Arctic Sea Level Variation in the Context of Climate Change: Accelerated rise period and Change of Key Influencing factors

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December 20, 2022

Abstract

This study finds that sea level height in Arctic marginal sea in melting season enters an accelerated rise period since the beginning of the 21st century. It is found that precipitation is the dominant factor affecting the change of sea level height in melting season in 1979-1998. Polar vortex and Arctic Oscillation become dominant factors since the accelerated rise period, especially in Norwegian Sea, Barents Sea and Kara Sea. Main reason for the change of dominant factors may be that a clockwise surface wind anomaly in strong polar vortex year became more significant in these regions during the accelerated rise period. The strong wind anomaly affects distribution of sea water through processes such as surface wind stress. Specifically, a polar vortex-wind-sea level height mechanism is strengthened, thus affecting the change of sea level height. CESM2 future scenario simulation results show that sea level height will rise by 0.4m by 2100.

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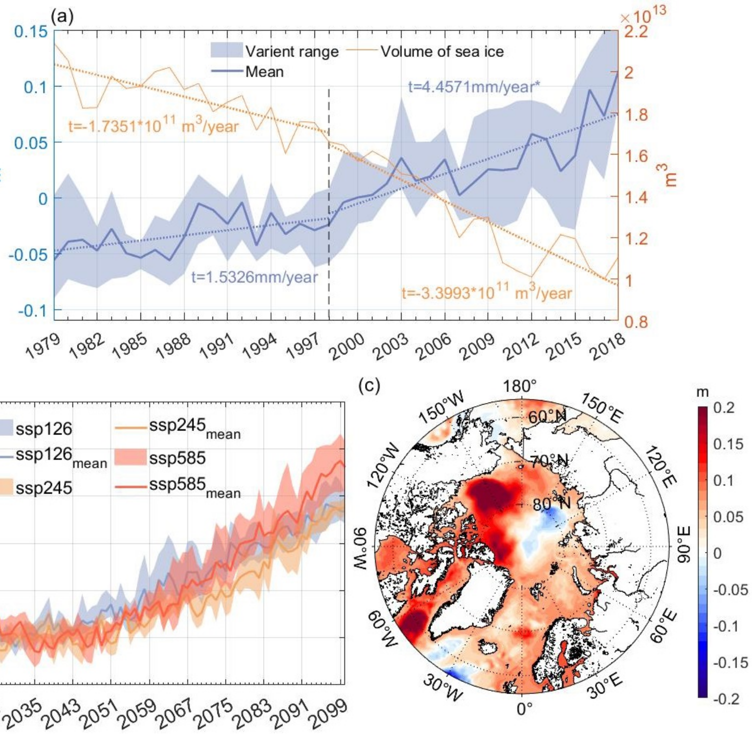
(a)
Varient range
Mean
Volume of sea ice
t=4.4571mm/year*
t=-1.7351*10^11 m^3/year
t=1.5326mm/year
t=-3.3993*10^11 m^3/year
m
m^3
×10^13
(b)
ssp126
ssp126_mean
ssp245
ssp245_mean
ssp585
ssp585_mean
m
(c)
180°
150°W
150°E
120°W
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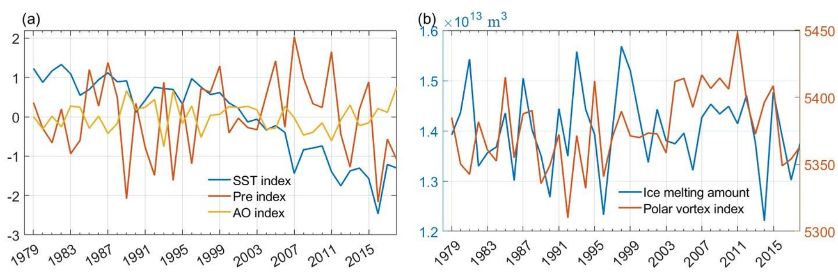
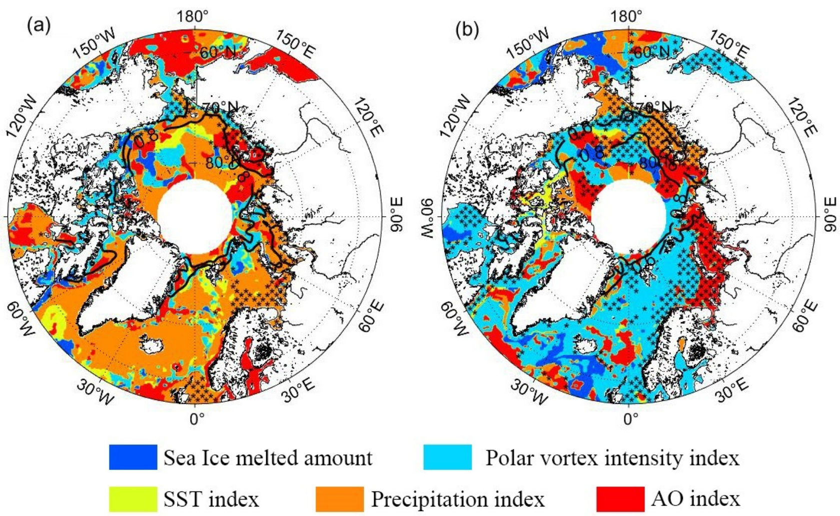
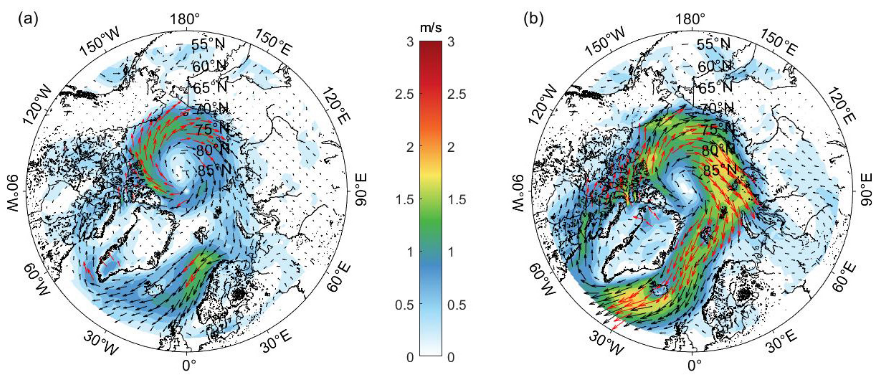
m


(a)
SST index
Pre index
AO index
(b)
×10^13 m^3
Ice melting amount
Polar vortex index


(a)
(b)
Sea Ice melted amount
Polar vortex intensity index
SST index
Precipitation index
AO index


(a)
(b)
m/s

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Key Points:

- Sea level height entered an accelerated rise period since the 2000s in the Arctic, which is one of the fastest rising areas in the world.
- Effect of polar vortex and Arctic Oscillation enhances sea level rise in Barents Sea and Kara Sea since the acceleration period.
- A polar vortex-surface wind-sea level height mechanism may explain the change of dominant factors affecting sea level height.

