Arctic sea ice and Eurasian climate: a review

GAO Yongqi[1, 2] (郜永祺), SUN Jianqi[*, 1](孙建奇), LI Fei[1](李菲), HE Shengping[1,5](贺圣平), SANDVEN Stein[2], YAN Qing[1](燕青), ZHANG Zhongshi[1, 3] (张仲石), LOHMANN Katja[6], KEENLYSIDE Noel[4, 2], FUREVIK Tore[4], SUO Lingling[2]

1 Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

2 Nansen Environmental and Remote Sensing Center/Bjerknes Center for Climate Research, Bergen, Norway

3 Uni Research/Bjerknes Center for Climate Research, Bergen, Norway

4 Geophysical Institute, University of Bergen and Bjerknes Center for Climate Research

5 Climate Change Research Center, Chinese Academy of Sciences, Beijing, China

6 Max-Planck Institute for Meteorology, Hamburg, Germany

* Corresponding author: sunjq@mail.iap.ac.cn

Abstract

The Arctic plays a fundamental role in the climate system and has shown significant climate change in recent decades (IPCC 2013) including the Arctic warming and decline of Arctic sea-ice extent and thickness. In contrast to the Arctic warming and the reduction of Arctic sea ice, Europe, East Asia and North America have experienced anomalously cold conditions with record high snowfalls during recent years. We present a review here of the sea-ice impacts on Eurasia climate. Paleo, observational and modelling studies have indicated that Arctic sea ice has multi-decadal variability, which is likely governed by Atlantic Multi-decadal Variability (at least for Arctic sea ice in Atlantic sector); that Arctic sea ice decline during the satellite era is likely consequence of these multi-decadal variations and greenhouse gas emissions; that climate impact of Arctic sea ice changes in all season had been addressed with most of studies focused on the climate impact caused by reduced autumn and winter Arctic sea ice; that the reduction of the Arctic sea ice could cause the surface warming at mid-and-high-latitudes during paleo-climate and had potential to change the glacier-inter-glacier cycles; that there is a negative feedback between the Arctic sea ice and the Arctic Oscillation (AO)/North Atlantic Oscillation (NAO), although it is unclear whether the reduction in autumn Arctic-sea-ice-induced negative AO/NAO could persist into winter; that some studies that did not show negative AO/NAO response to the reduction in autumn Arctic sea ice; that the reduction in autumn Arctic sea ice can cause the recent Eurasian winter cooling by either the negative AO or AO-like response or the intensified Siberia High (SH); that some studies suggested that winter atmosphere circulation is more associated with change in winter Arctic sea ice; that change in spring Arctic sea ice has been linked to the summer precipitation in East Asia though different pathways have been suggested; that the reduction of autumn Arctic sea ice has also been linked to the increase in spring snowfall over Eurasia and the cooling; that the reduction of autumn Arctic sea ice might modulate the linkage between the AO and East Asia Winter Monsoon (EAWM); that linkage between Arctic warming and mid-latitude extreme weathers has been suggested through the change in the planetary waves, although the pathways have not been clearly demonstrated; that the remote climate response (e.g., atmosphere circulation, air temperature) to change in Arctic sea ice is hard to be detectable due to atmosphere internal variability. For future prospective, we recommend long-term and reliable data, coordinated multi-models experiments, model improvement, including better representation of troposphere-stratosphere interaction, along with the comparison of results from atmosphere general circulation models and coupled climate models to understand the linkage between Arctic sea ice and Eurasian climate.

1. Introduction

Global warming is enhanced at high latitudes where the Arctic surface air temperature has risen twice as large as the global average in recent decades - a feature called Arctic amplification. Although the Arctic warming implies a melting sea ice cover (e.g., Johannessen and Bjørgo, 1995; Johannessen, 2008; Johannessen et al., 2004), its dynamic–thermodynamic response is neither straightforward nor necessarily linear (Zhang et al., 2000), nor is the response of the atmosphere to sea ice reductions (Magnusdottir et al., 2004; Deser et al., 2004, 2008). Sea ice plays an important role in the climate system due to its reflection of solar radiation back to the atmosphere and its blocking of direct exchange of energy and mass between the atmosphere and the ocean. In addition, melting and formation of sea ice can influence the surface sea water density and therefore potentially change the ocean circulation.

Satellite observation (1979 to present) indicates that Arctic sea-ice cover declined over the past decades and the declining rate is getting larger (e.g., Comiso et al., 2008). Arctic sea-ice cover reached a record-low in September 2012. Analyses indicate that the recent Arctic warming signal is consistent with the reduction in sea-ice cover (Screen and Simmonds, 2010).

Reduction in Arctic sea-ice cover could have potential impact on the climate in the Northern Hemisphere (NH) (Ma et al., 2012; Zhou and Wang, 2014). Impact of Arctic sea ice on global climate has been reviewed by Budikova (2009). Linkage between Arctic sea ice, storms and NAO has been reviewed by Bader et al. (2011). Recently, Vihma (2014) reviewed the influence of Arctic sea ice reduction on climate and weather. Considering new studies on the linkage between the Arctic sea ice and the Eurasia climate in recent years, the purpose of this paper is to summarize available literatures with special focus on the impact of Arctic sea ice on the Eurasian climate and the uncertainty related to this. We also include the sea ice impact studies from paleo-climate research. The rest of the paper is organized as follows: Section 2 briefly summarizes the status of the Arctic sea ice including past, present and future. Section 3 summarizes atmospheric and oceanic forcing on the Arctic sea ice. Section 4 summarizes the impact of Arctic sea ice on the paleo-climate, present-climate and projected–climate, including both observational and modelling studies. The uncertainty is discussed in section 5 and finally followed with summary and future perspective in section 6.

2. Arctic sea-ice change: past, present and future

Paleo-proxy reconstruction suggested that winter Arctic sea ice appeared in approximately 47 Ma (million years ago) with the global cooling in the Cenozoic (~65 Ma); with year-round sea-ice cover in at least part of the Arctic beginning in 14–13 Ma; and widespread Arctic sea-ice cover being present during the last 2–3 million years. Arctic sea-ice cover showed clearly oscillations during the glacial-interglacial cycles. The last low-ice event related to orbital forcing (high insolation) was in the early Holocene (Polyak et al., 2010; Stein et al., 2012).

Historical records and high-resolution of paleo-proxy reconstructions have been used to investigate the multi-decadal variation of Arctic sea ice. For example, Miles et al. (2014) synthesized available historical records of Arctic sea-ice over the past several centuries in the Atlantic sector and found the strong co-variability between Arctic sea ice and the Atlantic Multi-decadal Oscillation (AMO), suggesting the intrinsic linkage between the AMO and Arctic sea ice. This was also suggested by early modelling studies (e.g., Jungclaus et al., 2005; Mahajan et al., 2011). Kinnard et al. (2011) also suggested that meridional ocean heat transport to the Arctic could possibly be the key driver for the multi-decadal variations in Arctic sea-ice cover.

Since October 1978, the satellite-observed Arctic sea-ice extent shows downward trends in all month with the largest downward trend appearing in September (Stroeve et al., 2012a; Cassano et al., 2013) and two record minima occurring in 2007 and 2012 (Francis 2013). For example, using mean of 1981-2010 as a base period, the declining trend in sea ice extent is -0.40×10^{6} km^{2}/per decade (or 3% per decade) in March and -0.89×10^{6} km^{2}/per decade (or 12% per decade) in September from 1979 to 2013 (Miles et al., 2014). The observed reduction in sea-ice extent has been significantly faster than simulated by most numerical models using realistic anthropogenic increases in greenhouse gases (Stroeve et al., 2012b). The projections from the IPCC AR5 models show that the summer (September) Arctic sea ice could nearly disappear (sea ice extent less than 1×10^{6} km^{2} for at least 5 consecutive years) by the mid of 21st century under a high emissions scenario (IPCC, 2013; Overland and Wang, 2013).

3. Arctic sea ice: atmospheric or oceanic forcing?

Numerous studies have investigated causes for the Arctic sea-ice variations and trends. Simmonds and Keay (2009) suggest that low Arctic sea-ice extent conditions in September provide additional energy for cyclonic systems, which could further exert greater mechanical forcing to move more sea ice into warmer waters and result, in turn, in less sea ice extent. The wintertime sea-ice cover variability shows a seesaw pattern between the Labrador Sea and the Greenland–Barents Seas (Gerdes, 2006) that is driven by the NAO through wind forcing, oceanic heat transport, and surface heat exchanges (Frankignoul et al., 2014). Koenigk et al.

(2009) suggest that negative phase of NAO leads to anomalous high pressure over Novaya Zemlya and anomalous low pressure over Svalbard strengthening the winds across the northern border of the Barents Sea and thus the sea ice transport into the Barents Sea increases. Ding et al. (2014) found that the annual mean tropical sea surface temperatures during 1979-2012 could stimulate an anomalous Rossby wave-train activity which extended from the central tropical Pacific towards the Arctic region, leading to a negative trend in the NAO. The negative trend of NAO was strongly associated with the surface and tropospheric warming in northeastern Canada and Greenland since 1979, which could potential impact the variation of the Arctic sea ice. Matsumura et al. (2014) revealed that earlier spring snowmelt over Eurasia caused a warmer land surface and therefore amplified stationary Rossby waves, leading to a deceleration of the subpolar jet. As a result, an anomalous anticyclone emerged over the Arctic Ocean. The intensified surface anticyclonic circulation played a contributing role in accelerating the sea ice decline during 1988-2011, via transpolar drift and export out of the Arctic Ocean through Fram Strait.

In particular, numerous studies have investigated the causes of the remarkable low Arctic sea-ice extent in 2007. It is agreed that a primary driver for the rapid sea-ice cover decrease in 2007 is the summer Arctic Dipole (anomalous high sea-level pressure over the Beaufort Sea and anomalous low pressure over the Siberian Arctic), which has persisted through June of 2012 and therefore creating an intensified meridional flow across the Arctic (Overland et al., 2012). Such a mechanism has been revealed by Stroeve et al. (2008), who suggested that this promoted persistent southerly winds anomaly in the Laptev and East Siberian Seas favors strong melt and ice transport away from the coast. L'Heureux et al. (2008) suggest that the anomalous anticyclone associated with anomalous strongly positive phase of the Pacific-North American pattern contributed to a precipitous decrease in Arctic sea ice through increasing solar radiation, enhancing poleward transport of warm air, and increasing sea ice drift away from the western Arctic.

