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이학석사학위논문

# The Impact of Arctic Sea Ice Loss on the Eurasian Winter Surface Air Temperature Change in Recent Decades

## 북극 해빙의 감소가 최근 유라시아 지표 기온변화에 미치는 영향

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# Abstract

The high variability of the Arctic sea ice concentration (SIC) is an important factor for understanding the weather and climate change in the northern mid-latitude. In recent decades, the surface air temperature (SAT) trend over the continents in the northern hemisphere has turned negative. Moreover, the number of extremely cold days is increasing. This sudden change in the weather and climate in the mid-latitudes is thought to be influenced by the Arctic sea ice loss because there is a high correlation between the Arctic SIC and the SAT over the mid-latitude. In this study, we examine the impact of the Arctic sea ice loss on the SAT trend and the variability in Eurasia. We analyzed in-situ observation and reanalysis data to see what happened and carried out the transient climate model with the coupled general circulation model (CGCM) and the linear baroclinic model.

**Keywords:** Arctic sea ice, Eurasian cooling, climate model, blocking high

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# 1. Introduction

Since the 2000s, surface air temperature (SAT) trend has begun to decrease in almost all areas of the northern mid-latitude in boreal winter. This sudden cooling trend is strong enough to beat the global warming with the constant increase in greenhouse gas emissions (Cohen et al. 2012a; Kosaka and Xie 2013; Li et al. 2015). The leading mechanisms for this broad cooling trend are not clearly understood.

The sudden SAT decrease has occurred in mainly two regions of northern midlatitudes: North America and Eurasia. The trend changes in both regions appear almost at the same time, but the dynamic mechanisms associated with the changes are distinguishable. The changes in SST and ocean heat uptake in the Pacific (Meehl et al. 2011; Meehl et al. 2013; Trenberth and Fasullo 2013), Atlantic (Chen and Tung 2014), and Indian Oceans (Lee et al. 2015) can cause the mid-latitude cooling trend. Kosaka and Xie (2013) show evidence by using the climate 7model simulation GFDL-CM2.1 for the ocean impact on the cooling trend in North America, but not in Eurasia. The Arctic sea ice loss can also derive the cooling trend in winter in both regions (Cohen et al. 2014; Cohen et al. 2012a; Kug et al. 2015; Liu et al. 2012; Mori et al. 2014; Peings and Magnusdottir 2014). Kug et al (2015) demonstrates in observations that the impacts of Arctic warming on Eurasia and North America have different timescales, which means the leading mechanisms are

possibly different each other. Here we have focus on the relationship between Arctic sea ice loss and Eurasian winter cooling.

The relationship between the Arctic and the SAT over Eurasia is well known as the Warm Arctic Cold Eurasia, the so-called WACE pattern. The physical mechanisms associated with this WACE pattern are thought to be one of either natural variability or the forced response. In order to understand comprehensively, various types of climate model experiments have been carried out. Most of the studies using the atmospheric general circulation model (AGCM) show inconsistent results by the used model configurations. (Kim et al. 2014) and (Peings and Magnusdottir 2014) show slightly underestimated surface cooling with the equilibrium experiment in CAM5. They explain the stratospheric pathway can transport the released energy due to the sea ice melt to mid-latitudes. (Li et al. 2015) used the AMIP experiments with the warming over the Arctic, and they suggest the recent observed cooling trend is not the forced response but the result of the natural variability. However, in up-to-date research using coupled general circulation mode (CGCM), the strengthened Siberian high is well reproduced with the Arctic forcing (Deser et al. 2016). Until now, the possibility that the recent declined SAT in Eurasia is a forced response to Arctic has seemed the most probable one, but we do not have any general consensus for its mechanisms yet.

In this study, we examine the mid-latitudinal temperature change

using various statistical skills to find the evidence for the WACE pattern. In order to investigate the Arctic warming due to the sea ice loss over the Barents and Kara seas, we carried out the linear baroclinic model (LBM) experiment. Additionally, the Arctic warming influence is examined by using idealized coupled GCM and GFDL-CM2.1 in terms of trend and variability.

# 2. Data and Method

## 2.1. Data

We used the Hadley Centre-Climate Research Unit combined land SAT and SST (HadCRUT) version 4.2.0.0 SAT to examine trend change of the observed SAT (Morice et al. 2012). It served as a 5-degree gridded temperature anomaly relative to the reference period of 1961–1990. Because it is based on the in situ measurements, the number of non-missing grids is inhomogeneous in time. We interpolated data if the number of the missing data in each grid was less than 25% of the total analyzed period, from 1979 to 2013, and ignored otherwise. We also used Japanese 55-year Reanalysis (JRA-55) to further evaluate SAT trends in the regions where observations were sparse (Ebita et al. 2011). We used Hadley Centre sea-Ice and Sea Surface Temperature (HadISST) for the sea ice concentration (SIC) data to see the relationship between the changes in Eurasian SAT trends and sea ice loss in the Arctic (Rayner et al. 2003).

All seasonal means are based on 3-month averages. In order to examine the seasonality of the SAT trend change, we averaged SAT from June to August (JJA) and December to February (DJF). We focused on the variation of Arctic SIC in autumn, so we averaged Arctic SIC from September to November (SON), October to December (OND), November to January (NDJ), and December to February (DJF). Denoted years in seasonal mean indicate the

year of the firth month of the season. For instance, the 2000 DJF means the average from December 2000 to February 2001. Here we used the regional domain of north of 20°N for the extratropics, 35–60°N and 70–140°E for Eurasia, 25–50°N and 75–120°W for North America, and 70–80°N and 30–90°E for the Barents and Kara seas.

## 2.2. Blocking index

We further analyzed the atmospheric blocking high to examine the temperature variability change related with the sea ice loss in the 2000s. There are various indices to define the atmospheric blocks. Among them, we use the hybrid index, which combine the two common indices, the Dole-Gordon type (DG) index and the Tibaldi-Molteni type (TM) index (Dunn-Sigouin et al. 2013; Dunn-Sigouin and Son 2013). The DG index captures blocking events with the persistence of the geopotential anomalies at 500hPa in 2-D statistics, but it has possibilities that detect the arbitrary blocking or overestimate blocking events by capturing the quasi-stationary ridges. The TM index identifies blocking events with the reversal of the meridional gradient of the geopotential height at 500hPa. Because it needs the references latitude to define the reversal of gradient, TM index is a function only of longitude. However, by combining the two different indices, we can identify the blocking events in 2-D statistics, and it minimizes the possible misdetection. More

details in Dunn-Sigouin and Son (2013) and Dunn-Sigouin et al. (2013).