Abstract

This study finds that sea level height in Arctic marginal sea in melting season enters an accelerated rise period since the beginning of the 21st century. It is found that precipitation is the dominant factor affecting the change of sea level height in melting season in 1979-1998. Polar vortex and Arctic Oscillation become dominant factors since the accelerated rise period, especially in Norwegian Sea, Barents Sea and Kara Sea. Main reason for the change of dominant factors may be that a clockwise surface wind anomaly in strong polar vortex year became more significant in these regions during the accelerated rise period. The strong wind anomaly affects distribution of sea water through processes such as surface wind stress. Specifically, a polar vortex-wind-sea level height mechanism is strengthened, thus affecting the change of sea level height. CESM2 future scenario simulation results show that sea level height will rise by 0.4m by 2100.

Plain Language Summary

Under the background of the decrease of Arctic sea ice in recent decades, sea level height in the Arctic marginal sea has risen significantly, and the rising rate has accelerated significantly since the beginning of the 21st century. A relationship between polar vortex and sea level height has been found for the first time in this study. Further analysis shows that during the accelerated rise period, dominant factor affecting sea level height switch from precipitation to Arctic Oscillation and Polar Vortex. The reason for this change may be that under the background of Arctic warming and sea ice reduction in the accelerated rise period, the anticyclone wind field anomaly is more significant in the year when the polar vortex is strong. This discovery is important for future research on sea level height variation in the Arctic marginal sea.

1 Introduction

In the context of global climate change in recent years, the change of sea level height has attracted more and more attention (Palmer et al., 2020; Wang et al., 2022). Sea level height has been found to respond to climate change, specifically via thermal expansion of seawater and freshwater transport caused by global warming (Jia et al., 2022). The change of sea level height also affects local climate and ecology (Bramante et al., 2020; Chini et al., 2010; Vitousek et al., 2017). With the dramatic changes of Arctic sea ice in recent decades, the Arctic has become an indicator of global climate change (Box et al., 2019; Previdi et al., 2021).

Air temperature, sea surface temperature and precipitation in the Arctic have changed significantly in recent years(Hu et al., 2020; Kopec et al., 2016; McCrystall et al., 2021; Screen & Simmonds, 2010). Therefore, changes in sea level height in the Arctic are also of particular concern(Rose et al., 2019). Andersen and Piccioni (2016) combined altimetry data from multiple satellites and believed that the rising rate of Arctic sea level height was 2.2 ± 1.1 mm/year, and the maximum rate could reach 15 mm/year in 1993-2015. Limitations of using satellite data on studying Arctic sea level height was pointed out by (Ludwigsen & Andersen, 2021). Koldunov et al. (2014) analyzed the changes of arctic sea level height from 1970 to 2009 based on a variety of ocean models, found that the model could reflect the interannual interdecadal changes, and pointed out that the current model could be used for low-frequency changes of arctic sea level height. Armitage et al. (2016) found that seasonal change of Arctic sea level height was mainly affected by fresh water input in summer, while non-seasonal change was affected by fresh water accumulation in the Beaufort Sea area.

What factors may be related to the change in the height of the Arctic sea level? According to previous studies, the main factors that may affect the change of sea level height are the freshwater flux caused by sea ice melting (Milne et al., 2009); Seawater expansion due to temperature rise (Koldunov et al., 2014; Vermeer & Rahmstorf, 2009); Atmospheric precipitation and terrestrial freshwater inflow (Hünicke & Zorita, 2006); The regional distribution of seawater caused by atmospheric factors (Armitage et al., 2018). In addition, Proshutinsky et al. (2007) found that the change of sea level height in Arctic was related to Arctic Oscillation (AO) based on the AOMIP (Arctic Ocean Model Inter comparison Project) results. In recent years, Xiao et al. (2020) found that sea ice reduction contributes to the sea level rise of the Asian margin sea. On the other hand, sea ice reduction did not change the average sea surface height in the Arctic Ocean, but instead changed the spatial distribution of sea surface height.

The above-mentioned researches have analyzed the changes of sea level height on annual and monthly scales, as well as factors that may affect the Arctic sea level height. However, climate process in the Arctic varies in different seasons. In summer, the sea ice extent is 3.5-7.5 million km^2, and has the fastest inter decadal sea ice decrease rate (about 0.77 million km^2/year). In winter, the sea ice extent is about 14.5-16 million km^2, with a weak downward trend (Stroeve et al., 2014). In the sea ice melting season, melted sea ice brings a large amount of fresh water.

Under the background of Arctic sea ice reduction and Arctic warming amplification effect, does sea ice melting in the melting season (May-August) significantly affect the Arctic sea level height? Is there a significant change in Arctic sea level height during the melting season? To address the issues discussed above, this study analyzes the variation of the Arctic sea level height during the melt season from 1979 to 2018. The spatial differences and interdecadal changes of the dominant factors affecting the Arctic sea level height are analyzed using a multiple regression method.

2 Data and Methods

2.1 Data

The sea level height reanalysis data used in this work is obtained from Ocean Reanalysis System 5 (ORAS5) dataset produced by European Centre for Medium-Range Weather Forecasts (ECMWF). ORAS5 is a widely used ocean reanalysis dataset (Kumar et al., 2020; Wang et al., 2021; Zuo et al., 2019). It is based on NEMO V3.4.1 and LIM2 sea-ice model, assimilated with sea ice concentration from OSTIA and AVISO reprocessed DT2014 SLA + NRT. The horizontal resolution of this data is 0.25°×0.25°. In order to analyze the possible future changes of sea level height, the simulation results of the scenarios of ssp126, ssp245 and ssp585 in the CESM2 model are also used in this study.

Sea surface temperature, total precipitation, 10m wind data are obtained from ECMWF ERA5 dataset (Hersbach, 2019). The northern hemisphere polar vortex central intensity index of China National Climate Center is also used. The sea ice melted amount is defined as the difference between the Arctic sea ice volume in August and May. NSIDC 0051 sea ice concentration product (DiGirolamo, 2022) and PIOMAS sea ice thickness product (Schweiger et al., 2011) are used to calculate the Arctic sea ice volume change. For the convenience of analysis, all data are interpolated to the polar projection grid of NSIDC 0051 with a resolution of 25km.

2.2 Methods

Multiple variable linear regression is one of the most widely used attribution method (Nair et al., 2018; Wang et al., 2021; Wang et al., 2017; Xia et al., 2021). In order to analyze the contribution of different factors to the change of sea level height, the normalized series of different factors are used as independent variables, and the normalized sea level height change series are used as dependent variables for multiple linear regression. Linear trends are removed in both independent and dependent variables. After standardization, regression coefficient between a factor and sea level height can show the contribution of corresponding factor to sea level height.