However, the atmospheric forcing seems to become less effective to recover Arctic sea ice. For example, the extreme negative phase of the Arctic Oscillation (AO) in 2009/2010 winter should have favored retention of Arctic sea ice through the 2010 summer melt season. Nevertheless, it ended up as the third lowest in the satellite record (Stroeve et al., 2011b). Consequently, the potential impact of ocean forcing needs to be fully understood. Jackson et al. (2010) indicated that the stronger near surface stratification from increasing ice melt stores the heat in the near surface (20–25 m depth) which can then be used to melt ice and reduce ice thickness. Comiso et al. (2008) revealed that the increased absorption of solar radiation induced by the increasing open water area in the Arctic basin is likely the primary cause for recent Arctic sea ice reduction. Besides, the extensive open water in recent Septembers leads to an increasing thin, first-year ice in the following spring that is vulnerable to melting out in summer (Stroeve et al., 2012a). Additionally, the Arctic winter sea ice retreat has been related to the warmer Pacific waters inflow to the Arctic through the Bering Strait that may act as a trigger for the onset of solar-driven melt (Woodgate et al., 2010). The increase of the Atlantic inflow to the western Barents Sea and the increased delivery of oceanic heat to the ice sheet margin also contribute to the Arctic winter sea ice reduction (Stroeve et al., 2012a). The decreasing of summer snowfall over the Arctic Ocean and Canadian Archipelago results in loss of snow-on-ice, leading to a substantial decrease in the surface albedo over the Arctic Ocean. Accordingly, the solar input to the Arctic Ocean is increased, causing additional surface ice melt (Screen and Simmonds, 2012). Langehaug et al. (2013) investigated the Fram Strait sea-ice area export in the CMIP5 models, and found that the simulated southward export of sea-ice in the Fram Strait constitutes a major fraction of Arctic sea-ice reduction in five models (sea-ice area export in Fram Strait can be diagnosed in six of CMIP5 models) over 1957 to 2005. They have found low but significant correlations on inter-annual timescales between the Fram Strait sea-ice export, both in terms of area and volume, and the Arctic Basin sea-ice thickness. All six models (NorESM1-M; CNRM-CM5; MPI-ESM-LR; MRI-CGCM3; ACCESS1-3; MPI-ESM-P) show that an increase in ice area export leads a decrease in the sea-ice thickness. Sandø et al. (2014) diagnosed the historical simulation (1850 to 2005) performed by the Norwegian Earth System Model (NorESM) and they found that the ocean has stronger direct impact on changes in sea-ice mass in terms of freezing and melting than the atmosphere, both in the mean and with respect to variability over 1950 to 2005. Day et al., (2012) used model and satellite data to suggest that the AMO warming phase could explain 5–30% of the satellite era (1979–2010) summer sea-ice reduction and an even higher proportion for the winter sea ice. Recently, Wyatt and Curry (2014) suggest that the North Atlantic Ocean halocline, which is generated because the sea ice in the Eurasian Arctic is exposed to the open ocean, is mostly responsible for wintertime sea ice cover. This is because the halocline could result in vertical density structure and prevent ocean heat at depth from reaching the surface. So, where a strong halocline exists, sea ice growth is promoted.

4. Arctic sea ice and Eurasian climate

4.1 Paleo Studies

Due to the uncertainties in sea-ice reconstruction in the past climate, it remains difficult to investigate impact of sea ice on the paleo-climate. A few modeling studies show that sea-ice cover likely played an important role in the paleo-climate.

The mid-Pliocene (~3 Ma) is thought to be an analogy of future climate owing to the high CO_2 concentration (~405 ppmv) with reduced ice sheets and northward expansion of boreal forest (e.g., Dowsett et al., 2010; Yan et al., 2014). Multi-proxies show that the mid-Pliocene Arctic was likely warmer than today (Salzmann et al., 2013). During the mid-Pliocene period, the reduced sea-ice cover contributed significantly to the surface warming at mid-high latitudes in the NH. For example, based on energy balance calculations from eight mid-Pliocene coupled-model-simulations, Hill et al. (2014) point out that the albedo feedbacks, particularly those of sea ice and ice sheets, could provide the most significant enhancements to high-latitude warming during the mid-Pliocene. Using the Atmospheric General Circulation Model (AGCM) CAM3, Ballantyne et al. (2013) show that with perennially ice-free conditions across the Arctic, the simulated annual mean surface temperatures over the NH agreed better with terrestrial reconstructions during the mid-Pliocene. They further attribute this to the removal of Arctic sea ice that led to loss of latent heat from the ocean to the atmosphere and contributed to the warming of continental interiors including the Eurasian continent.

During the Quaternary (about 2.6 Ma),~ sea ice feedbacks likely played an important role in the glacial-interglacial cycles. Although it is often believed that shifts of the glacial-interglacial cycles were controlled by Earth orbital changes, Gildor and Tziporman (2000) suggested that the sea ice, via its albedo and insulating effects, could rapidly switch the climate system from a growing ice-sheet phase to a retreating ice-sheet phase and hence regulate global climate. Using a coupled atmosphere–slab ocean model forced by different orbital parameters, Vavrus (1999) found that the atmosphere over central Arctic (80°–90°N) was warmed (cooled) up by 0.7 (2.0) °C in the experiment with sea-ice dynamics compared to the experiment without sea-ice dynamics, indicating the important role of sea-ice motion to regional temperature changes. By conducting a set of sensitivity experiments with varied albedo and thickness of sea ice, Gildor et al. (2013) investigate the albedo and insulating effects of sea ice in the hydrological cycle focusing on rain- and snow-fall over the major ice sheets during Last Glacial Maximum. They find a warmer climate and an increase in snow-fall over the ice sheets as a result of reduced sea-ice cover. The insulating effect of the sea ice on the hydrological cycle was found to be larger than the albedo effect.

During the past 2000 years, the expanded Arctic sea ice may be crucial to sustain the cold climate during the Little Ice Age (LIA; ca. 1400~1700 AD). Miller et al. (2012) suggest that strong volcanic eruptions produced abrupt summer cooling at these times allowing Arctic sea ice to expand. The increased sea-ice export may then have engaged a self-sustaining sea-ice/ocean feedback in the northern North Atlantic that maintained suppressed summer air temperatures over North Atlantic-Arctic land (>60°N and 90°W to 30°E) for centuries after volcanic aerosols were removed from the atmosphere. Lehner et al. (2013) also indicated that an increase in the Nordic Sea sea-ice extent on decadal timescales during the LIA as a consequence of major volcanic eruptions led to a spin-up of the subpolar gyre and a weakened Atlantic meridional overturning circulation, eventually causing a persistent, basin-wide cooling.

To summarize, paleo-climate studies suggest that the Arctic sea ice was a key player for the surface warming in mid-and high-latitudes in the NH during different paleo periods and that the Arctic sea ice has the potential to shift glacier-inter-glacier cycles.

4.2 Observation Studies

Observational-based studies suggested that the change in Arctic sea ice was linked to the change in Eurasian climate. Most of the studies focused on the impact of reduced autumn and winter Arctic sea ice on the Eurasian climate in winter.

Observational-based studies in early 20th century, as briefly summarized by Herman and Johnson (1978), suggest: a potential linkage between the winter conditions in Europe and the ice conditions in East Greenland during the previous summer (Hildebrandsson, 1914); a correlation between the Arctic sea ice margin and air temperatures and pressures over Europe (Schell, 1956, 1970). In addition, Tao (1959) summarized the weather forecast in China from 1949 to 1958 and noticed that almost all extreme cold spells (air temperature drops more than 10^{o}C within 24 hours) in East Asia were originated from the Barents Sea or the Kara Sea with different pathways. They also noticed there was an adjustment in the planetary waves over the Eurasian continent when the extreme cold spells took place in China. More recent studies (Liu et al., 2007; Li and Wang, 2013b), using the Arctic sea-ice concentrations retrieved from the Scanning Multichannel Microwave Radiometer on the Nimbus 7 satellite and the Special Sensor Microwave/Imager on several defence meteorological satellites and NCEP–NCAR reanalysis datasets, demonstrated a close relationship between the variability of the North Pacific sea ice and East Asian winter climate. Their analysis indicated that associated with negative sea ice anomalies in the Sea of Okhotsk and positive ones in the Bering Sea, the East

Asian jet stream and East Asian trough were weaker than normal, leading to warm and wet conditions in northeast China and central Siberia. When the winter sea ice displays uniform negative anomalies throughout the North Pacific, the East Asian winter monsoon was stronger which led to cold and dry conditions in the east coast of Asia (Wang and He, 2012, 2013; He, 2013; He and Wang, 2013a; He et al., 2013; Wang et al., 2013). Based on the sea-ice concentration data derived from Met Office Hadley Centre's sea ice and sea surface temperature (SST) data set version 1 and NCEP–NCAR reanalysis datasets, Honda et al. (2009) find that the reduction of sea-ice cover over the Barents-Kara Seas in late autumn could stimulate a stationary Rossby wave in early winter. This tends to induce an amplification of the Siberia High (SH) and results in significant cold anomalies over the Far East in early winter and zonally elongated cold anomalies from Europe to Far East in late winter. On the basis of the sea ice concentration obtained from the British Atmospheric Data Centre, NCEP–NCAR reanalysis and Japanese reanalysis data, Wu et al. (2011) showed that low autumn sea-ice concentration in the Eastern Arctic and Eurasian marginal seas and thus higher sea surface temperature led to higher surface air temperatures confined to the Barents-Kara Seas. Involving a negative feedback loop this caused positive sea level pressure anomalies over northern Eurasia, thereby strengthened the SH. Wu et al. (2013a) used NCEP–NCAR reanalysis and Japanese 25-yr Reanalysis (JRA-25) winter daily (1 December–28 February) data for the period 1979-2012 to reveal that the negative phase of the tripole wind pattern corresponded to an anomalous anticyclone over northern Eurasia during winter, as well as two anomalous cyclones occurring over southern Europe and northeastern Asia. These anomalous cyclones in turn led to enhanced winter precipitation in these two regions, as well as negative surface temperature anomalies over northern Asia. The intensity of the tripole wind pattern and the frequency of its extreme negative phase were significantly correlated with autumn Arctic sea-ice anomalies. Using the Arctic sea ice obtained from the National Snow and Ice Data Center, snow cover obtained from the Rutgers University Global Snow Lab and NCEP-NCAR reanalysis II data, Liu et al. (2012) indicated that the increase in snowfall over the United States and Eurasia in recent winters could be attributed to an increase in the frequency of blocking events caused by the recent Arctic autumn sea-ice loss. During light ice winters in the Barents Sea, Inoue et al. (2012) showed that, the lower baroclinicity over the Barents Sea prevents winter cyclones over the Nordic Seas traveling eastward, and anomalous warm/cold advection prevailed over the Barents Sea/eastern Siberia due to an anticyclonic anomaly over the Siberian coast of the Barents Sea. Composite analysis of Japanese 25-yr Reanalysis (JRA-25) atmospheric reanalysis, based on years with the five lowest (2002, 2005, 2006, 2007, 2008) and five highest (1980, 1983, 1986, 1992, 1996) September Arctic sea-ice extents, showed that more open water associated with less sea ice during autumn in Arctic Ocean reduced the atmospheric stability and led to more frequent and more intense autumn cyclone in the Atlantic sector of the Arctic (Stroeve et al. 2011a). Tang et al. (2103a) analyzed the reanalysis data from European Centre for Medium-Range Weather Forecasts and Arctic sea-ice extent derived from passive microwave satellite data. They suggested that a winter high-pressure anomaly prevailed over the sub-arctic associated with winter sea-ice reduction and this favoured the occurrence of cold winter extremes at mid-latitudes of the north continents. Furthermore, these winter atmospheric circulation anomalies were more strongly associated with the simultaneous sea-ice reduction instead of summer or autumn sea-ice changes. However, recent studies pointed out the influence of Arctic sea ice on the Eurasian climate might be unstable. Based on the NCEP–NCAR reanalysis and Hadley Centre sea ice and SST dataset, Li and Wang (2012) revealed that the relationship between the variation of autumn sea-ice cover over the Kara–Laptev and winter AO has been strengthened since the early 1980s and suggested the impact of Kara–Laptev autumn sea-ice cover on the northern Eurasian winter precipitation is intensified. Using the NCEP–NCAR reanalysis and Hadley Centre sea ice and SST dataset, Li and Wang (2014) found that the co-variability between the autumn sea-ice cover in the region of (65°N–82°N, 105°E–135°W) and East Asian winter monsoon (EAWM) became stronger since the early 1990s. In addition, analysis using the NCEP–NCAR reanalysis and Hadley Centre sea ice and SST dataset, showed that the recent reduction of autumn Arctic sea-ice cover in the domain of (67°–85°N, 30°–135°E) caused the East Asian jet stream to extend westward toward East Asia after the 1980s. This led to the strengthening and southward shift of Rossby wave over East Asia and therefore resulted in a strengthening of the AO-EAWM relationship (Li et al., 2014).