## 2.3. Statistical analysis

Many approaches have been used to capture the change in linear trends. Here we used the Perron-Yabu testing procedure for structural change (PY procedure) (Estrada et al. 2013; Perron and Yabu 2009). It is the linear regression using ordinary least square fit while considering one break in trend.

$$y = \mu + \beta t + \delta DT + \tilde{u}_t$$

The difference between PY procedure and a simple linear regression is the DT term, which is $DT = t - T_B$ if $t > T_B$ and 0 otherwise. This allows for the presence of the break at time $T_B$ in the trend. Therefore, μ is y intercept, $\beta$ is the first trend before it changed, the second trend after it changed becomes $\beta + \delta$ and $\tilde{u}_t$ is the noise component. This method is only valid when the data has integrated or stationary noise.

So, before applying the PY procedure, we needed to test the stationarity of data with the unit root test (Kim and Perron 2009). As we already knew, the temperature time series does not have a continuous slope. The standard unit root test is not appropriate for verifying the data generating process. Thus, we needed a new method to figure out the data structure. The Kim-Perron unit root test allows one time break in trend and documents the stationarity of the temperature data (Kim and Perron 2009). All data rejected the null hypothesis

of the Kim-Perron test at a 1% significance level. As a result, we were able to easily consider that the temperature time trend has a statistically significant break point.

However, it also could contain the cases of multiple breaks in slope with the most dramatic change, compared to the other breaks detected as the break or one break, which are physically meaningless. To separate the warming hiatus event from these irrelevant cases caused by the statistical analysis, we used a 95% confidence interval of the break point. We defined the trend is statistically changed only if the 95% confidence interval was perfectly included in the time period. If the interval range was partially out of the used time period, the estimated breaks were regarded as meaningless points calculated from the statistics, which means arbitrary trend change. In this case, we assumed that the data fit the simple linear regression model.

## 2.4. Model configurations

### 2.4.1. Coupled GCM

We used the GFDL CM2.1 coupled climate model developed by the Geophysical Fluid Dynamics Laboratory (GFDL). To examine the Arctic warming influence, the observed SST based on the ERSST v3 is restored over the north of 70°N with 5 days relaxing timescale to the present run, which is a pre-industrial-like experiment. We generated 9 ensemble members, and 5 of

them were exactly the same output used in Kug et al. (2015)

### 2.4.2. Linear baroclinic model

Linear baroclinic model (LBM) was used to investigate the response to the Arctic warming due to the sea ice loss with linear dynamics. Watanabe and Kimoto (2000) developed the version of LBM we used. It integrates the linearized simple primitive equations with the given atmospheric steady forcing. Here we used the composite field of the December to February (DJF) mean diabatic heating profile as a thermal steady forcing and the composite field of the JRA55 reanalysis data when the October to December (OND) mean SIC over the Barents and Kara seas was recorded under 40% as a basic state. T42L20 horizontal resolution was used for the experiments.

# 3. SAT trend change

## 3.1. Observational evidence of Arctic impacts on Eurasian SAT trend

Global warming due to the increase in greenhouse gas has been a general consensus for many decades. One of the main features of global warming is Arctic amplification, which means the SAT over high latitudes in the Northern Hemisphere have a more intensive warming rate than in the tropics. We calculated linear trends of annual, DJF-, and JJA- mean SAT based on the least square fit for 36 years, from 1979 to 2013, using the in-situ observational SAT, HadCRUT4. Annual mean SAT had a warming trend in almost all the regions, and the Arctic amplification patterns are clearly shown (Fig. 1a). This spatial pattern is also clear in the JJA season but not in the DJF season. In DJF, the SAT trend over Eurasia shows strong cooling, and the SAT trend over the middle of North America shows neither strong cooling nor significant warming (Fig.1b–c).

We examined the observed SAT changes in the Northern Hemispheric (NH) extratropics (North of 20°N), Eurasia (35–60°N and 70–140°E), and the middle of North America (NA) (25–50°N and 75–120°W) to understand what happened in recent decades (Fig. 2a–c). In all the regions, the summer SAT showed a continuous increasing trend since 1979, but the winter SAT started

to decrease statistically in 2006 (estimated) in NH extratropics and 1998 (estimated) both in Eurasia and NA. Thus, we consider the recent winter SAT cooling started in 1998. Focusing on the significant changes in the winter season, we further calculated the winter SAT trend before and after 1998 in each grid (Fig. 2d–e). The spatial feature of Arctic amplification is dominant, and the warming trend is especially strong over the continents in the Northern hemisphere before 1998. Most of the strong warming trends are statistically significant despite the short time scale (Fig. 2d). It has fully reflected the global warming signal, but the aspects are quite different after 1998 when the mid-latitudinal winter cooling started. The SAT trend turned negative in most continental regions in the Northern midlatitudes after 1998. Even if the intense coolings are not statistically significant and the amount of the descended SAT is irrelevant, it is more than 2K/decades and exceeds 3K/decades in some grids in Eurasia (Fig. 2e). Another big difference between Figures 2d and 2e also appears in the Pacific, but it seems to be from the reflected signal of the phase change of the Interdecadal Pacific Oscillations (IPO).

The recent winter cooling over the northern mid-latitudes has been spotlighted because the cooling is strong enough to cancel out the global warming and even cause the annually averaged global mean SAT trend to slightly decrease while one of main causal factors for the global warming,

atmospheric CO2 concentration, is constantly increasing (Cohen et al. 2012a; Cohen et al. 2012b; England et al. 2014; Estrada et al. 2013; Kaufmann et al. 2011; Kosaka and Xie 2013; Meehl et al. 2013; Santer et al. 2014; Solomon et al. 2010). The main issue was whether the global warming was paused or not, and if so, whether it was because of anthropogenic efforts such as the Montreal Protocol that controls the emission of the concentration of chlorofluorocarbon (CFCs), which is well known as Freon gas to the public. However, it turns out that the reduced incoming radiation due to the regulated emission of CFCs or other natural variabilities could possibly cool the SAT, but these impacts are not dominant (Estrada et al. 2013).

Previous studies insist that the recent winter cooling over the Northern mid-latitudes is caused by the atmospheric circulation changes that induce the cold air from the arctic to the mid-latitudes (Cohen et al. 2014; Honda et al. 2009; Mori et al. 2014). What is interesting is that the physical mechanisms that decrease the winter SAT in Eurasia and North America are thought to be different from each other. Sea surface temperature (SST) in the tropics has significant impacts on the mid-latitude weather and climate. El Niño Southern Oscillation (ENSO) is the typical example. The phase of ENSO modulates the whole phase of the atmospheric circulations in the tropics, and it has a strong teleconnection to North America. The recent few decades were in the negative phase of the ENSO-like decadal oscillation in the Pacific, and

this was nominated as the causal factor of winter SAT decrease in North America (England et al. 2014; Meehl et al. 2011; Meehl et al. 2013). However, it failed to explain the extremely cold winter in Eurasia. By considering the changes in the tropical Pacific in the climate model experiment, the Eurasian SAT shows a warming trend while the strong cooling trend appears over North America (Kosaka and Xie 2013). There is another approach to understanding the related mechanisms. Kug et al. (2015) suggests that the Arctic warming due to the sea ice loss caused the recent cooling over the mid-latitudes. It shows high correlations between the Arctic SST and the SAT in the mid-latitudes, but the spatial patterns and the timescale of the correlations shows different aspects. It implies the Arctic amplification could affect the mid-latitudinal cooling but the accompanied dynamical mechanisms are distinguishable. In this context, we have focused on the Eurasian winter cooling and its variability with the Arctic amplification.