3 Results

3.1 Variation of sea level height in marginal sea in Arctic

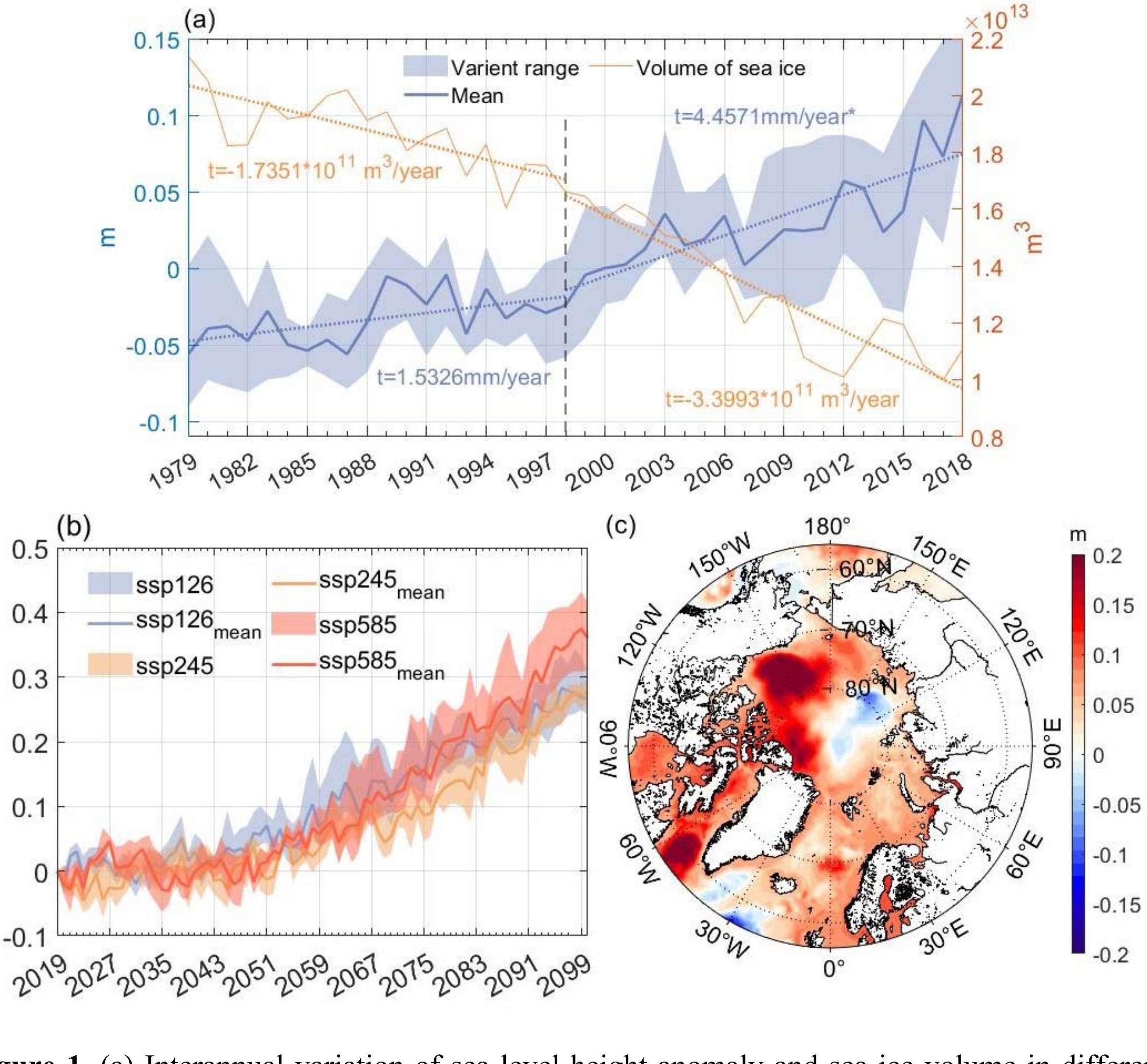

Figure 1. (a) Interannual variation of sea level height anomaly and sea ice volume in different Arctic sea areas during ice melting season from 1979 to 2018. (b) Sea level height changes in different Arctic sea areas during the melting season from 2019 to 2100 simulated by the CESM2 model. (c) Sea level height difference between 2009-2018 and 1979-1988.

Figure 1a shows the interannual changes of the Arctic sea level height (SLH) anomaly and sea ice volume during the ice melting season from 1979 to 2018. The grey area is the variation range of SLH anomaly of six marginal seas, including the Beaufort Sea, Chukchi Sea, East Siberian Sea, Laptev Sea, Kara Sea and Barents Sea (Figure S1). Through Mann-Kendall test (Mann, 1945), it is found that the Arctic SLH shows a significant upward trend and enter an accelerated rise period after 1998, reaching 4.45mm/year, which is greater than the rate of global sea level rise in recent years (Wang et al., 2022). By 2018, the maximum sea level anomaly of the six marginal seas is about 0.15 meters. Under the ssp585 scenario (Figure 1b), it is predicted that the SLH may rise 0.3-0.4m by 2100 compared with 2019. The rise of sea level height would be most significant in the Beaufort Sea, reaching about 0.25m (Figure 1c), which is consistent with Carret et al. (2017). In the Greenland Sea, the Norwegian Sea, the Barents Sea, the Kara Sea and the East Siberian Sea, the sea level would also rise by more than 0.05m. The yellow solid line in Figure 1a indicates the interannual change of the volume of Arctic sea ice during the ice melting season. From 1979 to 1998, rate of sea ice volume reduction is about 1.7 * $10^{11}$$m^3$/year. Since the accelerated rise period, the rate of sea ice volume decrease is twice as high as before (about 3.4 * 10^{11} m^3/year).

In the context of significant changes in the Arctic region and shrinking sea ice margin (Batté et al., 2020), which factors have the largest contribution to the interannual changes in sea level height in the Arctic region in recent years? What are the spatial differences in the contributions of different factors?

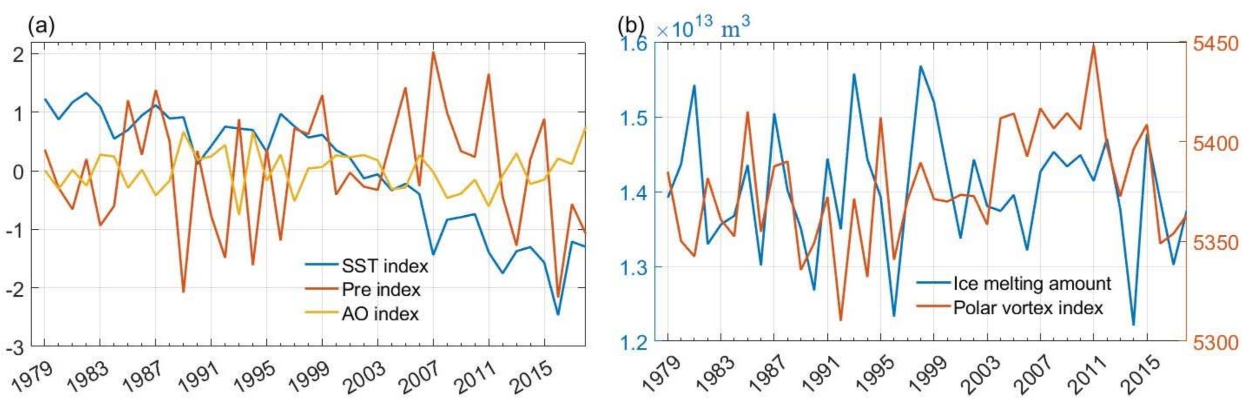

Figure 2. Variation in Ice melting season in the Arctic from 1979 to 2018. (a) Sea surface temperature, precipitation EOF first mode PC1 series and AO index. (b) Ice melting volume and polar vortex intensity index