Li and Wang (2013a), using the NCEP–NCAR reanalysis and Hadley Centre sea ice and SST dataset version 1, found that the rapid decline of autumn Arctic sea-ice cover could enhance moisture transport to Siberia and consequently contributed to the increased snow cover there during the following spring. This favoured the southward invasion of cold air via strong radiative cooling and large-scale descending motion and further contributed to spring surface cooling trend along the coast of East Asian after the late 1990s.

Change in Arctic sea ice has also been linked to the summer precipitation in Eurasia. As already summarized by Vihma (2014), early studies suggested that the extent of spring Arctic sea-ice cover had close connections with summer precipitation in East Asia (Zhao et al, 2004;

Wu et al., 2009; Guo et al; 2013) though the pathways or mechanisms were different among the different studies.

Summarized also by Vihma (2014), Francis and Vavrus (2012), using the NCEP–NCAR reanalysis, identified that the sea-ice loss related Arctic warming, by reducing meridional temperature gradient and favouring a weakened poleward gradient in 1000-500 hPa air thicknesses, could slow down eastward progression of Rossby waves in upper troposphere. They suggested that slower movement of waves would cause associated weather patterns in mid-latitudes, such as drought, flooding, cold spells and heat waves, to be more persistent. By combining satellite observations of early summer snow cover and summer sea-ice extent with atmospheric reanalysis data, Tang et al. (2013b) suggested the summer extreme weather events in mid-latitudes were more frequent associated with summer sea-ice extent reduction, which could increases upper-level height, weakens upper-level zonal winds at high latitudes, and lead to a general northward shift in the jet stream. The contribution of Arctic sea-ice decline to the change in 1000–500 hPa air thickness was revealed by Overland and Wang (2010). By analyzing the NCEP–NCAR reanalysis, they suggested that reduction of summer Arctic sea-ice extent led to more open water in late summer, the additional heat was therefore stored in the Arctic Ocean and then released to the atmosphere during the following autumn. As a result, the surface air temperature during late autumn was higher than normal, contributing to an increase in the 1000–500 hPa air thickness in October-December of 2002 to 2008. They concluded that reduction in Arctic sea ice had a direct connection to increased thickness fields in every year, but not necessarily to the sea level pressure fields. However, the mechanism suggested by Francis and Vavrus (2012) is still under-debate. Based on three reanalyses [ERA-interim, NCEP1, NASA’s Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis], Barnes (2013) investigated trends in the meridional extent of atmospheric waves over North America and the North Atlantic and suggested that previously reported positive trends in Rossby waves were likely an artifact of the methodology. There was no significant and robust decrease in planetary-scale wave phase speeds and no significant increase in the frequency of blocking occurrence in any season in any of the three reanalyses over the reanalysis period (1980-2011). A recent study by Screen and Simmonds (2013) using ERA-Interim reanalysis also provided evidence that the trends in planetary waves suggested by Francis and Vavrus (2012) may be an artifact of the methodology. They demonstrated that, an alternative metric that was insensitive to a shift of Z500, did not yield significant positive trends in wave amplitude, which suggested that the wave elongation reported by Francis and Vavrus (2012) was at least partially an artifact of the poleward shift of the isopleths with polar warming.

To summarize, statistical analysis on the observation data and the reanalysis data showed that the reduction/change of autumn and/or winter sea ice in the Arctic marginal seas (the Barents/Kara Seas in the Atlantic sector; the Bering Sea and the Sea of Okhotsk in the Pacific sector) were linked to the winter and spring climate change (atmosphere circulation, air temperature and snowfall) in Eurasia. Change in the spring Arctic sea ice has been linked to the East Asia summer rainfall. Recent studies also suggested that the linkage between the autumn Arctic sea ice and EAWM is unstable. More observation data is needed to test the linkage between the Arctic warming and the extreme weather in mid-latitudes via a slowdown of Rossby waves.

The connection between the NAO and the Arctic sea ice has drawn much more attention. The NAO presents one of the most prominent anomaly modes of inter-monthly to inter-decadal variability in the NH (Sun et al., 2009; Sun and Wang, 2012; Zhou et al., 2013) and is characterized by a large-scale alternation of atmospheric mass with centers of action near the Icelandic low and the Azorian high (e.g., Hurrell 1995). There are indications that atmosphere drivers ocean on seasonal to inter-annual timescales whereas ocean may force atmosphere on multi-decadal timescale (e.g., Gulev et al., 2013). Early studies also suggested that there is a negative feedback between the Arctic sea ice and the NAO.

As reviewed by Bader et al. (2011), there were observational-based studies addressing the sea ice impact on NAO (Yamamoto et al., 2006; Hondal et al., 2009; Francis et al., 2009; Wu and Zhang, 2010). Based on the sea-ice concentration data measured by passive microwave sensors, the Scanning Multichannel Microwave Radiometer on board the Nimbus–7 satellite and the Special Senser Microwave Imager on board the Defense Meteorological Satellite Program satellite and NCEP–NCAR reanalysis, Yamamoto et al. (2006) suggested that the dominant inter-annual mode of mid-winter NH sea ice variability, a seesaw pattern in both Atlantic and Pacific sectors, tended to affect the NAO in late winter via Rossby wave trains triggered by the Pacific sea ice anomalies. Using NCEP-NCAR reanalysis and the satellite-observed SIC, it was found that the negative NAO-resembling pattern in autumn/winter was likely a response to the reduction in summer/autumn sea ice (Francis et al., 2009; Wu and Zhang, 2010). Using Granger causality and time series of the weekly SIC seesaw and the NAO, which were calculated from the National Snow and Ice Data Center sea ice concentrations and NCEP–NCAR reanalysis, Strong et al. (2009) showed that the positive phase NAO caused a seesaw during winter to early spring (Dec.-Apr.) with positive SIC anomalies in the Labrador Sea and negative ones in the Barents Sea; the seesaw, in turn, drive a NAO with the opposite phase. It means a negative feedback: the sea ice patterns associated with the positive polarity of the NAO tends to generate negative NAO-like atmospheric response patterns. As reviewed by Bader et al. (2011), a negative phase of the NAO during winter could also be associated with positive sea-ice concentrations in the Sea of Okhotsk (Mesquita et al., 2011). In addition, on the basis of the ECMWF ERA-Interim data and monthly SIC data from the Met Office Hadley Centre, Jaiser et al. (2012) indicated that the reduced SIC in August/September and associated Arctic warming exerted a remote impact on the large-scale atmospheric circulation during winter. The amplified warming in autumn reduced the atmospheric stability and led to an enhanced baroclinicity in autumn, which could further impact the structure of large-scale planetary waves in the following winter. This provides a possible pathway for how the autumn sea ice anomalies impact the atmospheric flow patterns (i.e., NAO, AO). Jaiser et al. (2013) discussed the stratospheric response to Arctic sea ice retreat by analyzing the ECMWF ERA-Interim data and monthly SIC from the Met Office Hadley Centre. It was revealed that August/September Arctic SIC had a significant impact on tropospheric and stratospheric geopotential heights in the following winter. During August/September low ice conditions, the upward EP fluxes due to planetary waves were enhanced, leading to additional tropospheric wave energy into the stratosphere which favored warmer stratospheric temperatures and therefore weakened the tropospheric polar vortex. Consequently, a negative tropospheric AO/NAO pattern was found. However, considering the major conclusions of above studies were usually drawn from a very limited number of years (generally since 1979), Hopsch et al. (2012) suggested that the reported results had often not been conclusive or robust enough for further statistical analysis. Hopsch et al. (2012) revisited the issue by comparing results for two different time periods: satellite-era period (1979-2010) and a longer time series that also included the pre-satellite period (1950-2010) and confirmed the emergence of an NAO-like pattern in mid-troposphere geopotential height in the winter months following September sea ice concentrations decline, however, the pathway suggested by previous studies were not robust enough from a statistical significance perspective. They suggested that longer and reliable datasets are needed before the conclusions of impacts and feedbacks between autumn Arctic sea ice and following winter NAO. The interaction between the NAO and a sea-ice concentration seesaw between the Labrador Sea and the Greenland–Barents Sea had also been revealed by Frankignoul et al. (2014) by using the sea ice concentration from the National Snow and Ice Data Center and sea level pressure anomalies obtained from the NCEP Climate Forecast System Reanalysis. The

NAO drives the seesaw and in return the seesaw precedes a midwinter/spring NAO-like signal of the opposite polarity but with a strengthened northern lobe, thus acting as a negative feedback, with maximum squared covariance at a lag of 6 weeks. Changes in the November sea-ice cover in the Barents Sea could lead to an additional heat source and intensified cyclones in downstream Arctic regions in the following months. This effect seemed to exhibit a character similar to NAO/AO without extending into the stratosphere, but it generated cold anomalies over the northern continents, potentially adding to anomalies directly induced by a negative AO (Petoukhov and Semenov, 2010; Inoue et al., 2012).

