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Status of the Recent Declining of Arctic Sea Ice Studies

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Abstract In the past 30 years, a large-scale change occurred in the Arctic climatic system, which had never been observed before 1980s. At the same time, the Arctic sea ice experienced a special evolution with more and more rapidly dramatic declining. In this circumstance, the Arctic sea ice became a new focus of the Arctic research. The recent advancements about abrupt change of the Arctic sea ice are reviewed in this paper . The previous analyses have demonstrated the accelerated declining trend of Arctic sea ice extent in the past 30 years, based on in-situ and satellite-based observations of atmosphere, as well as the results of global and regional climate simulations. Especially in summer, the rate of decrease for the ice extents was above 10% per decade. In present paper, the evolution characteristics of the arctic sea ice and its possible cause are discussed in three aspects, i. e. the sea ice physical properties, the interaction process of sea ice, ocean and atmosphere and its response and feedback mechanism to global and arctic climate system.

Key words Arctic, sea ice, abrupt change, climate.

1 Introduction

Arctic is a substantial component of the global climate system. Research results show that in recent 30 years, in comparison with that in other areas on the earth, climate change in the Arctic is much more serious[1]. Sea ice has been continuously declining in large scale, ice cap in Greenland has been melting, global air temperature has been generally rising, and sea surface temperature has been becoming higher while salinity has been going down. Among all these changes, the drastic change of sea ice in the Arctic is the most notable[2]. Summer sea ice area in the Arctic has never stopped decreasing since the end of 1970s, and the speed is even faster in recent years. In September 2007, in particular, sea ice area reduced by 50% compared with the average value of summer sea ice area from 1950s to 1970s, presented the minimal value ever since satellite observation was adopted. Although summer sea ice extent in 2008 did not continue declining as predicted, the total amount of perennial sea ice[3] disappeared sharply, setting a new record minimum. Sea ice is one of the most significant factors that influence Arctic climate change. Obtaining accurate information of Arctic sea ice anomalies to identify the response of sea ice to global climate change would be one of the keys for researching and forecasting the trend of global climate change.

2 The decreasing trend of Arctic sea ice extent

The total amount of Arctic sea ice has been decreasing continuously in recent 30 years. Annual decrease of sea ice area is the most apparent evidence (Fig. 1). Peng Gongbing *et al*.[4] analyzed the annual sea ice change of the period from 1845 to 1976 in several main sea areas of the Arctic based on the in-situ and vessel-based sea ice measurements of the Former Soviet Union. Results showed that interannual change trends of Arctic sea ice in each season were similar: Arctic sea ice area decreased to a certain extent from mid 1950s to early 1960s, while it showed slight increase in the following years and reached the maximum value in 1967. By using global sea ice distribution observational data that cover different areas and time from five distinct sources , which are the Department of Sea Ice in Illinois University, Arctic and Antarctic Research Institute of Russia, NOAA Climate Prediction Center, Nansen Environmental and Remote Sensing Center in Norway, and NASA Goddard Space Flight Center, Konstantin[5] obtained similar results: from the beginning of 1970s to the mid 1980s, the annual average of Arctic sea ice area fluctuated around 12.5 million km^2; since late 1980s, northern hemisphere sea ice had abruptly decreased, leaving only 11.6 million km^2 at mid 1990s, and the annual change periods was rather unclear. Since the beginning of the 21st century, the continuous sea ice loss did not slow down but refreshed for several times the lowest historic point instead. The average decreasing rate of summer sea ice, which is more vulnerable than ever before, in particular, increased from 0.3% to 1.1% annually and to 8% in 2007 all of a sudden.

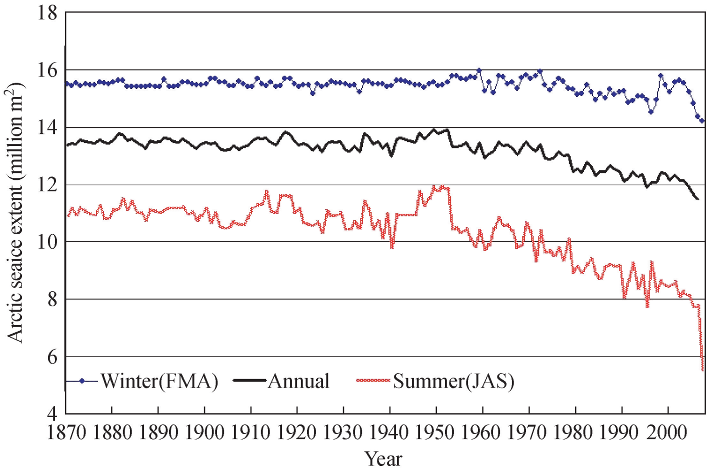

Fig. 1 Arctic seasonal sea ice extent, 1870-2007 (data from http://arctic.atmos.uiuc.edu/SEAICE/timeseries.1870-2007).