In order to analysis these questions, based on the previous research conclusions, this paper analyzes the changes of Arctic sea surface temperature, Arctic precipitation and Arctic sea ice melted amount. In order to comprehensively reflect the impact of sea surface temperature and precipitation, Empirical Orthogonal Function (EOF) analysis were conducted on the standardized field of sea surface temperature and precipitation in Arctic region (north of 65 °N). It is found that the first mode of sea surface temperature in the Arctic region is the gradual rise of SST in the entire Arctic Ocean region, with the variance contribution reaching 29.6% (Figure S2a). The blue line in Figure 2a is the corresponding time series. The first mode of precipitation is the reverse change between polar Beaufort Sea, the Chukchi Sea and the land around the Arctic, such as the Victoria Islands, Scandinavia and the Asian continent. The variance contribution is 13.1% (Figure S2b). The time series (red line in Figure 2a) shows the interdecadal change of positive and negative phases. In this study, the time series of the first mode of SST and precipitation are taken as SST index and precipitation index (blue and red line in Figure 2a). The blue line in Figure 2b is the melted amount of sea ice, which ranges from 1.22 to $1.57 * 10^{13}$ m^3 in recent years. In addition, following Armitage et al. (2018), the variation of AO index, which is reflecting atmospheric circulation, is also analyzed. A strong interannual variation of AO index in the melting season is shown by the orange line in Figure 2a. Previous study have found that the Arctic polar vortex also has significant changes (Zhang et al., 2016). Our study finds that the polar vortex intensity index (the red line in Figure 2b) also has a significant impact on the sea level height of the Arctic marginal sea (Figure S3), which shows a significant negative correlation at the edge of the Asian continent, and a significant positive correlation at the area covered by sea ice in the northern part of the East Siberian Sea. Therefore, this paper will also analyze the impact of polar vortex intensity index on sea level height. Although there may be other factors (fresh water inflow, glacier melting, etc.) that may affect sea level height changes, this study mainly considers large-scale factors that can affect the entire Arctic marginal sea, and finds the "trigger" factor that has the largest explanation variance for interannual changes in recent decades.

3.2 Attribution Analysis of Sea Level Height Changes in the Arctic marginal sea

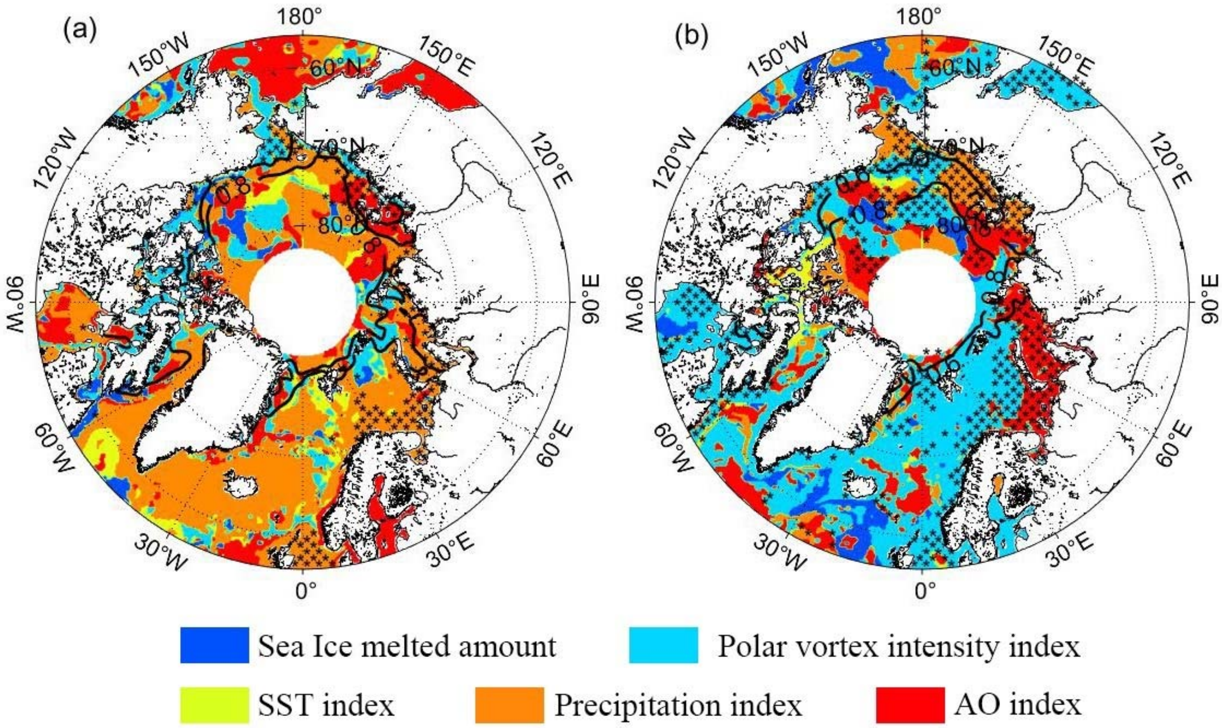

Figure 3. Spatial distribution of factors with the largest absolute value of the multiple regression coefficient of Arctic sea level height from (a)1979-1998 and (b)1999 to 2018. Contour lines show average SIC in the corresponding time. "*" represents the area where the regression equation passes the significance test.

In order to analyze the contribution of different factors to the change of SLH in the Arctic region, this paper use the multiple linear regression method to analyze the contribution of different factors and the variation of this contribution. It is found that the contribution of different factors has changed before and after the accelerated rise period. The results are shown in Figure 3. Area that passed 95% regression significance test is mainly distributed in the area of the Barents Sea, Kara Sea and Laptev Sea, where the dominant factor is precipitation index before the accelerated rise period. In the northern seas of the Bering Strait, the dominant factor is the polar vortex intensity index. According to Figure 3b, in the accelerated rise period, the region that passed the 95% significance test expanded significantly compared with the 1979-1998 period, especially in the East Siberian Sea and Chukchi Sea. The contour of sea ice concentration of 0.8 moved northward, as sea ice decrease after the accelerated rise period. The reduction of sea ice turned areas originally covered by sea ice in open waters or ice-water mixed area, which will directly affect water balance, energy balance (Kurita, 2011) and air-sea interaction process in the Arctic. In the accelerated rise period, sea ice melted amount doesn't seem to be the most significant contributing factor to the SLH, an observation similar to Xiao et al. (2020) which suggest that the reduction of sea ice has not changed the average SLH of the Arctic Ocean. Additionally, this paper finds for the first time that the polar vortex intensity index is the dominant factor in the Norwegian Sea, the Barents Sea north of New Land Island and Chukchi Sea in the accelerated rise period. Furthermore, in the area near the continent of Barents Sea, Kara Sea and Laptev Sea, AO index is the dominant factor, which is consistent with the conclusion of Armitage et al. (2018) and Proshutinsky et al. (2007). In the north of the Bering Strait and along the coast of the East Siberian Sea, the contribution of precipitation factor is greater.