To summary, using statistical analysis on different reanalysis products and sea ice data, a negative feedback between the AO/NAO and the sea ice is suggested though the pathway is not robust yet. Changes in summer/autumn/winter Arctic sea ice can likely affect autumn/winter AO/NAO.

4.3 Modeling Studies

Because changes in sea ice are also forced by changes in atmosphere and ocean, it has been difficult to demonstrate clearly whether an atmospheric anomaly correlated with a sea-ice anomaly is the cause instead of an effect of the anomaly. Climate models are ideal tools to explore and isolate the impact of sea ice on atmosphere. Both of the atmosphere general circulation models (AGCMs) and the coupled climate models (CCMs) including the regional climate models have been used to isolate/investigate the impact of sea ice on the climate. With regard to the sea ice perturbation experiments, the performed numerical simulations generally include two-type simulations. One is forced by the observed sea ice anomalies (Tab.1) and the other by the projected anomalies (Tab.2).

4.3.1 Response to observed/realistic sea ice

4.3.1.1 Winter sea ice impact

Sea-ice impact with numerical simulations started with the winter sea-ice anomalies since air-sea temperature gradient in winter is strongest and therefore a large impact of sea-ice is expected.

Herman and Johnson (1978) are among the first to investigate impact of the observed winter (January-February) sea-ice anomalies in the Arctic marginal seas on the atmosphere using AGCM developed at Goddard Laboratory for Atmospheric Sciences. The sea-ice anomalies were based on the observed sea ice during 1961-1977 in the Atlantic sector and during 1973-1977 in the Pacific sector. The simulated winter climate response showed the zonal mean air temperature below 800 hPa was 2 ^{o}C lower between 50-70^{o}N with sea-ice expansion in marginal seas. Particularly, they found cooling signal at 700 hPa over the northwest Russia. Yang et al. (1994) is among the first to explore Arctic sea ice impact on the East Asian summer monsoon (EASM) using the AGCM developed at Australian Numerical Meteorology Research Centre (ANMRC). They found that the EASM was strengthened in response to more sea-ice cover in the Greenland Sea and the Barents Sea. Honda et al. (1996) used AGCM (developed at Meteorological Research Institute) with horizontal resolution of 5.6×5.6 degree and investigated the impact of observed winter heavy/light sea-ice cover in the Sea of Okhotsk. They found that the response between the heavy and light ice cases showed significant difference not only around the Sea of Okhotsk but also downstream in the troposphere, which was a stationary Rossby wave response to an anomalous surface hear flux in the Sea of Okhotsk. Wu et al. (1999), using the AGCM developed at the Institute of Atmospheric Physics, suggested that winter heavy sea-ice condition in the Barents-Kara Seas was associated with weakened EAWM and inactive cold air activity in China by exciting the Eurasian teleconnection. Magnusdottir et al. (2004) and Deser et al. (2004), forcing the AGCM Community Climate Model (CCM3, the National Center for Atmospheric Research) with realistic spatial pattern of sea-ice cover following the observed trend during 1958-1997, found that reduction in the wintertime (Dec.-Mar.) sea-ice extent in the North Atlantic and Arctic Ocean could result in more zonally-oriented storm track, corresponding to the negative phase of NAO response. They also suggested that, in a sense, the extent of sea-ice and its concentration might play a different but important role in determining the atmospheric response. Deser et al. (2007), using CCM3 and the identical sea-ice (a positive NAO-driven sea-ice anomaly pattern) and SST forcing to those in Magnusdottir et al. (2004) and Deser et al. (2004), diagnosed the transient response of wintertime atmosphere circulation to wintertime sea ice anomalies in the North Atlantic sector, and found that the surface heat flux anomalies induced by the prescribed sea-ice anomalies were the driving force to the initial atmospheric response and that the response became gradually more barotropic and increased in both spatial extent and magnitude. In particular, the initial adjustment of the atmospheric circulation began with a localized baroclinic response which was characterized by an out-of-phase relationship between geopotential height anomalies in the lower and upper troposphere and reached maximum amplitude in 5–10 days and persists for 2–3 weeks. As the ice forcing continued, the response became progressively more barotropic. In 2–2.5 months, the atmosphere reached equilibrium stage which was characterized by an equivalent barotropic structure that resembled the negative polarity of the NAO, and this pattern was maintained primarily by nonlinear transient eddy fluxes of vorticity related in part to changes in tropospheric Rossby wave breaking.

Alexander et al. (2004), forcing the AGCM CCM3 with most and least wintertime (Nov.-Mar.) Arctic sea-ice cover (1982/83, 1995/96 for most and least Arctic sea-ice cover respectively), investigated the influence of Arctic sea-ice anomalies during winter on the atmospheric circulation. The Arctic sea-ice anomalies gave rise to surface heat flux anomalies in relative small spatial extents but with very large amplitude. Furthermore, they also found that the interactions between ice and atmosphere in the North Atlantic (North Pacific) sector damped (enhanced) the original atmospheric circulation, showing a negative (positive) feedback on the atmosphere of the wintertime sea ice in the North Atlantic (North Pacific). However, the large-scale response was distinctly different in the Pacific, where ice extent anomalies in the Sea of Okhotsk generated a wave train that extended downstream over North America but the wave train response was greatly diminished when the model was driven by ice concentration rather than ice extent anomalies. Singarayer et al. (2006) forced the Hadley Centre Atmospheric Model (HadAM3) with climatological SSTs and observed SIC from 1980 to 2000, with the aim to investigate the direct climate impacts of decreasing Arctic sea ice. The simulated surface air temperature (SAT) response to ice forcing most closely matched the observed SAT variability over the 1993–1996 period which saw the largest inter-annual variation in ice area, indicating sea ice forcing being an important factor (note that their simulation used climatological SSTs) in shaping the SAT anomalies. Model studies (Magnusdottir et al., 2004; Alexander et al., 2004; Gerdes, 2006) have suggested that North Atlantic sea-ice anomalies influence the NAO/AO which had great impact on the East Asian January temperature (He and Wang, 2013b), while North Pacific sea ice primarily influences the atmospheric circulation through the generation of stationary Rossby wave trains (Honda et al., 1999). By implying an improved and more realistic sea-ice and snow albedo feedbacks in CCM ECHO-G, Dethloff et al. (2006) investigated the feedbacks between regional Arctic climate processes and the global climate system. They found that disturbances in the wintertime Arctic sea-ice and snow cover exerted a strong influence on the mid- and high-latitude climate by modulating the strength of the sub-polar westerlies and storm tracks. Besides, changes in parameterization of Arctic sea-ice with annual cycle and snow albedo could trigger changes in the AO/NAO. By prescribing different values (50% and 20%) of SIC in Nov.-Apr. on the Barents–Kara Seas in the AGCM CAM3 and using the simulated results to force the RegCM4 (Regional Climate Model), Grassi et al. (2013) investigated the potential impact of Arctic sea-ice reduction during winter period (Jan-Mar) on the extreme climate events over the Mediterranean region. Simulations indicated that the large-scale atmospheric circulation response to sea-ice reduction in the Barents-Kara Seas resembled the negative phase of the AO and characterized by a wave activity flux from the North Atlantic toward the Mediterranean Basin during winter months. It was suggested that, associated with sea ice reduction in the Barents-Kara Seas, the extreme cold events over continental Europe and extreme precipitation events over the entire Mediterranean Basin became more frequent and more intensified.

Petoukhov and Semenov (2010) used the AGCM ECHAM5 to investigate the relationship between cold Eurasian winters and reduction in wintertime SIC in the Barents-Kara Seas. Forced by decreasing SIC in the Barents-Kara Seas, model simulations indicated that lower-tropospheric heating over the Barents-Kara Seas caused by sea-ice reduction could induce strong anticyclonic anomaly over the Polar Ocean and lead to anomalous cold easterly advection over northern Eurasia. By imposing SIC and SST variations in the region of 35^o-90^oN, 90^oW-110^oE during 1968–1976/1998–2006 on the AGCM ECHAM5 model, Semenov et al. (2012) suggested that the SIC decrease and a strong warming over the Barents Sea in the winter period could lead to a cooling over vast regions of the northern part of Eurasia and increases the probability of anomalously cold January months by two times or more (for regions in Western Siberia) by inducing positive pressure anomaly with a centre over the southern boundary of the Barents Sea and an anomalous advection of cold air masses from the northeast.

4.3.1.2 Summer and autumn sea-ice impact

Bhatt et al. (2008) forced the AGCM CCM3 with reduced realistic summer sea ice in the Arctic in the summer of 1995 (which had the lowest June–September ice extent in the satellite record before 2007) and investigated the atmospheric response including larger surface fluxes and higher surface air temperatures in the area of the open water as compared with climatological sea ice. They found that the strongest response was taking place during the month of August where the Arctic displayed a weak local thermal response with warmer surface air temperatures and lower sea level pressure. The large scale circulation response to reduced sea ice in the western Arctic was higher sea level pressure over the North Pacific, which was part of a northward expansion of the summertime subtropical high. By imposing heavy/light (90%/10%) SIC in the model from September to December, Honda et al. (2009) ran an AGCM AFES (atmospheric component of Earth Simulator) to investigate the influences of the Arctic sea-ice anomalies (Sep.-Dec.) on the winter atmospheric circulation.

They suggested that reduction of sea-ice over the Barents-Kara Seas in the autumn (September) resulted in anomalous open water in this region. Anomalous turbulent heat fluxes from the additional open water generated thermally a stationary Rossby wave, which tended to induce an amplification of the Siberian High causing significant cold anomalies over the Far East in the early winter (December) and zonally elongated cold anomalies from Europe to Far East in the late winter (February). Liu et al. (2012) forced the NCAR CAM3.1 with the autumn (Sep-Nov) SIC anomalies in the Arctic regions which was significantly related to the winter Eurasia climate in the reanalysis. They suggested that the diminishing autumn Arctic sea-ice did induce positive sea level pressure (SLP) anomalies over high latitudes and negative SLP anomalies over mid-latitudes in winter, which was accompanied by a significant surface warming in the Arctic Ocean and Greenland and cooling over northern North America, Europe, Siberia, and East Asia. Besides, increase of specific humidity was found in Europe and North America, which might be responsible for the increased snowfall over Eurasian continents and North America in recent years. They proposed a mechanism that the response of winter atmospheric circulation to reduced autumn Arctic sea-ice cover had some resemblance to the negative phase of AO but with broader meridional meanders in mid-latitudes, which would lead to increased cold surges over large parts of northern continents.