Recently, the Arctic sea ice has suffered intense melting (Cohen et al. 2014; Cohen et al. 2012b). The sea ice melting is quite severe because the Barents Sea was totally open to the ocean in September 2015. Figure 3 shows the SIC over the Arctic in the SON, OND, NDJ, and DJF seasons. There is no increasing signal in SIC over almost all of the Arctic seas. Sea ice is consistently melted out in autumn and early winter from SON to NDJ, but it starts to slowly recover in DJF. The Barents and Kara seas (BK seas) are the most important

because the SIC losses are the most sensitive regardless of season, and it is thought to play a key role in the Eurasian weather and climate system. We estimated the trend changes in the seasonally averaged SIC over the BK seas using the PY methods. The SIC timeseries shows simultaneous trend changes in 1998 in a linear sense, and it is synchronized with the statistically estimated SAT trend change.

At this point, we needed to figure out whether this surprising coincidence was dynamically correlated or not. It could have accidentally happened at the same time even though they are physically independent. It was also possible that the certain unknown dynamical process had modulated both the Arctic autumn SIC loss and Eurasian winter SAT cooling, or that the Arctic SIC had melted out first in autumn and affected the winter Eurasian climate as mentioned in previous studies (Cohen et al. 2014). In order to figure out what the most possible mechanism was, previous studies applied the various eigen value analyses. Mori et al. (2014) decomposed the Eurasian SAT into the AO-like mode and the warm Arctic cold Eurasia (WACE) mode by using empirical orthogonal function (EOF) analysis. The study said the Eurasian winter coolings induced by the AO-like mode and the WACE mode are independent and the WACE mode is highly correlated with the winter SIC in the BK seas. To cover up the dependency of the used regional and temporal domain of EOF analysis, (Kim and Son 2016) shows a consistent result by

using the more developed EOF, cyclostationary empirical orthogonal function (CSEOF). (Outten and Esau 2012) shows that there is a co-variability between the Arctic SIC and the Eurasian SAT in January by using the canonical correlation analysis (CCA) based on the singular vector decomposition (SVD). However, the earlier studies do not consider the time lag between the Arctic SIC and the Eurasian SAT.

Therefore, here we apply the CCA analysis based on the SVD with DJF mean SAT over the Eastern part of the North Hemispheric extratropics (20N~90N, 0E~180E) and three months mean SIC over half of the Arctic seas (60N~90N, 0E~180E). For the SIC, SON, OND, NDJ, and DJF, we used the mean. Except for the DJF SIC (0.44), other seasons have high covariance: 0.75 in SON, 0.77 in OND, and 0.64 in NDJ (Table 1) for the first mode. From these results we assume that the Arctic SIC in autumn more highly correlates with Eurasia than in winter. However, the difference between the SON, OND, and NDJ means is negligible. So, we chose the OND mean SIC as the representative autumn SIC in the Arctic to explain the Eurasian SAT change. (Fig. 4) We found high co-variability in the OND mean SIC in the BK seas and the DJF mean SAT in Eurasia. This WACE pattern seems to be the most dominant even if we consider the time lag (Fig. 4c–d). The more important finding is the recent trend changes in both the SIC in the BK seas and the SAT in Eurasia are reflected in the principle component timeseries of the first mode of CCA

analysis (Fig. 4a–b). This supports that the surprising coincidence of the trend changes in the SIC and SAT are not the just a coincidence, they are physically linked in terms of the linear trend and co-variability in inter-annual timescale.

From the eigen value analysis, we investigated the Arctic SIC is possibly related to the Eurasian SAT trend. However, we already know that the temperature cooling over Eurasia is not only related to the Arctic sea ice. We decomposed the linear trend of the SAT timeseries after 1998 with the SIC in the BK seas to verify how much of the trend could be explained by the Arctic SIC change (Thompson et al. 2000). We simply partitioned the SAT trend into linearly congruent and independent components with SIC as follows: 1) calculate the total linear trend of SAT to be decomposed in each grid, and a trend in a certain grid is denoted as $\gamma$; 2) regress the SAT time series in each grid on the SIC time series that averaged over the BK seas, and a regression in a certain grid is denoted as $\alpha$; 3) the linear trend of the SIC averaged over the BK seas is denoted as $\beta$. Then, the multiple $\alpha$ with $\beta$ is the linearly congruent trend of SAT in each grid with respect to the SIC averaged over the BK seas, and $\gamma$ minus the linearly congruent component is the independent component or residual trend.

Figure 5 shows the linearly congruent trend of SAT with SIC over the BK seas and the residual in the in-situ observation and reanalysis data. In the observations, the SIC related trends appear almost over all of Eurasia, and the

residual trend appears in the left side of Eurasia. The scale of the cooling related with the SIC is not negligible: almost half of the cooling trend is linearly congruent with SIC. It is clear in the reanalysis data, but the strong Arctic warming trend accompanies the Eurasia cooling trend linearly related with SIC. This is obvious because the SIC loss is caused by the induced warm air from the lower latitude, and the open seas where the sea ice is melted out released large amounts of sensible and latent heat. The strong cooling over North America seems not linearly related with the SIC over the BK seas, and this is consistent with the results in Kug et al. (2013).

## 3.2. Model experiments for the Arctic sea ice loss

In various analyses on the SAT change over Eurasia, we could strongly insist that the Arctic sea ice loss is highly connected to the Eurasian temperature change in the sense of trend and variability, but we still could not assume that the Arctic sea ice loss is caused by the Eurasian winter cooling because the timescale is too short to prove and, more importantly, statistics do not tell the dynamics. The modeling approach is essential to understanding the dynamics of the recent atmospheric circulations change.

Deser et al. (2016) already performed similar experiments to investigate the impact of the Arctic sea ice loss using the state-of-the-art CGCM and CCSM4. Because CCSM4 basically served the sea ice model that generates

the distribution of sea ice concentration and thickness, they artificially reflect the impact of the Arctic sea ice loss to induce the seasonal longwave radiative flux to the sea ice model. Additionally, because their experiments are based on the CO2 doubling experiments, they are unlike the real world. Here we reflected the impact of the Arctic sea ice loss by simply restoring the SST over the Arctic seas to the preindustrial-like experiment by using the chemical and physical forcing of 1990 (see section 2.4.1. for the details). Thus, we can compare the results from the model experiments with recent observations.