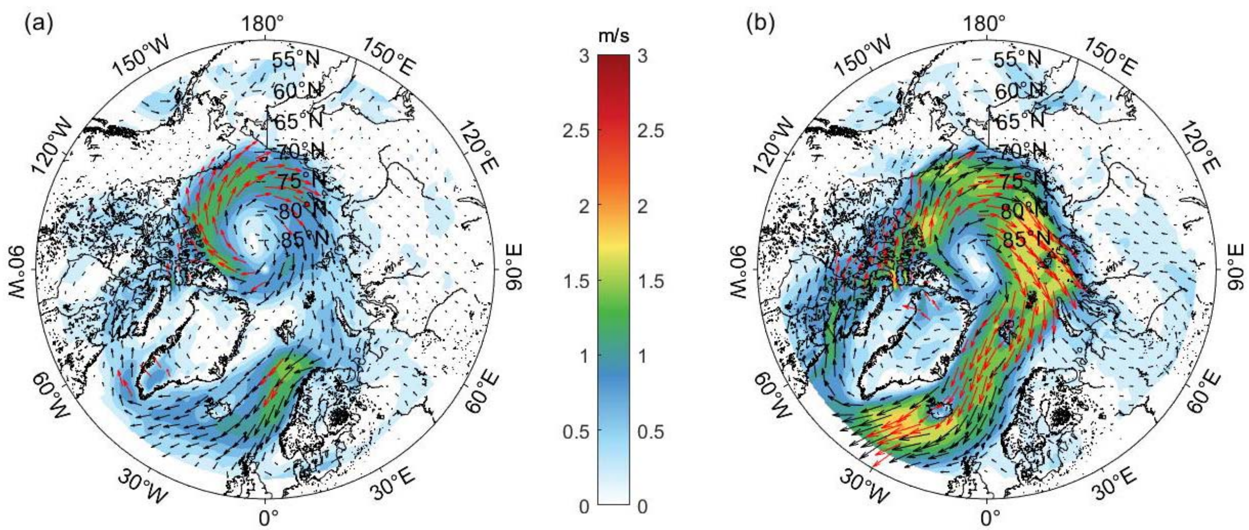

Figure 4. The anomaly of 10m wind in years with strong northern polar vortex center intensity index: (a) 1979-1998, (b) 1999-2018. The red arrow is the area passing the 95% significance test

Why the contribution of the polar vortex intensity index to the Arctic SLH has increased significantly in the accelerated rise period? In this study, a composite analysis is used to analyze wind anomalies in years when polar vortex intensity index is exceeds once its standard deviation before and after the accelerated rise period. It is found that the response of wind field to strong polar vortex increases significantly. In the years with strong polar vortex, there is an anticyclone wind field anomaly in the middle of the Arctic Ocean, which became more significant during the accelerated rise period (Figure 4). In Chukchi Sea, the East Siberian Sea, the Laptev Sea and the Kara Sea, the clockwise wind field increases significantly, from 1.2m/s in 1979-1998 to 1.9m/s in 1999-2018. Wind anomaly increased from 0.5m/s to 1.6m/s in Greenland Sea, the vicinity sea of the Svalbard Islands, and the Nordic Islands, an area that is consistent with where the polar vortex intensity index changed into the dominant factor in the accelerated rise period (Figure 3b). This stronger anticyclone wind field anomaly can drive the redistribution of surface seawater through processes such as surface wind stress (Sturges & Douglas, 2011; Timmermann et al., 2010), thus affecting the change of SLH. This is called the polar vortex-wind-sea level mechanism in this paper. During the accelerated rise period, in the northern Norwegian Sea and Barents Sea, response of the wind field from polar vortex is significantly enhanced, which leads to dominant factor of SLH in the above area switched from precipitation index to polar vortex intensity index.

4 Conclusions

In this study, ORAS5 data are used to analyze the changes of sea level height in the Arctic marginal sea area. The study finds that the sea level height in the Arctic marginal sea area gradually increased from 1979 to 2018 in the context of the reduction of Arctic sea ice. After 1998, the rate of sea level height rises significantly accelerates and enter an accelerated rise period. The Arctic polar vortex intensity index is found to have a strong correlation with the sea level height of the Arctic marginal sea for the first time. Amongst factors affecting sea level height (sea ice melting, sea temperature, precipitation, AO index, polar vortex intensity index), this study finds, via sliding correlation and multiple linear regression analysis of de-trended standardized series, that the key factors affecting sea level height have changed before and after the accelerated rise period. Before the accelerated rise period, in the marginal sea area of the Asian continent, the precipitation factor made a great contribution to the sea level height. During the accelerated rise period, in the marginal sea area of Barents Sea, Kara Sea and Laptev Sea, the dominant factor changed from precipitation factor to AO index. In the coastal area of the Norwegian Sea and the Barents Sea area to the north of Novaya Zemlya Island, the dominant factor changes from the precipitation factor to the polar vortex intensity index. The reason for this change may be that under the background of Arctic warming and sea ice reduction in the accelerated rise period, the anticyclone wind field anomaly in the year when the polar vortex center is more significant. The strong wind drives the distribution of surface seawater through processes such as surface wind stress. This polar vortex-wind-sea level height mechanism affects the change of sea level height. According to the CESM scenario simulation, the sea level height in marginal sea area of the Arctic will continue to rise in the future, with a maximum rise of about 0.4m. Under the background of global climate change and Arctic sea ice melting, the impact of atmospheric circulation factors such as AO and polar vortex on the sea level height in the future needs further analysis and simulation research.

Acknowledgments

The authors acknowledge the joint support of the National Natural Science Foundation of China (Grants 42175172 and 41975134) and the Fundamental Research Funds for the Central Universities (Grants 0207-14380169). We thank all anonymous reviewers for their insightful comments, which led to great improvements of this manuscript.

Open Research

The sea level height reanalysis data obtained from Ocean Reanalysis System 5 (ORAS5) dataset produced by European Centre for Medium-Range Weather Forecasts (ECMWF) are available in https://icdc.cen.uni-hamburg.de/thredds/catalog/ftpthredds/EASYInit/oras5/ORCA025/sossheig/opa0/catalog.html. The simulation results of the CESM2 are downloaded from https://esgf-node.llnl.gov/search/cmip6/. Sea surface temperature, total precipitation, 10m wind data are obtained from ECMWF(https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means). The Northern Hemisphere Polar Vortex Central Intensity Index of China National Climate Center is also used in this study(https://cmdp.ncc-cma.net/cn/monitoring.htm#basic). NSIDC 0051 sea ice concentration product and PIOMAS sea ice thickness product are downloaded from https://nsidc.org/data/nsidc-0051/versions/2 and http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/data/ , respectively.