4.3.1.3 Sea-ice change in all seasons

Kumar et al. (2010) explore the contribution of sea-ice loss to the Arctic Amplification using three AGCMs (NCAR CCM3; Geophysical Fluid Dynamics Laboratory Atmospheric Model Version 2.1: GFDL AM2.1; NCEP Global Forecast System: GFS) forced by monthly observed SST and SIC in 2007 and by monthly observed SST in 2007 and the monthly climatology SIC of 1971-2000. Their results indicated that the sea-ice loss did not contribute much of the observed 2007 land surface warming equatorward of 60^{o}N although it could essentially explain all of the estimated surface warming over the Arctic Ocean. Blüthgen et al. (2012) used observed 2007 sea-ice conditions to force AGCM ECHAM5 and found that the surface air temperature over northern Siberia and the Eastern Arctic increased by about 3 K and the oceanic heat uptake increased by about 40 W m^{-2} in summer and oceanic heat loss increased by 60 W m^{-2} in fall. In addition, they found a pronounced negative sea level pressure anomaly over the Eastern Arctic in late summer (Jul.-Sep.).

Wu et al. (2013b) used the AGCM ECHAM5 forced by the observed NH monthly SIC from 1978 to 2007 to explore Arctic sea ice impact and their numerical experiments demonstrated that the simulated winter atmospheric response to Arctic sea-ice decrease was dynamically consistent with the observed trend in the tripole wind pattern for 1979-2012 winters, which was one of the causes of the observed lower winter surface air temperature trend over Central and East Asia. The results of this study also implied that East Asia might experience more frequent and/or intense winter extreme weather events in association with the loss of Arctic sea ice. Screen et al. (2014) prescribed the observed variations of monthly (1979-2009) Arctic SIC in experiments performed with two different AGCMs. A slight negative NAO-like response was found in early winter (Nov-Dec), however, the NAO-type response was quite weak and was often masked by intrinsic (unforced) atmospheric variability. They suggested that the potential remote responses to Arctic sea ice change were hard to confirm and remained uncertain. By prescribing different sea ice conditions (using 1979 as high ice run and 2009 as low ice run) with annually repeating monthly cycles but holding other forcing constant in the AGCM UM (UK Met Office Unified Model version 7.3), Screen (2013) suggested that Arctic sea-ice loss induced a southward shift of the summer (Jun.-Aug.) jet stream over Europe and increased northern European summer precipitation. Peings and Magnusdottir (2014) used NCAR CAM5 with observed mean SICs of 1979-2000 and 2007-2012 respectively and suggested that the change in sea ice could cause the mid-latitudes cooling in recent winters. The anomalous Rossby waves trigged by the sea-ice change could penetrate into stratosphere in late winter (February) and weaken the stratospheric polar vortex and generate negative NAO anomalies which propagated downward after several weeks.

4.3.1.4 Regional model simulation

Regional climate models have also been used to examine the atmospheric response to altered sea-ice conditions. Most of studies focused on the local atmospheric response to the reduced Arctic sea ice. The local impact include heated, moistened atmosphere and increased cloud cover.

Rinke et al. (2006) forced the atmospheric regional climate model HIRHAM over an Arctic domain with two different winter (DJF) sea ice and SST boundary conditions but exactly the same lateral boundary conditions. Areas of higher SSTs and reduced sea-ice thickness and concentration were associated with stronger upward heat fluxes and higher 2m air temperatures. They did not find a simple relationship between anomalies in SST, sea ice, and change in storm tracks which they argue may result from a dominance of the lateral boundary forcing. Semmler et al. (2004) studied atmospheric impacts using two regional climate model experiments focused over the Fram Strait region. The experiments differed in the treatment of sea ice − one experiment had sea ice prescribed by satellite data and therefore grid cells could have partial sea ice, and in the other the sea ice was either 0 or 100% depending on the SST. For the experiment with more realistic sea ice, turbulent heat fluxes were often directed upwards due to the presence of leads and polynas leading to an increase in cloud cover and precipitation. The experiment with more realistic sea ice also compared more favourably to observations. Strey et al. (2010) used Polar WRF with the southern boundary of about 30^{o}N to explore 2007 sea-ice impact. The simulations used 2007 lateral atmospheric boundary conditions and SSTs for September–December. For ensemble members testing the impact of decreased sea ice, 2007 SIC was used. For control ensemble members, 1984 SIC and extent was employed. Focusing their results on October–November, they found increased latent heat fluxes and large temperature increases over the area of anomalous open water (focused in the western Arctic) and also over the Gulf Stream area which they attributed to a decrease in SLP over eastern North America and an associated increase in cold air advection in this area. Difference maps showed a ‘trough-ridge-trough’ pattern from the area of anomalous open water (a large decrease in SLP) roughly to the North Atlantic where positive SLP anomalies were modelled. In general, the simulations showed circulation changes throughout the atmosphere with higher tropospheric heights over western North America and lower constant pressure heights over eastern North America in the 2007 sea ice case, with these features broadening with height.

The subsequent WRF-based study by Porter et al. (2012) used observed sea ice and SSTs from a low (2007) and high (1996) ice year, in addition to an experiment using a mixed SST field between 2007 and 1996, for three 15-member ensembles to sample a large range of climatic variability. They found the largest local response in October and November with increased turbulent heat fluxes which heated and moistened a vertically deep layer of the atmosphere. They also found an increase in cloud cover affecting the surface and atmospheric energy budgets. Studies with global (Blüthgen et al., 2012) and regional (Porter et al., 2012) models had analysed ensemble runs with prescribed sea-ice extent of the record minimum in 2007. They confirmed the idea that increased oceanic heat uptake over the Arctic in summer was followed by increased oceanic heat release to the atmosphere in autumn, resulting in higher surface air temperatures, stronger heat fluxes and increased humidity.

4.3.1.5 Sea ice impact by CCMs

Orsolini et al. (2012) performed hindcast simulations with the European Centre for Medium-Range Weather Forecasts (ECMWF) high-resolution coupled ocean-atmosphere seasonal forecast model to analyse the impact of the 2007 sea ice minimum on the following autumn and early winter (Oct-Dec) atmospheric response. It was found that the obvious positive surface temperature anomalies as high as 10°C appeared over the Pacific and Siberia in October and November. By December, intensified surface Highs emerged on the American and Eurasian continents, which were associated with anomalous advection of cold (warm) polar air on their eastern (western) sides and brought cooler temperatures along the Pacific coast of Asia and Northeastern North America. Over the oceans the low pressure systems (i.e. Aleutian and Icelandic Lows) were deepened and the tropospheric jets were intensified. In addition to sea ice extent anomalies, realistic sea ice thickness changes could also induce atmospheric response. Using GFDL AM2 forced by largest (1964–1966) and smallest (1994–1996) Arctic sea-ice volume conditions, Gerdes (2006) suggested that thinning of Arctic sea ice thickness could lead to negative SLP anomalies in the central Arctic and positive ones over the subtropical North Atlantic, resembling the positive phase of NAO.

4.3.2 Response to projected sea ice

Fletcher (1968) is among the first to speculate the climate impact of extreme Arctic sea-ice conditions. He suggested that an ice-free Arctic would cause weaker meridional temperature gradients and a weaker zonal circulation, and would be accompanied by more high-latitude snowfall due to increased evaporation over Arctic Ocean. Newson (1973) is among the first to use the AGCM for illustrating the climate impact of fully removal of winter Arctic sea-ice cover with the Arctic SST at the freezing point. The simulated response was the surface warming over the Arctic basin with maximum warming of 40^{o}C and the surface cooling over the northern mid-latitude continents (cooling over Eurasia could reach -6^{o}C; Fig.1 in Newson, 1973). Newson noticed a distinct southward movement and weakening of the prevailing mid-latitude westerlies in response to the removed winter Arctic sea ice. Newson also suggested that weakening of mid-latitude westerlies could lead to the more blocked atmosphere circulation. Singarayer et al. (2006) forced the Hadley Centre Atmospheric Model (HadAM3) with predicted sea-ice reductions until 2100 under one moderate scenario and one severe scenario of ice decline and revealed that significant warming at high latitudes occurred during the twenty-first century and parts of Europe may experienced higher precipitation rates due to the intensification of storm tracks. Significant increases in SAT during 2090–99 occurred primarily in winter, which were primarily due to large upward sensible heat flux from the ocean directly over the areas within the ice extent where open water had increased. Seierstad and Bader (2009) forced the AGCM ECHAM5 with the projected climatological seasonal cycle of Arctic sea ice at the end of 21st century

(2081-2099) and found that the storminess during December and January in mid-latitudes displayed significant reductions associated with projected negative anomalies of sea ice. The projected decrease in storminess that hit Europe further to the south might be related to a negative phase of the NAO. Higgins and Cassano (2009) forced the Community Atmospheric Model version 3 (CAM3) with climatological sea ice from 1980 to 1999 and climatological sea-ice extent from 2080 to 2099 from an ensemble of CCSM3 A1B scenario runs with the aim to assess the direct impact of sea ice on winter (Nov-Feb) Arctic atmospheric circulation, precipitation, and temperature. They found that associated with reduced sea ice, the Aleutian lows in winter (Nov-Feb) was deepened and the geopotential height at 1000-hPa increased. Besides, large increases in precipitation was found across the Arctic, which was mainly due to thermodynamic changes such as increased moisture in the atmosphere, rather than changes in the frequency of cyclones. Deser et al. (2010) also used CAM3 to ascertain the atmospheric response to projected Arctic sea-ice conditions for 2080–2099 from the A1B scenario using an eight-member ensemble mean of CCSM3 simulations. Even though the loss of Arctic sea ice was greatest in summer and autumn (Jul–Nov), it is projected that the response of the net surface energy budget over the Arctic Ocean to sea ice loss was largest in winter (October–February). Besides, the air temperature and precipitation responses were greatest in November–December over Siberia and northern Canada, with values ~7°C and ~0.16 mm day^{-1}, respectively. As a result of enhanced winter precipitation (and despite the warmer air temperatures), snow depths over Siberia and northern Canada increased by ~1 cm liquid water equivalent in late winter (February–April). Guo et al. (2013) used both the atmospheric component of Bergen Climate Model and the Bergen Climate Model to investigate the mechanism on how the change in spring Arctic sea ice impacting the EASM. They set-up the numerical experiments using the projected spring Arctic sea ice and the projected SST where the sea ice was removed in the Arctic and they found that the SST anomalies in the North Pacific bridged the spring Arctic sea ice and the EASM. The change in spring Arctic sea-ice cover could lead to change in SST in North Pacific which could persist into summer and therefore influenced the EASM. The mediating role of SST changes was highlighted by the result that only the AOGCM, but not the AGCM, reproduced the observed sea ice-EASM linkage. Peings and Magnusdottir (2014) used NCAR CAM5 with observed and projected mean SICs of 1979-2000 and 2080-2099 respectively. They only find the negative NAO anomalies in the troposphere and weakened westerly as a result of tropospheric thermal expansion. The thermal-dynamic response beyond the Arctic offsets the dynamic response, implying the strong Arctic sea-ice forcing having limited impact on the intensity of mid-latitudes cold extremes. Though model study showed that the Arctic Ocean circulation changed in response to the doubled CO_2 in the atmosphere (Gao et al., 2009), it is difficult for the atmosphere-only model to explore the response of the ocean circulation to the sea ice anomalies.