Latest remote sensing data show that the standing stock of perennial sea ice (the minimum value of the distributed extent of sea ice in the Arctic) has decreased by 40%[2] since 1970s. As shown in figure 2, every ten years the standing stock of Arctic summer sea ice (September) would decrease 11.1% since 1979. By analyzing data collected before 2000, Comiso[7] found that the trend was -6.4% per decade, while earlier before that, the result of analysis of Parkinson *et al*.[8] was only 3% per decade. Compared with circumstance in the preoid 1958-1976, the average thickness of Arctic sea ice was decreased by 1.3 meters in the mid 1990s. With a coupled sea ice model, Lindsay and Zhang[10] found that during 1987-2007, the average sea ice thickness decreased from 3.7 m to 2.6 m. According to ICESat laser altimeter observation results announced by NASA Satellite Center for winter Arctic sea ice, the average thickness of perennial sea ice in the Arctic decreased sharply from 3.3 m to 2.8 m between 2007 and 2008, and the average thickness of annual sea ice decreased as well from 1.8 m to 1.6 m.

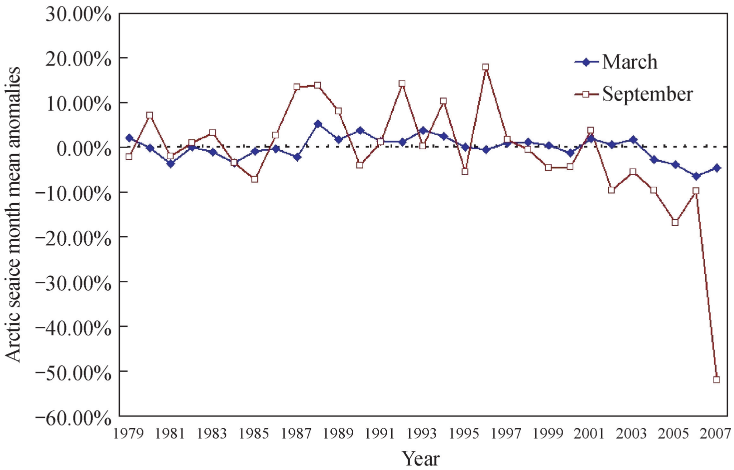

Fig. 2 Time series of the difference in ice extent in Mar (the month of ice extent maximum) and Sep (the month of ice extent minimum) from the mean values for the time period 1979-2007 (Data from NSIDC).

Due to the continuous thinning of winter sea ice and decrease of the total amount of summer sea ice, the average sea ice density of the Arctic Ocean in September decreased quickly. In a short period of time, the loss of Arctic sea ice is good for creating a new passage in the Arctic Ocean, and sea ice melt-water flow will provide a stable layer for the reproduction of phytoplankton. However, sea ice shrinking in the long run will definitely produce serious impact on regional and global climate and eco-environment, thus leads to catastrophic consequences.

3 Reasons for rapid decrease of sea ice

Till now, researches of the physical process of the abrupt change of Arctic sea ice have focused on two respects: one is the complicated change of sea ice itself; the other is changes contributed to interactions between sea ice and external environment, like atmosphere and oceans. Elements within the climate system that exhibit impact on the main process of the change of Arctic sea ice are Pacific inflow to the Arctic Ocean, water exchange and sea ice output between the Atlantic Ocean and the Arctic Ocean, runoff from Euro-Asia continent and North America continent, as well as responses of sea ice to atmospheric circulation. Meanwhile, change of sea ice may exsert important feedback on external environment, like ice-snow albedo feedback, cloud-radiation feedback and leads feedback in Polar Regions[12].