At first, we calculated the linear trend of the DJF mean SAT from 1979 to 2013 in the 9-ensemble mean of the experiments and compared it with the trend of DJF mean SAT in HadCRUT4 and JRA55 reanalysis. Although we fixed the concentration of CO2 as the level in 1990, the DJF mean SAT of the ensemble mean shows an overall increasing trend over the northern extratropics. It is obvious because we restored the SST over the all of the Arctic seas. The restored SST are partly explained with the Arctic amplification independent from the sea ice melting. It seems that there is no Eurasian winter cooling in terms of total trend in ensemble mean unlike the observation. However, the warming signal in Eurasia is weaker than observation, and the warming is not statistically significant. This means the total trend of the ensemble mean hints at Eurasian cooling after 1998 (Fig. 6).

We further carried out PY methods on the regionally averaged time

series and calculated the linear trend in each grid by using the least squared fit (Fig 7) with the ensemble mean only for the DJF season. The results from the ensemble mean are qualitatively consistent with the observations. The northern extratropics, Eurasia, and North America show the recent trend change, but there are two big differences between the observations and the ensemble mean: the statistically estimated trend-changed years are a bit delayed and the simulated cooling trend is underestimated in all regions (Fig. 7a-c). This is reasonable when we consider that the Arctic sea ice loss is not the only causal factor for the recent cooling in the mid-latitudes. 2002 is the estimate trend-changed year in Eurasia, which is delayed by four years compared to the observations. We calculated the linear trends before and after 2002 to compare the spatial pattern of cooling. The SAT trend change over Eurasia is detected as we expected, but the region of cooling is narrower than the observed cooling region (Fig. 7d–e).

The idealized transient CGCM experiments support that the Arctic sea ice loss is the dominant force for the SAT trend change. Still, we could not explain the possible dynamical mechanism with only the climate model because of its complexity. To investigate the linear dynamics related to the Arctic sea ice loss, we designed the simple linear dynamics model experiment (see section 2.4.2. for the details). Figure 8 shows the response of the induced heating over the BK seas. The upward propagating waves from the heat source

in the BK seas generate teleconnection patterns at 500hPa (Fig. 8c), but there are no surface responses in SAT and SLP over Eurasia (Fig. 8a–b). This means that the released heat due to the sea ice loss could have an impact on the upper level through upward propagation, but the Eurasian winter cooling is not explainable in the linear dynamics sense.

# 4. SAT variability change

The impact of the Arctic change on the mid-latitude climate and weather is not only apparent in terms of the linear trend. One of the recent hot issues related with the Arctic amplifications is the Francis, Vavrus, and Liu hypothesis (FVL hypothesis) (Francis and Vavrus 2012; Liu et al. 2012). The FVL hypothesis explains that the decreased meridional temperature gradient due to the Arctic amplification causes the increase in the outbreak of extreme weather resulting from the increased frequency of the blocking high. In the expansion of the hypothesis, we first examine that the frequency of the blocking high has really increased in the observation. Based on the OND mean SIC in the BK seas, we define the high ice (HICE) case with the composite of top-five maximum years SIC recorded and low ice (LICE) case with the composite of top-five minimum years. We plot the possibility distribution function during the 450 days in winter (5 years of 90 days from December to February) by each case (Fig. 9). As we expected, the mean temperature decreased when the sea ice recorded minimum, and, surprisingly, the number of extremely cold temperature tends to increase. This implies that it is possible that the sea ice reduction can cause both the temperature trend decline and also the increased temperature variability.

Blocking high is well known for the causal factors of the extreme cold weather in Eurasia. When there is a blocking high near the Ural Mountain, cold

advection from the Arctic is well developed by the cyclonic circulation and the induced cold air maintains the high anomaly (Barnes 2013; Barnes et al. 2012). In recent studies, the frequency of high-latitude blocking tends to increase in observation even if there are harsh criticisms because the results are sensitive to the methodology. Therefore, we investigated the blocking frequency in the observation and CGCM experiments (Fig. 10). Ural blocking has increased since 1998 in observations, but there is not a strong signal in a couple of model simulations.

# 5. Conclusions

The aim of this study is to further understand the possible impact of the Arctic sea ice loss on the Eurasian SAT in recent decades. We investigated the Arctic impact through linear trend and extreme weather, which account for the mean and variability of each SAT.

We first focused on the seasonal and spatial features of the recent cooling trend in observation. From the statistical approaches we were able to strongly build up the relationship between the Arctic autumn SIC and the Eurasian winter SAT. We supported the relationship and expanded the statistical relationship to the forcing and response by polar restoring simulations, but the dominant mechanism that modulates the SAT trend change is still unclear in a sense of the linear dynamics.

Induced cold air from the Artic by the atmospheric circulation system related with the Siberian high (SH) mostly causes the cold winters in Eurasia. We found a physical possibility of the enhanced SH by the climate model but explained the generation of a certain system with the recently released enormous amount of sensible and latent heat by the linear dynamics. We have considered the possibility that the released heat due to the Arctic sea ice loss enhances the preexisting SH and the synoptic winter weather system. Further studies on this are essential to the comprehensive understanding of the WACE pattern and its dynamics.

Secondly, we examined the SAT variability influenced by the Arctic sea ice loss. The extremely cold weathers take place, frequently followed by the Arctic change. The increase in frequency of the blocking high appeared somewhat in observation but not in the climate model experiments. In addition, there is no consensus that the blocking high increased in observation because the results are sensitive to the definition of the blocking index and the used observational data. We need to carry out both observational analysis and dynamic modeling to figure out the Arctic impact on extreme weather events.