5. Uncertain in Arctic sea ice impact

Most of the studies summarized in this paper used the satellite data, reanalysis products and numerical models. As reviewed by Budikova (2009) and Vihma (2014), there were uncertainties related to the satellite data, reanalysis products and the numerical models. Therefore, there are uncertainties in the conclusions from the cited studies and it is difficult to quantify the uncertainties. Here we focus the uncertainties originated from the atmosphere internal variability and the pathways.

5.1 Uncertain in atmospheric response

Although all CMIP3 and CMIP5 models projected decline in Arctic sea ice in 21^{st} century (REF1, REF2), AO showed positive trend in CMIP3 whereas negative trend in CMIP5. (Cattiaux and Cassou, 2013), implying that Arctic sea-ice feedback was not a dominant factor to regulate AO in the models. Seierstad and Bader (2009) used the AGCM ECHAM5 to explore the impact of a projected Arctic sea-ice cover on wintertime extratropical storminess and the NAO. As the Arctic sea-ice cover continues to decline, the storminess tends to decrease during December and January in both mid- and high-latitudes, which is also related to the negative phase of the NAO. Such a negative phase of the NAO in late winter was induced by a projected Arctic sea-ice reduction for all the seasons. By forcing CAM5 with two different sea-ice forcings representing the recent (2007-2012) and projected (2080-2099) sea-ice decline over the Arctic, Peings and Magnusdottir (2014) examined the impact of the Arctic sea-ice decline on the NH atmospheric circulation and cold extreme temperatures over mid-latitudes. The numerical experiments forced by the recent sea-ice conditions indicated that anomalous Rossby waves could penetrate into the stratosphere in late winter (February) and lead to negative anomalies of the AO penetrating downward and further leading to cold land surface temperatures over mid-latitudes. The numerical experiments forced by projected sea-ice conditions also showed a negative phase of the troposphere AO in early and late winter, which was mainly driven by the large warming of the lower troposphere over the Arctic. Owing to the large lower tropospheric warming that extended well beyond the Arctic, the stronger sea-ice forcing had limited impact on the intensity of cold extremes over mid-latitudes. Using AGCM ECHAM5, Semenov et al. (2012) investigated the sensitivity of Eurasian winter and summer SAT to the variations in SST and SIC during 1998-2006 and 1968-1976. They found that the variations of SST and SIC could well account for the SAT variations in Western Europe but could not well explain the warming in Eastern Europe and Western Siberia. By checking the coincidence between occurrences of European cold winter month and sea-ice reduction over the Barents-Kara Seas in 13 CMIP5 models simulations in 21^{st} century (2006-2100) for both the RCP4.5 and RCP8.5 scenarios, Yang and Christensen (2012) suggested that the moderate reduction of SIC in the Barents-Kara Seas during the future period of 2006–2050 seems to provide favourable condition for the occurrence of cold winters in Europe. Early studies also suggested that winter atmosphere circulation response to the autumn Arctic sea-ice reduction contained large uncertainties. For example, some studies showed that the negative AO resembling pattern could persist into the winter (Francis et al., 2009; Liu et al., 2012, 2013; Li and Wang, 2013b). Meanwhile, other studies (Blüthgen et al., 2012; Screen et al., 2014) argued that the autumn atmospheric circulation anomalies could not continue into winter. In addition, Screen et al. (2013b) and Liu et al. (2012) reported contrary winter AO tendency in response to the autumn Arctic SIC trend using the AGCM CAM3. The contrary could be caused by either different size in ensemble members or the difference in boundary conditions. For example, the Arctic SIC and the associated SST during the whole year were used in Screen et al. (2013b), whereas only the autumn and partly winter (persisting from autumn) SIC changes were in Liu et al. (2012).

Screen et al. (2014) investigated winter atmospheric response to the autumn Arctic SIC trend from 1979-2009 using two models (AGCM UM7.3; AGCM CAM3) and did not find the negative AO/NAO response. Instead, the SLP response with AGCM CAM3 showed the positive AO/NAO response, in contrast to the negative AO-resembling response with AGCM CAM3 in Liu et al. (2012). Such disagreement could come from the different size in ensemble members or the difference in setting-up boundary conditions: the Arctic SIC and the associated SST during the whole year were used to force the models in Screen et al. (2014), whereas only the autumn and partly winter (persisting from autumn) SIC changes were used to force the model in Liu et al. (2012).

Cohen et al. (2012) suggested that the Arctic sea-ice loss (in September, poleward of 65°N) could lead to increase of Eurasian snow cover (in October) due to the potential contributions to tropospheric moisture. The increasing snow cover resulted in stronger diabatic cooling and a strengthened SH in autumn and winter. This further led to an increase in upward propagation of planetary waves, a weakened polar vortex and westerly. Consequently, a negative AO emerged in the lower troposphere and increased Arctic cold air outbreaks into mid-latitudes. It is suggested by Grassi et al. (2013) that, associated with sea ice reduction in the Barents-Kara Seas, the extreme cold events over continental Europe and extreme precipitation events over the entire Mediterranean Basin became more frequent and more intensified. The large-scale atmospheric circulation response to sea-ice reduction in the Barents-Kara Seas resembled the negative phase of the AO. It was also suggested that the increase in snowfall over the United States and Europe might be attributed to an increase in the frequency of blocking events caused by the recent autumn Arctic sea-ice loss (Liu et al. 2012). However, Liu et al. (2012) argued that the change in atmosphere circulation in response to reduced autumn Arctic sea-ice cover was different from the classic AO with broader meridional meanders in mid-latitudes. In addition to autumn sea-ice, summer Arctic sea-ice variability could have an impact on the lager NH atmospheric circulation (Overland and Wang, 2010). It is suggested that reduction of summer Arctic sea-ice extent led to more open water in late summer, the stored additional heat in the Arctic Ocean was released to the atmosphere during the following autumn season. As a result, the surface air temperature during late autumn was higher than normal, contributing to an increase in the 1000–500 hPa thickness field which favoured westerly wind flow associated with the polar vortex. Therefore, cold polar air moved south to the mid-latitudes.

Unlike the impact pathways revealed by other studies, Wu et al. (2013a) suggested that autumn Arctic sea-ice loss showed significant correlation with negative phase of the tripole wind pattern during winter. The negative phase of the tripole wind pattern corresponds to an anomalous anticyclone over northern Eurasia as well as two anomalous cyclones occurring over southern Europe and in the mid- to high-latitudes of East Asia. These anomalous cyclones in turn led to enhanced winter precipitation in these two regions, as well as negative surface temperature anomalies over the mid- to high latitudes of Asia. Petoukhov and Semenov (2010) argued that the Changes in the November sea-ice cover in the Barents Sea could lead to an additional heat source and intensified cyclones in downstream Arctic regions in the following months, which was similar to a NAO/AO limited in troposphere with cold anomalies over the northern continents, potentially adding to anomalies directly induced by a negative AO.

Francis and Vavrus (2012) suggested that the Arctic warming could lead to meandering jet stream (especially in autumn and winter), slow down the eastward progression of Rossby waves and cause weather patterns in mid-latitudes to be more persistent. However, as we and others have summarized, this mechanism is still under-debate.

5.2 Atmosphere internal variability (AIV)

Screen et al. (2013) and Screen et al. (2014), based on their model simulations, proposed that the local response (near-surface atmosphere warming and precipitation) to the Arctic sea-ice reduction could be easily detected in observational records with high signal-to-noise ratios. However, the atmosphere circulation response (sea level pressure and upper level geopotential heights) and the response over mid-latitudes could be partially or fully masked by the AIV. In Wu et al. (2013b), only 5 members of totally 12 experiments forced by the observed sea-ice conditions from 1978-2007 could reproduce the observed anomalous SAT and atmosphere circulation patterns. This also implies the potential importance of the AIV. The results in the simulations with small-size ensembles are likely incapable to eliminate the AIV by using the ensemble mean and therefore be less reliable (Screen et al. 2013). Honda et al. (2009) used 28 of totally 50 experiments to explore the linkage between the autumn Arctic sea-ice reduction and the Eurasian cold winters. They found that the signal would be weaker if all 50 experiments were used though the tendencies were similar. They proposed it was likely related to the preconditioning of atmosphere state. Kumar et al. (2010) estimated the simulated internal variability of SAT and suggested that sea-ice reduction signal in SAT was very much detectable over the Arctic Ocean whereas it could be masked by internal variability for SAT over land between 50^{o}-60^{o}N.

6. Summary and Future Perspective

We have reviewed available literature on the climatic impact of Arctic sea-ice with special focus on Eurasia. Below is a summary to our review.