3.1 The complex characteristic of sea ice itself

Maykut, Weeks and Ackley, Parkinson *et al*., Barry *et al*. and Wadhams have conducted a series of detailed and in-depth study on the process of sea ice growth and melting[13-18]. Results show that at the initial stage, sea ice growth is effected mainly by wind field and external force of waves, under which sea ice may freeze, break, aggregate and accumulate on the sea surface[19]. After this period, sea ice growth is basically controlled by ice-atmosphere and ice-ocean heat budget transfer, oceanic heat flux, leads and other effects. Variation of sea ice thickness is mainly found on the bottom of sea ice. In spring, sea ice on the ice-atmosphere interface begins to melt, however, this warming process do not penetrate the whole sea ice layer, and therefore sea ice continues to grow at the bottom. Things are just the opposite in autumn. When autumn comes, sea ice grows very fast within the leads, but continues to melt at the bottom because low temperature can not effect the bottom sea ice. Thereby sea ice thickness will continue decreasing. The response of sea ice to seasonal forces is often delayed. For example, sea ice modeling exhibits that brine inclusion in sea ice will absorb solar shortwave radiation and store heat inside the ice (the so called ice heat reservoir effect), postponing both sea ice melting process in spring and sea ice growth in autumn.

Analysis on temporal and spatial characteristics of sea ice is also one of the focuses of the research on Arctic climate change [1-4][7-10]. In high latitude areas, the solar incident radiation is quite different in each season. The melting and freezing of sea ice need to absorb and release a great amount of heat. This, undoubtedly, includes an energy accumulation process, so that Arctic sea ice is obviously characterized by seasonal periodic change and delayed response. Although the lowest temperature in the Arctic appears in January and February, and the highest appears in July and August, judging from years of remote sensing data of Arctic sea ice, the maximum value of monthly sea ice coverage usually appears in February and March, and the minimum in September. In other words, seasonal change of sea ice is later than those of seasonal solar radiation and temperature.

Also, because that the sea ice area in the Northern Hemisphere is very broad, ranging from 45 ° N to 90 ° N of the North Pole, spanning 45 of latitude, the solar incident radiation presents great difference in different areas. Whrere the closer the latitude is from the North Pole, threre the thicker is the sea ice, and the longer is the time needed for energy accumulation process for melting and freezing. In this case, in areas that locate near the North Pole, time to appearing maximum value of sea ice will be delayed. The seasonal difference is also related to location of the seas and currents. For example, the Greenland Sea is situated to the southwest of Barents Sea, but its southern part is already in the area of the Arctic Circle. Therefore, generally speaking, sea ice concentration of the Greenland Sea is smaller than that of the Barents Sea, and both the maximum and minimum values appear earlier than the Barents Sea. However, as the Eastern Greenland Current is flowing southward toward the eastern side of the Greenland, sea ice flow out of the center the Arctic Ocean with the current, bringing comparatively more sea ice into the Greenland Sea in summer and thus making the sea ice area index in summer slightly higher than that of the Barents Sea[21].

3.2 Changes of Arctic sea ice caused by external environment

The abnormal change of Arctic sea ice is closely related to environment change of the Arctic[7,23-31]. The Arctic sea ice is interacting with different factors like temperature rising in sub-polar region, temperature rising and expansion in the Atlantic Ocean water layer, sea surface air pressure decrease in winter, phase changes of the Arctic Oscillation, and dipole anomaly, etc.

Fist of all, the temperature change is the main reason for the drastic change of Arctic sea ice.

Makshtas *et al.* [32] use the climate-state temperature and the daily temperature to force the same model respectively and found after comparison of 40 years of accumulative points that the contribution rate of sea surface temperature change to general change of sea ice was more than 20%。As shown in figure 3, between 1930s and1940s and from late 1980s up to now, the Arctic near-surface temperature presents the trend that it was higher than the average temperature. However, unlike the circumstance in recent 30 years, Arctic sea ice did not decrease in large scale during 1930-1950. According to Polyakov, this might be due to the global temperature which, as a whole, was comparative stable in that period of time. Given that the Arctic region is obviously getting warmer, due to the effect of atmospheric circulation, temperature may go down in some other region in the same period of time[34]. However, during the past few decades, regional warming in the Arctic was happening under the context of global warming. Most places on the earth are being effected by global warming, among which high latitude region in the northern hemisphere is the most seriously influenced area, leading to the continuous sea ice shrinking in large scale over the recent 30 years. The reason for the ahead singnal response of climate system in the Arctic region to climate change is sea-air-ice feedback effect, an important component of the Arctic climate system. Long wave and shortwave radiation going downwards in the feedback process, nevertheless, could be the key factor of changes of temperature and total amount of the sea ice