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**Table 1** CCA analysis with Arctic SIC and Eurasian SAT

| CCA 1st MODE | Total variance (%) | SIC variance (%) | DJF SAT variance (%) |
|---|---|---|---|
| SON SIC | 75.5 | 40.9 | 26.3 |
| OND SIC | 77.8 | 43.9 | 27.2 |
| NDJ SIC | 64.4 | 39.7 | 24.4 |

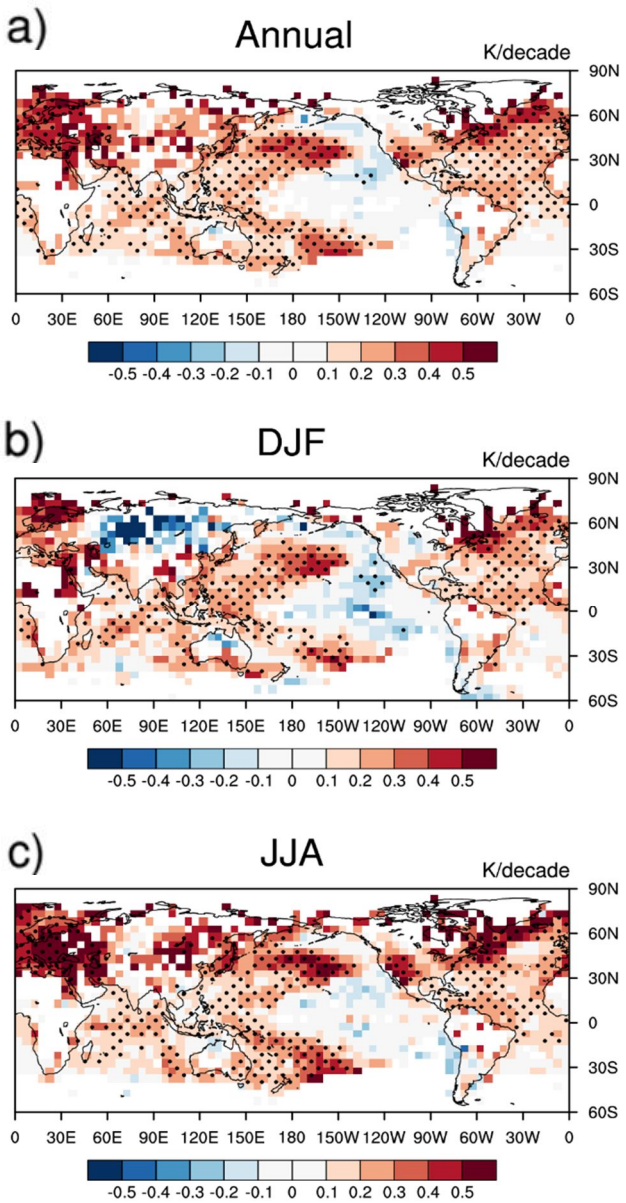


**Figure 1** Linear trends of the observed (a) annual, (b) DJF- and (c) JJA-mean SAT. Units are K/decades. The values that are statistically significant at 5 % level are dotted.

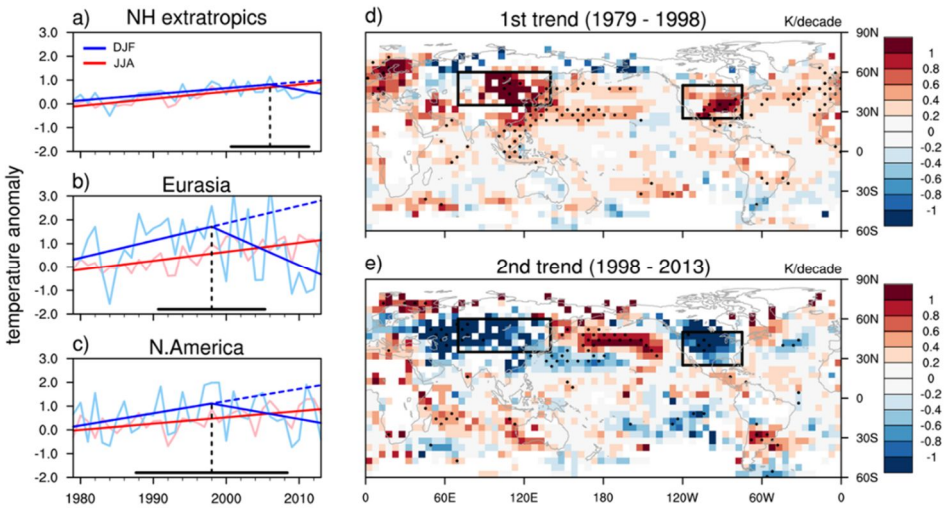


**Figure 2** Observed (blue) DJF- and (red) JJA-mean SAT and their linear trends in (a) North Hemispheric extratropics averaged over north of 20N, (b) Eurasia averaged over 70E-140E and 35N-60N (boxed in d), (c) North America averaged over 75W-120W and 25N-50N (boxed in d) in HadCRUT4. Dashed lines are extended trend in the absence of a breakpoint and the black solid lines running parallel to x axis are the 95% confidence interval of the estimated break point. The DJF-mean SAT trend (d) before and (e) after 1998. The values that are statistically significant at 5 % level are dotted.