- *Arctic sea ice exhibits multi-decadal variability. The multi-decadal variations of Arctic sea ice are likely governed by the pole-ward ocean heat transport related to the Atlantic Multi-decadal Variability (also referred to as AMO; at least for the Arctic sea-ice variations in the Atlantic sector).*
- *Arctic sea-ice decline during the satellite era is likely consequence of multi-decadal variation and anthropogenic forcing.*
- *Climatic impact of changes in Arctic sea ice in different seasons has been addressed, but most of focus has been on the reduction of autumn and winter Arctic sea ice.*

- *Paleo-studies suggested that the reduction of the Arctic sea ice could cause the surface warming at mid-and high latitudes and had the potential to change the glacier-inter-glacier cycle.*
- *A negative feedback between the Arctic sea ice and the AO/NAO has been suggested. However, there is a debate whether the reduction in autumn Arctic-sea-ice-induced negative AO/NAO can persist into winter. There are also modelling studies that did not show negative AO/NAO response to the reduction in autumn Arctic sea ice.*
- *There are studies that suggested change in autumn Arctic sea ice can cause the recent Eurasian cooling by either the negative AO or AO-like response or the intensified Siberian High. There are studies that suggested winter atmospheric circulation is more associated with change in winter Arctic sea ice*
- *Change in spring Arctic sea ice has been linked to the summer precipitation in East Asia though different pathways have been suggested.*
- *The reduction of autumn Arctic sea ice has also been linked to the increase in spring snowfall and cooling over Eurasia.*
- *The linkage between the AO and the EAWM is stronger after 1980s. The sea-ice reduction related surface warming over Arctic caused change in the meridional temperature gradient and thus led to westward penetration of the East Asian jet stream that strengthens the impact of AO on the EAWM.*
- *Linkage between Arctic and mid-latitudes has been suggested through the change in the planetary waves, however, the pathways have not been clearly demonstrated.*
- *Modeling studies suggested that the remote climate response (e.g., atmosphere circulation, air temperature) to change in Arctic sea ice is hard to detect.*

For future perspective, long-term and reliable data is needed to consolidate the sea-ice impact on climate over Eurasia and coordinated multi-model ensemble experiments with identical sea-ice and SST boundary conditions are needed to understand the mechanisms. Along with the model improvement, the representation of troposphere-stratosphere interaction should receive more attention. Furthermore, comparison between the results from AGCM and CGCM should be performed to assess the role of two-way coupling.

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Tab. 1 Modeling studies to explore climate impact of observed change in Arctic sea ice

Study	Model	Model resolution	Sea ice forcing	SST forcing	Ensemble number	Time of analysis
Herman and Johnson (1978)	Goddard general circulation model (Somerville et al., 1974)	9 layers / 5° × 4° (lon, lat) (*same as below*)	Climatologically minimum (maximum) ice cover occurring in Jan-Feb in the Atlantic and Pacific in the **CTRL (PERT)**	Unchanged, as model's	Six of **CTRL** and two **PERT**	14 January – 12 February
Yang et al. (1994)	AGCM developed at Australian Numerical Meteorology Research Centre	9 sigma levels/ 15 wavenumber	**CTRL:** sea ice of July **PERT 1:** positive annual sea ice anomaly in Greenland-Barents Seas **PERT 2:** positive annual sea ice anomaly in Siberian Sea- Beaufort Sea **PERT 3:** negative annual sea ice anomaly in Siberian Sea- Beaufort Sea	SST of July	one	Integrated for 60 days; analyzed the last 30 days
Honda et al. (1996)	AGCM developed at Meteorological Research Institute	30 layers / 5.6° × 5.6°	**CTRL:** monthly sea-ice cover **SENS 1**: maximum sea-ice cover in the Sea of Okhotsk (1978, 1979, 1980, and 1983 Dec-Feb) **SENS 2**: maximum sea-ice cover in the Sea of Okhotsk (1975, 1984, 1991, and 1994)	climatological-mean SST where sea ice is absent	5	Integrated eight years, focus on Jan-Feb
Wu et al. (1999)	AGCM developed at the Institute of Atmospheric Physics (Zeng et al., 1989)	2 layers / 4°×5°;	**CTRL:** integrated 12 years without any change in physical conditions; **PERT 1 (heavy ice):** climatic SIC in the Kara and the Barents Seas from 1 Jan to 30 Nov; increased 5 grid points SIC in Dec, 8 grid points in Jan, and 11 grid points in Feb **PERT 2 (light ice):** climatic SIC in the Kara and the Barents Seas from 1 Jan to 30 Nov; decreased 14 grid points SIC in Dec, 8 grid points in Jan, and 4 grid points in Feb	As model's	One	Dec-Feb
Magnusdottir et al. (2004)	NCAR CCM3 (Kiehl et al., 1998)	18 layers/ 2.8°×2.8° (T42)	**CTRL:** climatological sea ice extent in the North Atlantic and Arctic Ocean ($\mathrm{SICE}_{\mathrm{clim}}$) **PERT 1:** $\mathrm{SICE}_{\mathrm{clim}} + \mathrm{W}_{\mathrm{trend}} \times \mathrm{E}_{\mathrm{trend}}$ [$\mathrm{W}_{\mathrm{trend}}$: west of Greenland trend (1958-1997), $\mathrm{E}_{\mathrm{trend}}$: west of Greenland trend (1958-1997)] **PERT 2:** $\mathrm{SICE}_{\mathrm{clim}} + 2 \times (\mathrm{W}_{\mathrm{trend}} + \mathrm{E}_{\mathrm{trend}})$ **PERT 3:** $\mathrm{SICE}_{\mathrm{clim}} + 2 \times \mathrm{W}_{\mathrm{trend}}$ **PERT 4:** $\mathrm{SICE}_{\mathrm{clim}} + 2 \times \mathrm{E}_{\mathrm{trend}}$	**CTRL:** climatological SST **PERT 1:** Same as above **PERT 2:** Same as above **PERT 3:** Same as above **PERT 4:** Same as above	one	run for at least 61 yr; focus on Dec-Mar

Alexander et al. (2004)	NCAR CCM3.6 (Kiehl et al., 1998)	18 layers/ 2.8°×2.8° (T42)	**CTRL:** Ice extent repeats the seasonal cycle each year based on the average of the 1979–99 period **PERT 1:** Ice extent varies over the entire Arctic in 1982/83 winter [highest] **PERT 2:** Ice extent varies over the entire Arctic in 1995/96 winter [lowest] **PERT 3:** Ice concentration varies over the entire Arctic in1995/96 winter	Climatological SST were used everywhere ice was not present except at grid boxes adjacent to the ice where the SST was constrained not to exceed the average of 20.88C (the lowest ice-free temperature) and the warmest SST in an adjacent grid box	50	Integrated form Oct to Apr, focus on Dec-Feb
Singarayer et al. (2006)	AGCM HadAM3	19 layers/ 3.75°×2.5°	**spinup:** climatological sea ice in 1970–1980 **PERT:** observed sea ice of 1980-2000	**PERT:** climatological SST of 1980-2000, grid points that were ice covered at any time for a particular month were given an SST of 271.35 K in the climatology	6	All months
Deser et al. (2007)	NCAR CCM3 (Kiehl et al., 1998)	18 layers/ 2.8°×2.8° (T42)	**CTRL** : climatological seasonal cycle **PERT 1**: climatological seasonal cycle **PERT 2**: observed monthly trend in sea ice extent over the North Atlantic–Arctic region during 1958–97, multiplied by approximately a factor of 2.	**CTRL** : climatological seasonal cycle **PERT 1**: observed SST trend computed separately for each month during 1954–1994 over the North Atlantic north of 30°N, multiplied by a factor of -5; **PERT 2**: climatological seasonal cycle	240	Integrated for 5-month from 1 Dec to 30 Apr; daily
Petoukhov and Semenov (2010)	AGCM ECHAM5 (Roeckner et al., 2003)	19 layers/ 2.8°×2.8° (T42)	**Barents-Kara** (30°-80°E, 65°-80°N): May through Oct. was assigned to the 1987-2006 climatology, while Nov. to Apr. SIC was set to 100%, 80%, 60%, 40%, 20% and 1% in six corresponding simulations; **Elsewhere**, 1987-2006 climatological monthly mean	Jan. to May set as in the year 2006; Jun. to Aug. set average for the years 2005 and 2006; Sep. to Dec. set as in the year 2005; open water within the Barents-Kara Seas: -1.8°C	6	Dec-Feb
Grassi et al. (2013)	NCAR CAM3 (Collins et al., 2006);	26 layers/ 2.8°×2.8° (T42)	climatological monthly-mean Sea ice concentration for 1950–2001, with the only exception of the Barents–Kara region where, from November to April, sea ice concentration has been set to 50% and 20% to	climatological monthly-mean values of SST for 1950–2001	48	Run for 12 consecutive years;

			produce the two simulation cases			
	RegCM4 (Giorgi et al., 2012).	18 sigma layers/ horizontal about 60km	Results from CAM3 simulations	Results from CAM3 simulations	one	Jan-Mar
Semenov et al. (2012)	AGCM ECHAM5	19 layers/ 2.8°×2.8° (T42)	Global data 1968–1976 in the sector (35°–90°N, 90°W–110°E) minus data for 1998–2006	Global data 1968–1976 in the sector (35°–90°N, 90°W–110°E) minus data for 1998–2006	one	100 model years; focus on winter and summer
Bhatt et al. (2008)	AGCM CCM3.6 (Kiehl et al., 1998)	18 layers/ 2.8°×2.8° (T42)	**CTRL** : seasonal cycle, average of the 1979–1999 **PERT 1**: Ice extent varies over April to October of 1995 **PERT 2**: Ice concentration varies over April to October of 1995	In regions where the ice extent was lower (*above*) than the mean extent, the exposed ocean was set to the climatological SST (*blended from −1.8°C at the ice edge with climatological values from two grid boxes*)	51	August
Honda et al. (2009)	AGCM AFES	20 layers/ 2.8°×2.8° (T42)	**CTRL:** climatological sea-ice **PERT 1:** set the prescribed concentration ice (IC) as 90% where the climatological (1979–2000, Sep-Dec) IC is between 15% and 90%; **PERT 2:** the prescribed IC is set as 0% where the climatological IC is less than 90%	**CTRL**: climatological SST **PERT 1 and 2:** climatological mean SST is prescribed where ice is absent	50	Integrated from Sep to Feb; focus on Nov, Dec, and Feb
Liu et al. (2012)	NCAR CAM3 (Collins et al., 2006);	26 layers/2.8°× 2.8°	**CRTL:** seasonally varying Arctic sea ice based on the climatology of the Hadley Centre sea ice concentrations for 1979–2010; **PERT:** sea ice loss in autumn (Sep-Nov) and winter (Dec-Feb) based on regressions with regard to the standardized autumn (Sep-Nov) Arctic sea ice index for 1979–2010 that are statistically significant at the 90% confidence Level	**CTRL:** climatological monthly for 1979-2010; **PERT:** where sea ice is removed, SST is set to −1.8°C	20	Nov-Dec, Dec-Jan
Blüthgen et al. (2012)	AGCM ECHAM5 (Roeckner et al., 2003)	31 layers/1.875 °×1.875°	**CTRL**: climatological (1979–1996) SIC with annual cycle from SIC of AMIP II **PERT 1**: SIC for Jan through Dec 2007 taken from the HadISST1 dataset north of 60°N, AMIP II climatology SIC south of 40°N, and a linear interpolation of both datasets between 40°N and 60°N;	**CTRL**: climatological (1979–1996) SST with annual cycle from SST of AMIP II **PERT 1**: SST for Jan through Dec 2007 taken from the HadISST1 dataset north of 60°N, AMIP II climatology SST south	conducted for 40 years ; regard the total simulation period as an	Jul to Oct