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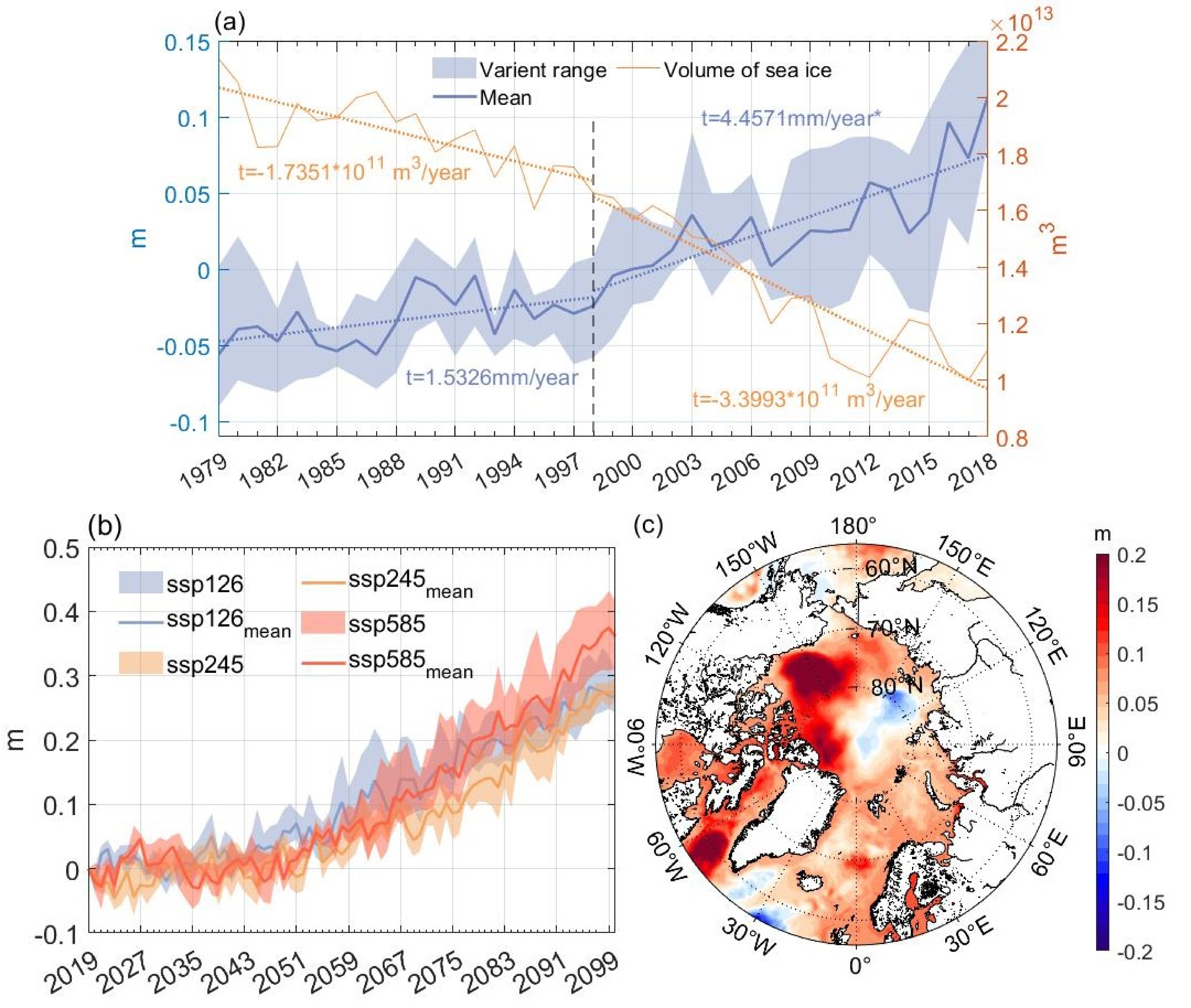
Figure 1.



(a)
Varient range
Volume of sea ice
Mean
t=4.4571mm/year*
t=-1.7351*10^11 m^3/year
t=1.5326mm/year
t=-3.3993*10^11 m^3/year
m
m^3
×10^13
(b)
ssp126
ssp126mean
ssp245
ssp245mean
ssp585
ssp585mean
m
(c)
180°
150°W
150°E
120°W
120°E
90°W
90°E
60°W
60°E
30°W
30°E
0°
60°N
70°N
80°N
m

Figure 2.

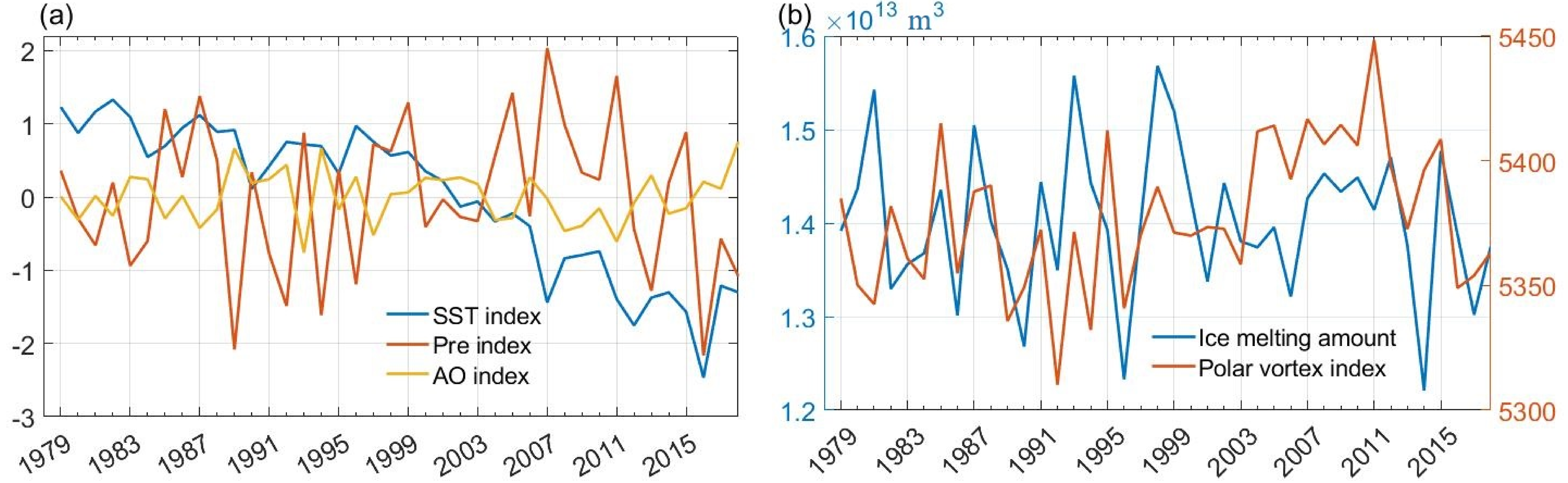

(a)
SST index
Pre index
AO index
(b)
$\times10^{13}$ m^3
Ice melting amount
Polar vortex index

Figure 3.

