SAT has increased a lot in December – March (seven-month lead time), reducing the annual maximum ice thickness (Stroeve et al., 2018), and therefore favoring reduction of SIC in the following summer. Further, the second peak correlation with a four-month lag time (Figure 5) can be interpreted as an effect of reduced summer SIC on winter SAT. Reduced summer SIC generates persistent negative SIC anomalies lasting through autumn and early winter. The effect of these anomalies

on SAT becomes detectable in cold seasons when the temperature difference between the open water and near-surface air is large enough to generate a strong upward sensible heat flux (Uhlikova et al., 2024).

5) From the dominance analysis, it is clear that the key factor influencing interannual variations of Arctic SIC is SST, followed by SAT, which contribute 53.0% and 35.1% to the detrended interannual variance, respectively.

6) The results of this study show that both the rapid decrease and interannual variations in Arctic SIC are closely related to the Arctic SST and Arctic SAT. More work is needed to better distinguish between statistical and causal relationships, and to quantify the strength of latter, which is complicated by various process interactions and feedbacks.

Code Availability

The code used for the data analysis and processing in this study is available upon request.

Data Availability

All data used in this study are open source and have been appropriately cited in the Methods section.

Author Contribution

D. C. conceived the ideas, Q.S. secured the funding, D.C. and T.V. examined the information gathered, and D.C. first drafted the manuscript; The final text was developed with input from all writers, who also gave their approval for publishing.

Competing Interests

The authors declare that they have no conflict of interest.

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