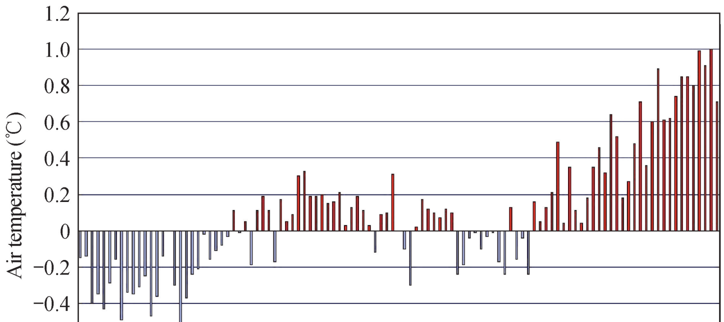

Fig. 3 Annual average change in near surface air temperature from 1900-2008 (data from NOAA).

in the Arctic.

On one hand, the albedo of sea ice is at least over 60%[4] compared to that of sea water. This reduces greatly the absorption efficiency of solar shortwave radiation in areas covered with sea ice. The albedo of sea ice varies with its state and physical properties. Melting of the snow layer, decrease in sea ice thickness, increase of the leads and melt pools might all contribute to the decrease of surface albedo. The sea ice may absorb more shortwave radiation in the process of melting. The extra energy will enter into sea water through ice, thereby produce influence on the melting and freezing of bottom sea ice. On the other hand, earth surface is releasing long wave radiation into the space while absorbing shortwave radiation. Long wave radiation will rebound to the earth surface through clouds and greenhouse gases reflects, making the Arctic region absorb more radiation heat flux, and leading to temperature rising and more serious sea ice shrinking in the region. Francis[35] believes that the greenhouse effect caused by long wave radiation downwards is further enlarged in the process of polar region warming. And this might be the main reason for the abnormal change of summer sea ice concentration between 1979 and 2004.

Secondly, apart from rainfall and runoff, the Arctic water is completely a mixture of the Atlantic Ocean and the Pacific Ocean waters. Waters of low salinity and density from the Pacific Ocean flowes into the upper layer of the Arctic Ocean through the only passage——the Bering Strait, and contribute 1/3 of the fresh water in the Ocean[36]. Recent researches show that along with the dramatic changes of the Arctic climate system, flux and thermohaline characteristics of the Pacific inflow throught Bering Strait are also changing quickly[37,38]. Over the past ten years, the average heat flux of the Pacific inflow increased in great extent[39]. In contrast, inflow heat flux increased form 3.87TW in 2003 to 5.96TW in 2007, with a rise of over 50%. Being a very shallow shelf sea, the Chukchi Sea is greatly effected by Pacific inflow, especial on its water mass property and sea ice. When entering the melting period, with the help of leaning south winds, great amount of Pacific water flow into the Chukchi Sea, bringing a huge amount of heat that results in the characteristics of high temperature and low salinity, accelerating the melting process in its watershed. Direct impact of the Pacific water on the upper layer of the Arctic Ocean is mainly happened west of the Northern Arctic Ocean, i.e. Beaufort Sea and the Canada Basin. Besides, the Pacific inflow, which plays an important role in halocline growth in the Arctic Ocean, is also one of the basic sources of freshwater in the surface mixture layer of the Ocean.

On the contrary of the Pacific Ocean case, the Atlantic water of high temperature and salinity flow into the Arctic Ocean via the Fram Strait and the Barents Sea. Due to its higher density, most water flows downwards below the halocline, joining in the deep sea basin circulation of the Arctic Ocean and forming the layers of deep water and bottom water. The halocline which located in water layer of 50-100 meters deep of the Arctic Ocean is an important ocean layered structure in the Ocean. By blocking the vertical convection of the upper and lower layers, the halocline maintains very well the hydrological characteristic of low temperature and low salinity in the upper layer while high temperature and high salinity in the lower layer. According to McLaughlin *et al*.[41], in correspondence with sea ice distribution and thickness changes, middle and upper layers of the Arctic Ocean water also present distinctive changes. In recent ten years, halocline of the Arctic Ocean gradually disappeared, especially in the Euro-Asia ocean basin. Middle layer water of the Arctic Ocean is warming up from the Atlantic Ocean side and spread to the Pacific Ocean side. Warming of the surface layer water, without doubt, heavily enlarged the ice-ocean feedback effect and promoted melting of sea ice in summer.