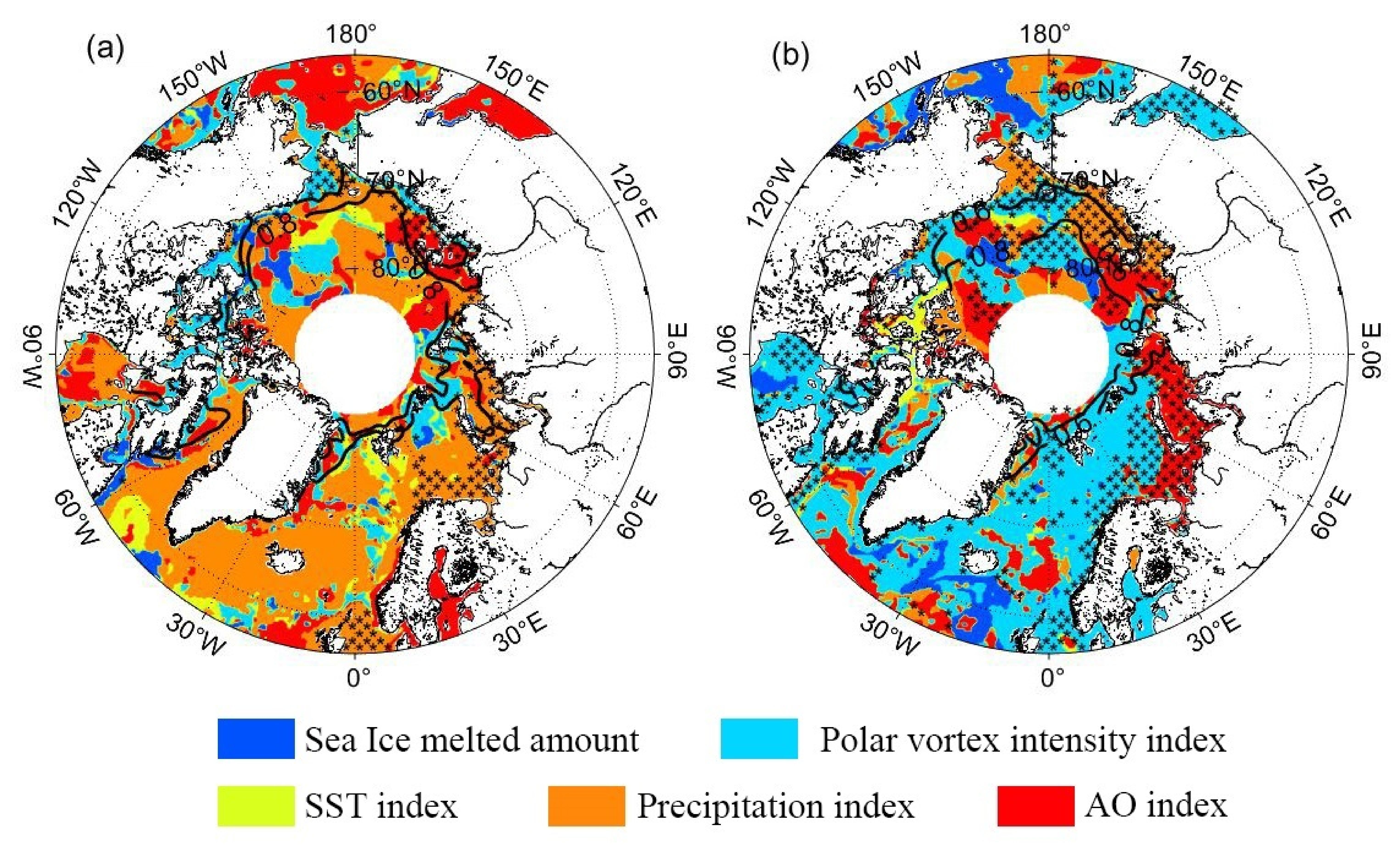
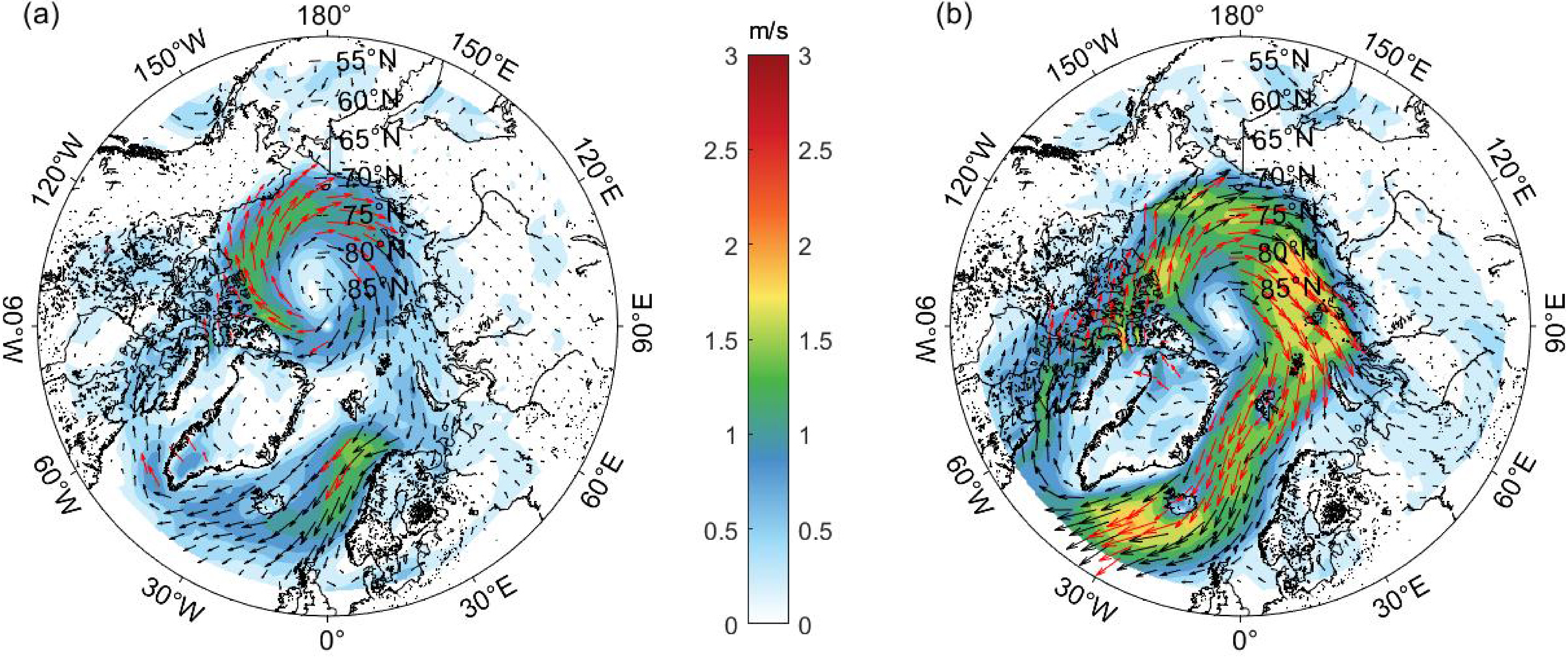

(a)
(b)
180°
150°W
150°E
120°W
120°E
90°W
90°E
60°W
60°E
30°W
30°E
0°
60°N
70°N
80°N
0.8
Sea Ice melted amount
Polar vortex intensity index
SST index
Precipitation index
AO index

Figure 4.



(a)
180°
150°W
150°E
120°W
120°E
90°W
90°E
60°W
60°E
30°W
30°E
0°
55°N
60°N
65°N
70°N
75°N
80°N
85°N
m/s
3
2.5
2
1.5
1
0.5
0
(b)

Geophysical Research Letters

Supporting Information for

Arctic Sea Level Variation in the Context of Climate Change: Accelerated rise period and Change of Key Influencing factors

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Contents of this file

Figures S1 to S3

Introduction

This supporting information provides the division of Arctic Ocean Region (Figure S1), Spatial distribution of the first mode of EOF of SST and precipitation (Figure S2) and correlation between northern hemisphere polar vortex central intensity index and sea level height (Figure S3).