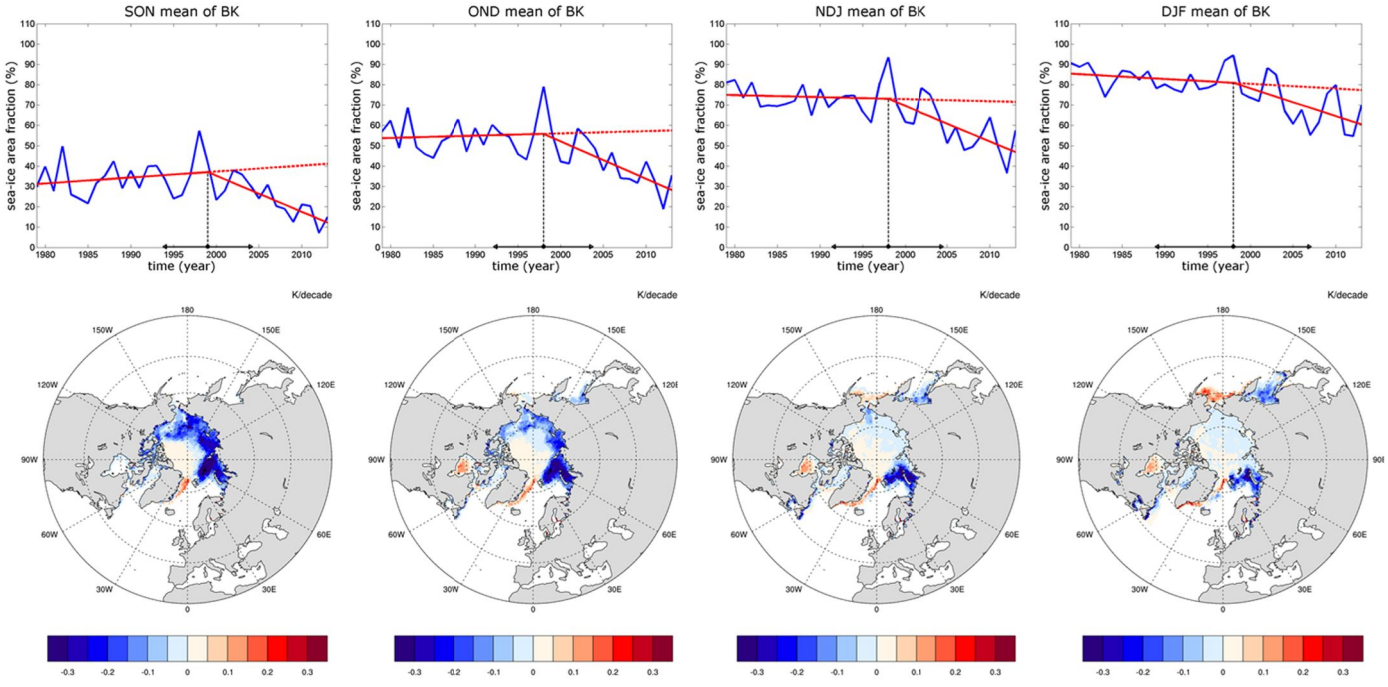


**Figure 3** Observed (blue) (a) SON-, (b) OND-, (c) NDJ-, and (d) DJF-mean SIC and their linear trends in Barents and Kara seas. Dashed lines are extended trend in the absence of a breakpoint and the black solid lines running parallel to x axis are the 95% confidence interval of the estimated break point. Linear trends of (e) SON-, (f) OND-, (g) NDJ-, and (h)DJF-mean SIC in each grid over the Arctic are shown.

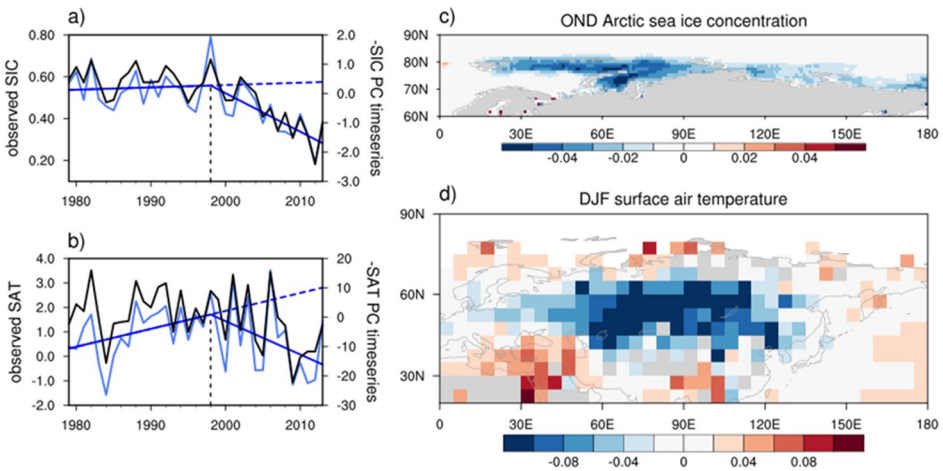


**Figure 4** (a) the observed SIC over the BK seas (blue) and leading CCA principle component of timeseries of OND-mean SIC over 0E-180E and 60N-90N (black) and (b) the observed SAT over the Eurasia (blue) and leading CCA principle component of timeseries of DJF-mean SAT over 0E-180E and 20N-90N (black). The blue solid line is the estimated linear trend with the presence of a break point and the blue dashed line is the prolonged trend. The black dashed line indicates the statistically estimated break point. The leading CCA eigen vectors of (c) OND SIC and (d) DJF SAT

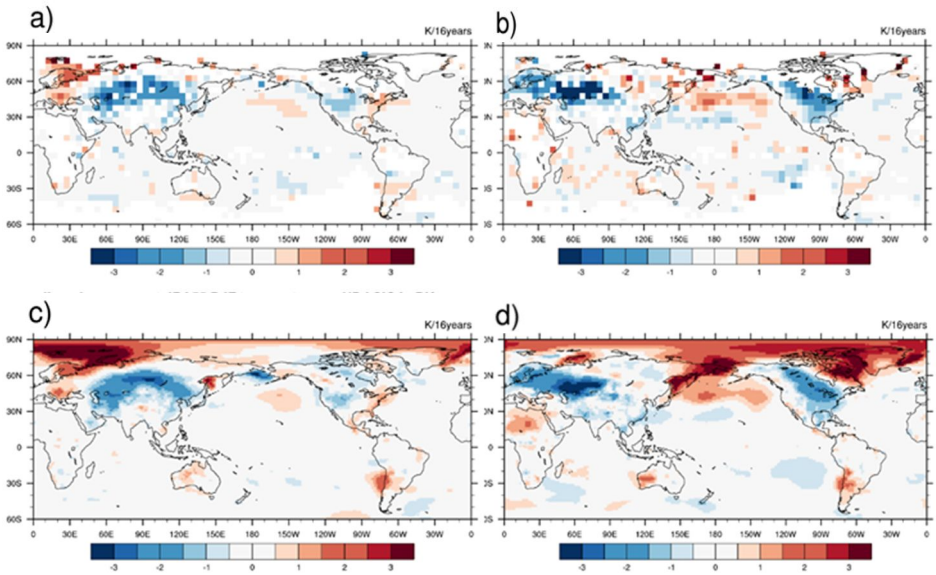


**Figure 5** (left) the linearly congruent and (right) the residual component of the linear trend of DJF-mean SAT in (top) HadCRUT4 and (bottom) JRA 55 reanalysis.

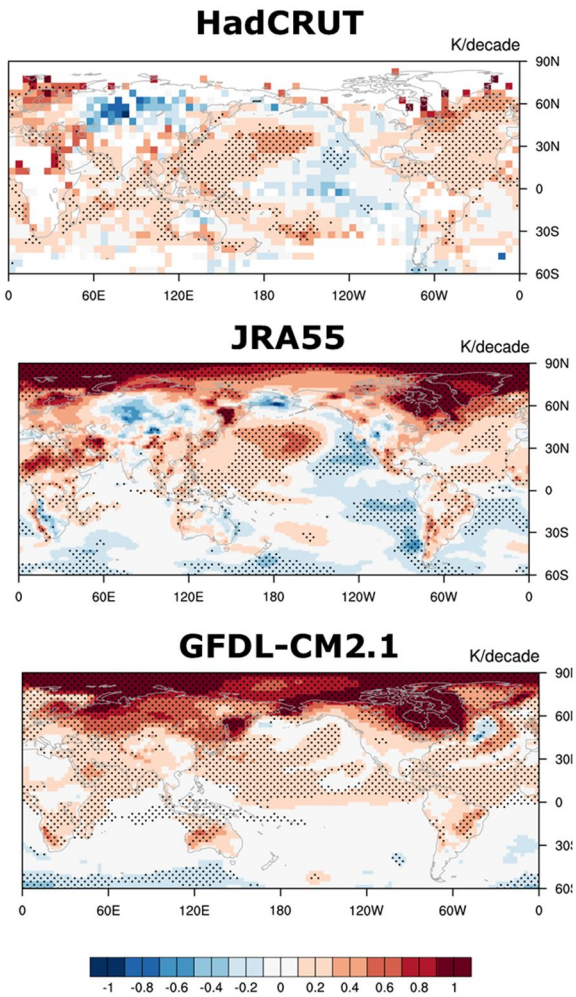


**Figure 6** Linear trends of DJF-mean SAT in (a) HadCRUT4, (b) JRA 55 reanalysis, and (c) GFDL-CM2.1 experiments. The values that are statistically significant at 5 % level are dotted.