			PERT 2: with global SIC from the HadISST1 dataset for 2007	of 40°N, and a linear interpolation of both datasets between 40°N and 60°N; **PERT 2**: with global SIC from the HadISST1 dataset for 2007	ensemble of 40 independent annual cycles	
Wu et al. (2013b)	AGCM ECHAM5 (Roeckner et al. 2003)	19 layers/ T63	**CTRL:** climatological monthly SIC **PERT**: observed Northern Hemisphere monthly SIC from 1978 to 2007	**CTRL:** climatological monthly SST **PERT**: climatological monthly SST	12	simulated for 30-yr; focus on winter
Screen (2013)	AGCM UM7.3 (Martin et al., 2011)	38 layers/1.25° ×1.875°	**High/Low ice run**: Arctic SIC were representative of observed conditions in 1979/2009; Antarctic SIC were held constant at climatological (1979–2009) values	**In both run**, held constant at climatological (1979–2009) values, except that grid-boxes where the SIC differed between the low ice and high ice runs, SSTs were prescribed in the same manner as SIC	Run for 100 years [*each year is considered to be an independent ensemble member*]	All seasons but only discussed MJJA
Screen et al. (2013)	NCAR CAM3 (Collins et al., 2006);	26 layers/2.8°× 2.8°;	**CTRL** : an annually-repeating monthly cycle of climatological SIC **PERT**: linear trend (TRD) in SIC over 1979–2009 for each month was added to the climatological (CLM) monthly values	**CTRL** : an annually-repeating monthly cycle of climatological SST **PERT**: In grid-boxes and months where the SIC trend is not zero, then the CLM+TRD SST were prescribed, Elsewhere, CLM SST was prescribed	**CTRL** and **PERT** were run for 100 years in the UM and for 60 years in CAM	Model simulation period [*each year is considered to be an independent ensemble member*]
	AGCM UM7.3 (Martin et al., 2011)	38 layers/1.25° ×1.875°	**PERT*2**: CLIM + (TRD*2)	PERT*2: similar as PERT, but with CLIM + (TRD*2)	**PERT*2**: run for 100 years in the UM only	
Screen et al. (2014)	NCAR CAM3 (Collins et al., 2006);	26 layers/2.8°× 2.8°;	**north (*South*) of 40°N**, if the SIC observed during a particular month deviated from the climatological mean (1950-2000) by more than (***within***) 10% (in absolute terms), the observed (***climatological***) SIC values were used	**north (*South*) of 40°N**, if the SIC observed during a particular month deviated from the climatological mean (1950-2000) by more than (***within***) 10% (in absolute terms), the observed (***climatological***) SST values were used	5	1979-2009 All months
	AGCM UM7.3 (Martin et al., 2011)	38 layers/1.25° ×1.875°			8	
Rinke et al. (2006)	Regional climate model (RegCM) HIRHAM (Christensen et al.,	19 layers/0.5°× 0.5°	**EXP1**: sea ice fraction from the ERA15 data, and the sea ice thickness is fixed to 2 m for all sea ice grid points **EXP2**: sea ice fraction, and sea ice	**EXP1**: SST from the ERA15 data **EXP2**:SST from the Naval Postgraduate School ice-ocean model output	one	1979-1993 winter (DJF)

	1996)		thickness from the Naval Postgraduate School ice-ocean model output			
Gerdes (2006)	GFDL AM2 (Anderson et al., 2004)	24 layers/2°×2.5°	**PERT 1: s**easonal cycles of sea ice conditions (concentration and thickness) for 1994-1996; **PERT 2:** same as above, but for 1964-1966 **PERT 3:** sea ice thickness averaged for 1948-1998 **PERT4**: composite SIC fields from 1994–1996 and 1964–1966	climatological seasonal cycle SST	40 year integrations; [*Each year is regarded as an realization of the atmospheric state*]	Jan-Mar
Strey et al. (2010)	WRF 3.0.1	28 layers/40km ×40km	**CTRL:** 1984 sea ice condition **PERT**: SIC in 2007	**CTRL:** 2007 atmospheric conditions and SST **PERT**: SST in 2007	10	Oct-Nov
Porter et al. (2012)	WRF 3.2.0	40 layers/50km ×50km	**High/Low ice run:** daily SIC of 1996/2007 **Mixed EXP**: SIC of 2007	**High/Low ice run:** daily SST of 1996/2007 **Mixed EXP**: SSTs from 2007 (*1996*) north (*south*) of 66°N	started on 16 Jun to 1 Dec [1994-2008]; taken as 15 members	1 Jul to 15 Nov
Koenigk et al. (2009)	CCM ECHAM5/MPI-OM (Roeckner et al., 2003)	31 layers/1.875 °×1.875°	**CTRL:** 465-year pre-industrial simulation under present day greenhouse gas forcing **SENS**: SIC and sea ice thickness in the Barents Sea are replaced by the ice conditions of May 602 (largest ice volume) from the control integration	As models'	20	All months
Orsolini et al. (2012)	CCM IFS/HOPE3 (ECMWF)	62 layers/T159	**Hindcasts:** observed sea ice extent (2002-2006)	Observed SST	30	Oct-Dec
			SENS: actual 2007 sea ice extent		5	
Peings and Magnusdottir (2014)	NCAR CAM5	30 layers/1.9^{o}Lat.×2.5°Lon.	**CTRL:** mean of 1979-2000 SIC from HadISST	Mean of 1979-2000 SST from HadISST	50	Oct-Dec
			PERT: mean of 2007-2012 SIC from HadISST		50	

SENS: sensitivity experiment; **CTRL**: control run; **PERT**: perturbed experiment; **SIC**: sea ice concertration; **SICE**$_{\mathbf{clim}}$: climatological sea ice extent; **SST**$_{\mathbf{clim}}$: climatological SST

Tab. 2 Modeling studies to explore climate impact of projected change in Arctic sea ice.

Singarayer et al. (2006)	AGCM HadAM3	19 layers/ 3.75°×2.5°	**spinup:** climatological sea ice in 1970–1980 **PERT 1:** sea ice for 2001-2100 **PERT 2**: sea ice for 2001-2100	**PERT 1:** climatological SST field; grid points that were ice covered at any time for a particular month were given an SST of 271.35 K in the climatology **PERT 2**: increase in SSTs as sea ice decreases	one	All months	Bootstrap observations (Comiso et al.1997) GISST
Seierstad and Bader (2009)	AGCM ECHAM5 (Roeckner et al., 2003)	19 layers/ 2.8°×2.8° (T42)	**EXP 1**: climatological seasonal cycle SIC for 1981-1999 **EXP2:** Projected climatological seasonal cycle for 2081-2099 ECHAM5/MPI-OM IPCC SRESA1B scenario output of three ensemble members; sea-ice thickness is fixed at 2m	**EXP 1**: climatological seasonal cycle SST for 1981-1999 **EXP2:** northern hemisphere, replaced with projected SSTs at grid points where sea ice has changed; elsewhere, climatological seasonal cycle SST for 1981-1999	one	Nov-Mar	HadISST1.1 (Rayner et al., 2003)
Higgins and Cassano (2009)	NCAR CAM3 (Collins et al., 2006)	26 layers/ 1.4°×1.1° (T85)	**CTRL:** Monthly climatology sea ice extent from 1980 to 1999 from an ensemble of fully coupled CCSM3 preindustrial control runs **PERT**: monthly climatology sea ice extent from 2080 to 2099 from an ensemble of CCSM3 A1B scenario	SST climatology data; where sea ice is removed, SSTs were set to -1.8°C	60-year runs;	Nov-Feb	Ensemble simulation of CCSM3
Deser et al. (2010)	NCAR CAM3 (Collins et al., 2006)	26 layers/ 1.4°×1.4° (T85)	**CTRL:** repeating seasonal cycle of sea ice (concentration and thickness) for the period 1980–99, obtained from the 7-member ensemble mean of 20th century CCSM3 **PERT**: a repeating seasonal cycle of Arctic sea ice (concentration and thickness) for the period 2080–99, taken from the 8-member ensemble mean of 21th century CCSM3 simulations under A1B	**CTRL:** repeating seasonal cycle of SST for the period 1980–99, obtained from the 7-member ensemble mean of 20th century CCSM3 **PERT**: As CTRL; where fractional sea ice cover in the late 20th century is replaced by open water in the late 21th century, SST are set to -1.8°C	60-year runs	All months	Ensemble simulation of CCSM3
Guo et al. (2013)	Bergen Climate Mode	30 layers/ 2.8°×2.8° (T85)	**present-day CTRL:** with atmospheric CO_2 concentrations kept constant at the year 2000	**Coupled CTRL**: Inside the Arctic region, spring Arctic SST	one	Feb-Apr; Jun-Aug	monthly sea ice area from the National Snow and Ice Data

			level**;** **future CTRL:** IPCC A2, during 101-120 years, the CO_2 concentration is fixed at 992 ppm **Coupled CTRL**: Inside the Arctic region, spring Arctic SIC are prescribed with daily climatological values that are obtained from the last 20 years of *present-day CTRL*. Outside the Arctic region, the system remains fully coupled. Integrated for 60 years **Atmosphere-only PERT:** the spring Arctic SIC from the daily, climatological mean of the last 20 years of *future CTRL* when the spring ASIC in the Sea of Okhotsk and the Barents Sea is essentially zero **Coupled PERT:** same as *Coupled CTRL* but with the spring Arctic SIC obtained from the last 20 years of *future CTR*L. Integrated for 60 years.	are prescribed with daily climatological values that are obtained from the last 20 years of *present-day CTRL*. Outside the Arctic region, the system remains fully coupled. Integrated for 60 years **Atmosphere-only PERT:** the spring Arctic SST from the daily, climatological mean of the last 20 years of future CTRL when the spring ASIC in the Sea of Okhotsk and the Barents Sea is essentially zero **Coupled PERT:** same as *Coupled CTRL* but with the spring Arctic SST obtained from the last 20 years of *future CTR*L. Integrated for 60 years.			Center; monthly SIC from the British Atmospheric Data Centr
Peings and Magnusdottir (2014)	NCAR CAM5	30 layers/1.9°Lat.×2.5°Lon.	**CTRL:** mean of 1979-2000 SIC from HadISST	Mean of 1979-2000 SST from HadISST	50	Oct-Dec	Projected SIC from ensemble mean of CCSM4 under RCP8.5
			PERT: mean of 2080-2099 SIC		50		