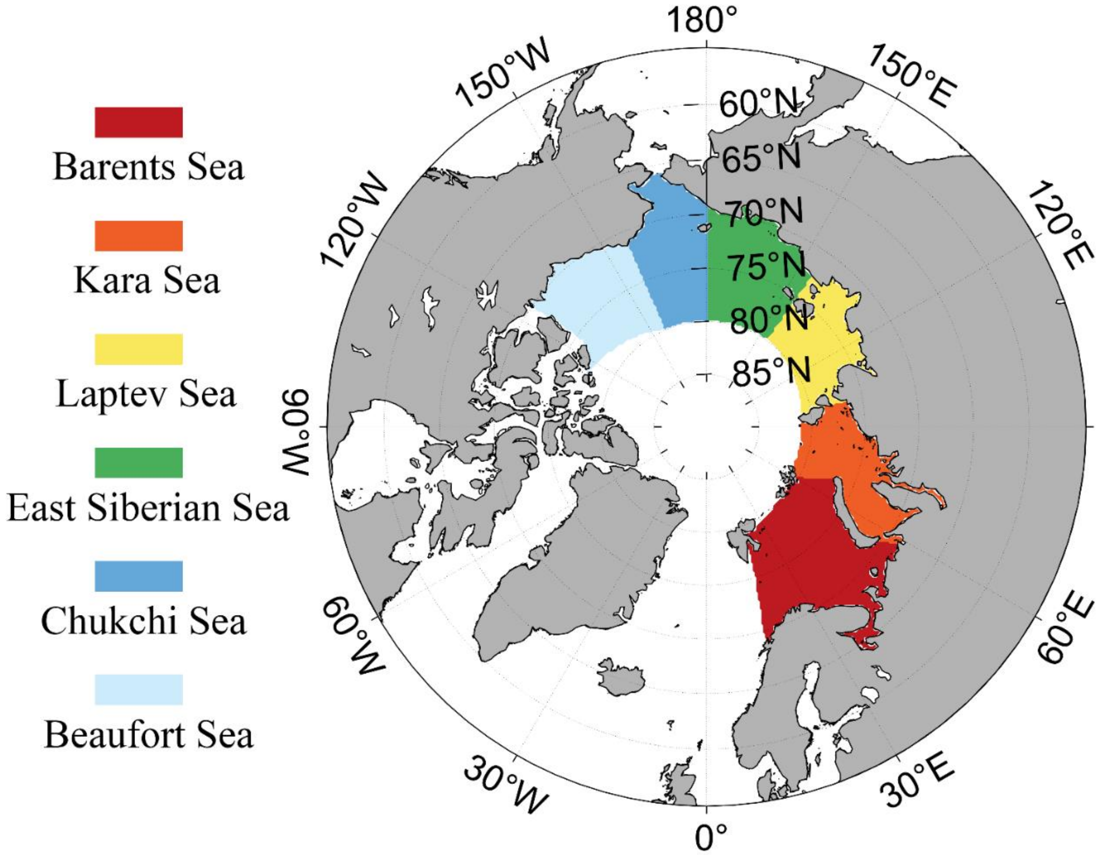

Figure S1. Division of Arctic Ocean Region.

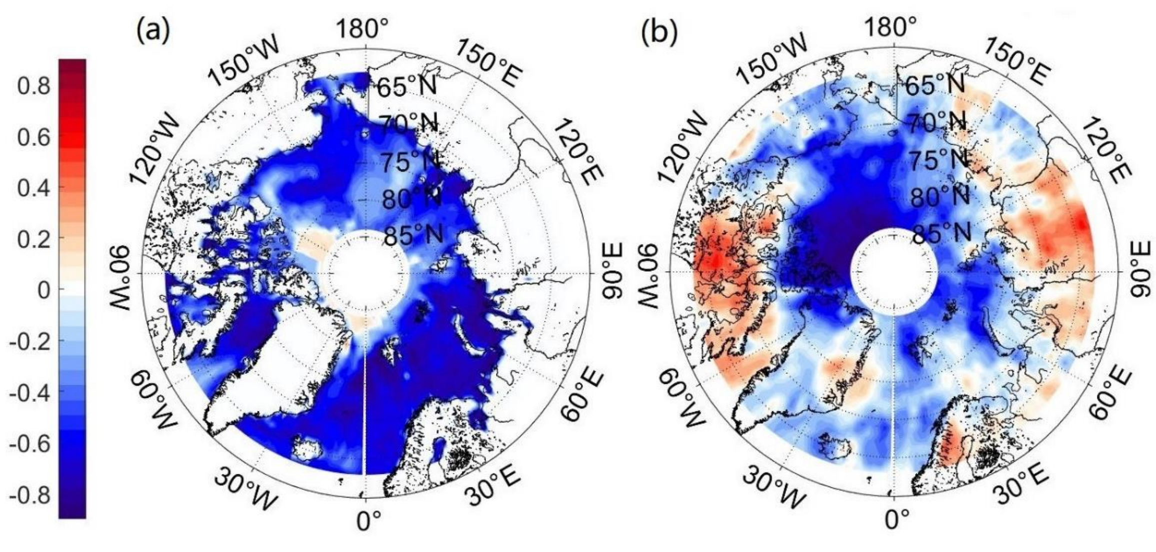

Figure S2. (a) Spatial distribution of the first mode of EOF of SST and (b) precipitation in the melting season of 1979-2018.

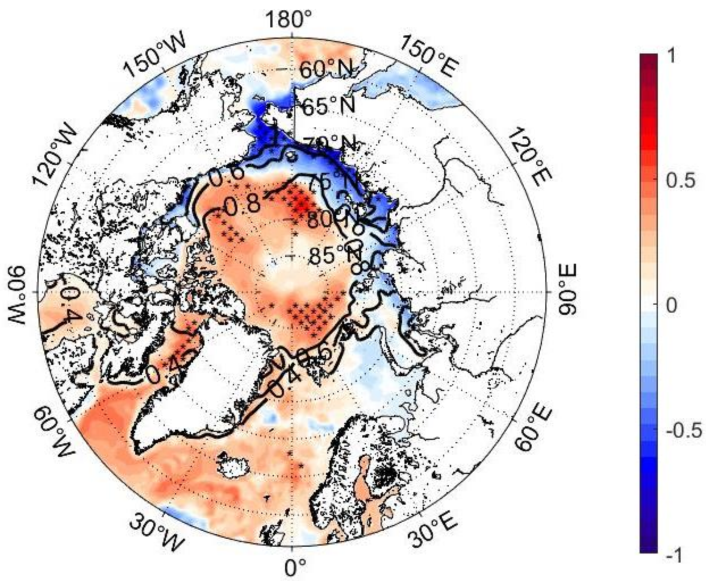

Figure S3. Correlation between northern hemisphere polar vortex central intensity index and sea level height from 1979 to 2018.