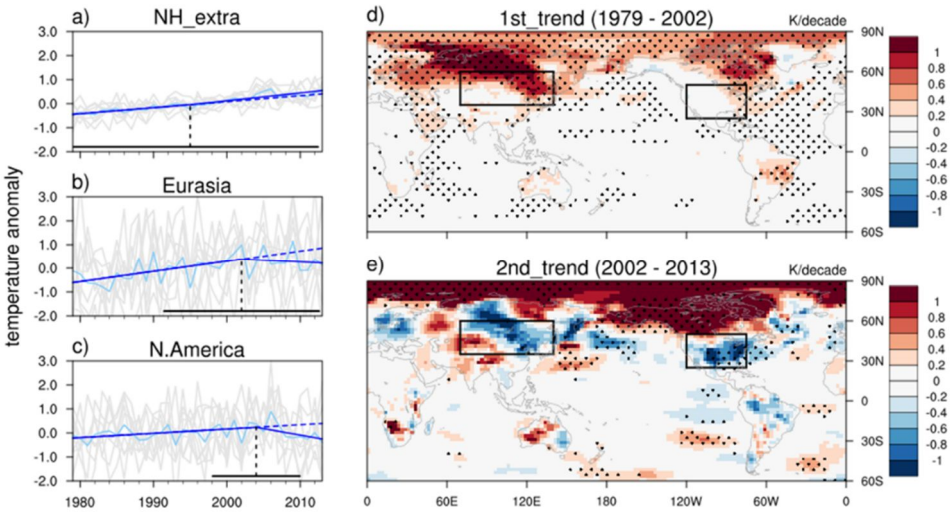


**Figure 7** same as Figure 2 but for GFDL-CM2.1 in DJF

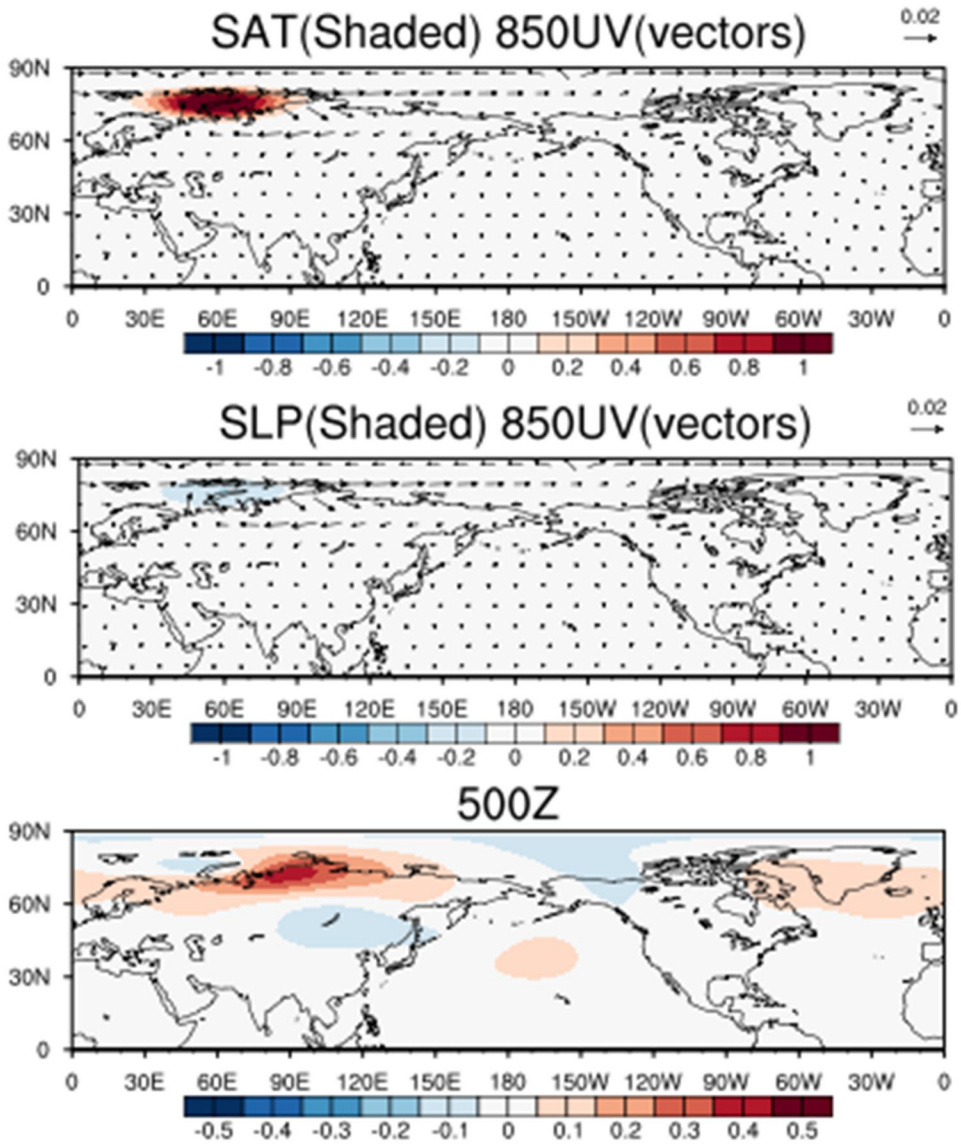


**Figure 8** (a) SAT, (b) SLP, and (c) geopotential height at 500hPa response for the steady forcing experiments in BK seas from the linear model are shaded. Vectors are zonal and meridional wind at 850hPa.