Thirdly, the outstanding change of atmosphere circulation change in the Arctic is also one of the direct factors causing change of sea ices. Begin with the late 1990s, dynamical factors gradually became a hot spot of research on rapid change of the sea ice. The anomaly of sea surface air pressure in winter may intensify or weaken the cyclone wind field that deliver direct impacts on sea ice in spring and summer, and thereby changes sea ice circulation mode[23]. Cyclone wind field can also expand the extent of the open water and thin ice area, leading to the decrease of surface albedo but increase of solar radiation absorption, and therefore speed up the melting process of side and bottom sea ice[25,42]. Meanwhile, observations approved that the sea ice output through the Fram Strait was increased due to the common effects of wind stress and sea currents. And this has become one of the important reasons of sea ice loss. Over the past few years, sea ice out put from the Fram Strait has reached more than 10% of the total amount of sea ice[43].

In addition, there are many studies linking the above mentioned elements with such atmospheric circulation modes as the North Atlantic Oscillation, Arctic Oscillation or dipole anomalies[39,44-47]. Scholars hold different views of what mode on earth played the leading role in the rapid change of Arctic sea ice. However, they have reached consensus on how circulation influenced change of sea ice, i. e. : in a period of time (usually three months), when a certain circulation mode is in a specific phase, it may greatly intensify the cross-polar current in the Arctic Ocean . Under the impact of warm and wet air and warmed Pacific inflow, the sea ice melts continuously. Pushed by cross-polar current, thinner ice accumulates ceaselessly and is transported quickly through the Fram Strait, and finally disappears in the warmer Atlantic Ocean Basin.

4 Summery and discussion

The rapid shrinking of sea ice in the recent 30 years has attracted extensive international attentions. Scholars from different countries are working hard to identify the physical factors and driving mechanism influencing change of sea ice, trying to develop and improve global, regional and polar climate modes for stimulating more exactly the changing process, and to predicting sea ice changing trend in the future. However, as time passes by, and with the development of research works, many viewpoints that could be used to explain the abnormal shrinking of sea ice in the past period are now insufficient to explain the current change of sea ice. Lindsay *et al*.[27] questioned that 'if we were experiencing a completely new phase of climate change now'? If, before 1990s, sea ice presented a linearly decreasing trend, then as the positive and negative feedback effects between sea ice and climate system continue to superposing, change of sea ice might have transferred to the state of index decrease.

As pointed out in the above section, in order to explore factors causing rapid sea ice shrinking in the Arctic over the past 30 years, the interaction between the complex physical process and external environment that cause change of sea ice should be make clear first. Factors like solar shortwave radiation transfer in atmosphere-sea ice-ocean system, distributions and changes of vapor, CO_2, ozone in the Arctic atmosphere, radiation absorption of various wave bands by clouds of different types, cloud surface radiation feedback[48], vapor feedback[49] and other important feedback effects that together formed the climate system are all need to be understood. When solar radiation penetrates sea ice or directly enters through the sea-atmosphere interface into the ocean, solar radiation albedo on atmosphere underlying surface may be influenced by the folloeings: sea ice diversity, ice-snow surface state, brine inclusion and air bubbles, various crystal structures, impurity content and other elements. Ice and snow albedo feedback is therefore formed. Besides, the factors mentioned in the above section such as water exchange between the Arctic Ocean and the Atlantic Ocean, Pacific inflow effect, feedback of hermohaline circulation and the temperature and salt field at the high latitude, all these factors may produce major impacts on the polar region and global climate change. Based on the understanding of the physical process of the rapid change of sea ice, it could be realized to improve the parameterization design and treatment of the physical process of atmospheric module, ocean module and ice module in the global climate model, and thereby improve the reliability of prediction of the trend of the change of sea ice in the future.

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