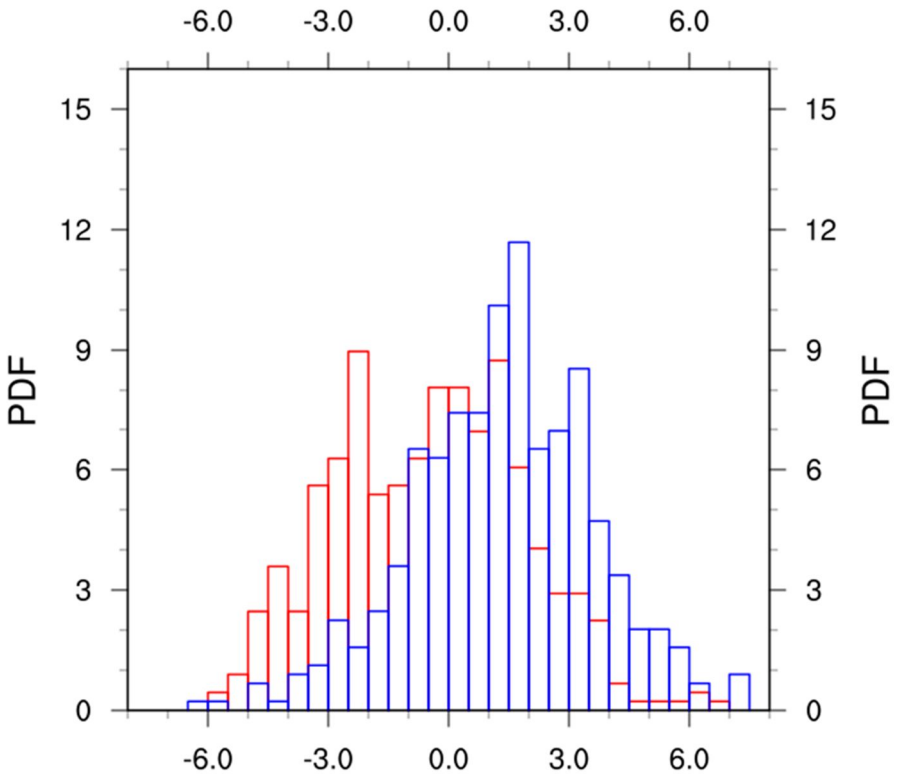


**Figure 9** Probability distribution function of 450 days in LICE case which is 90days winter day composite of top 5 minimum years of OND mean SIC over BK seas (red) and in HICE case which is 90days winter day composite of top 5 maximum years of OND mean SIC over BK seas (blue)

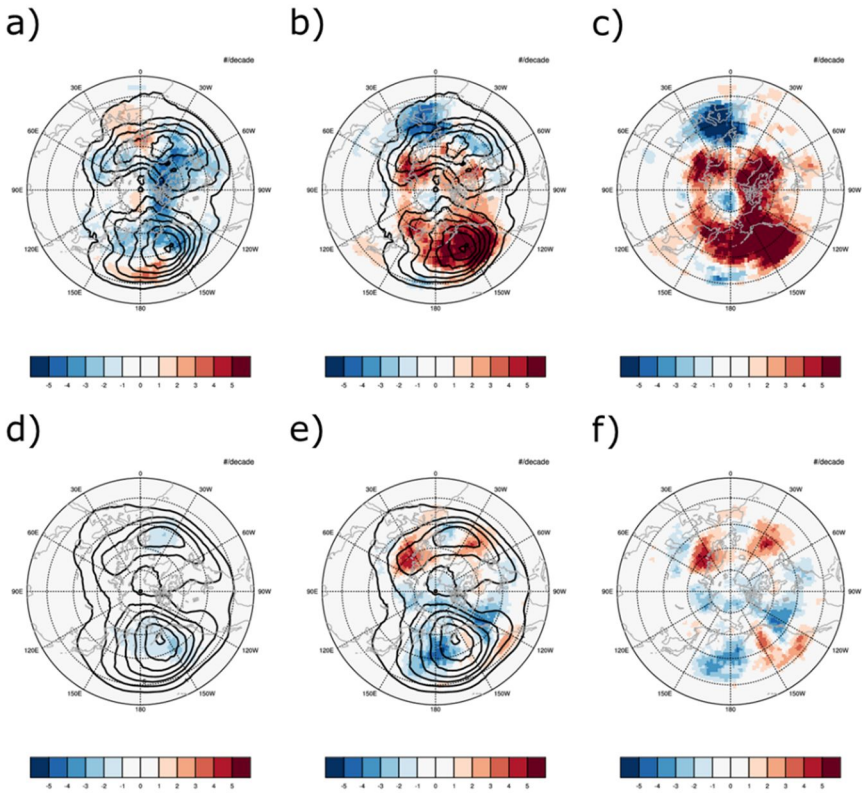


**Figure 10** Blocking frequency trend (shaded) and climatology (contour) in (a) from 1979 to 1998, (b) from 1998 to 2013, (c) difference between the two (b-a) in JRA 55 reanalysis. Blocking frequency trend (shaded) and climatology (contour) in (d) from 1979 to 1998, (e) from 1998 to 2013, (f) difference between the two (e-d) in GFDL-CM2.1 9-ensemble mean.

## 초록

# 북극 해빙의 감소가 최근 유라시아 지표 기온변화에 미치는 영향

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최근 십여 년간 북반구 중위도 대륙지역에서 겨울철 기온이 급격하게 감소하기 시작하였으며 이는 온실기체의 증가로 인한 지구온난화의 효과를 일시적으로 상쇄할 정도의 거대한 변화의 양상을 보인다. 북반구의 겨울철 기온 하강 현상의 발생 기작에 대한 연구가 활발히 진행 중인 가운데 유라시아 지역의 겨울철 기온 변화와 늦가을 북극 해빙의 감소 사이의 상관관계가 확인되었으나, 북극 해빙의 감소가 유라시아 지역의 기온변화에 어떻게 영향을 주는지에 대하여 아직 밝혀진 바가 없다. 기존 연구들에서는 다양한 기후 모형을 사용하여 북극 해빙의 감소가 유라시아 겨울철 기온 감소를 야기할 수 있다는 가능성은 제시했으나 모형적 분결과를 검증하기에는 관측 기간이 짧아 통계적인 분석이 불가능하다. 또한 일부 모형에서는 북극 해빙의 감소에 의한 영향이 확인되지 않아 오히려 자연변동성에 의한 일시적인 변화에 대한 가능성이 제기되어 학계에서 관련 주제에 대한 연구가 발빠르게 진행되고 있다.

본 연구에서는 유라시아 지역에서 겨울철 기온이 급격하게 감소하는 현상을 통계 기법을 도입하여 정량적으로 정의하고 북극 해빙의 감소와의 상관성을 분석하였다. 또한 기존 연구에서 북극 해빙의 감소를 반영하여 실험한 모형들은 해양의 피드백을 고려하지 않는 AGCM 모형이라는 점에서 착안하여 해양의 피드백을 반영하는 CGCM 모형을 적분하여 유라시아 겨울철 기온 변화를 모의하였다. 또한 발생 기작을 이해하고자 선형 역학 모형실험을 진행하였다. 최근 관측에서 평균기온 감소와 더불어 나타나는 혹한일의 증가에 대한 추가적인 이해를 위해 저지고기압의 발생 빈도와 관련한 분석을 진행하였다.

주요어: 북극 해빙, 유라시아 기온 감소, 기후 모형, 저지고기압

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