

# The research of Polar sea ice and its role in climate change

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**Abstract** As an important part of global climate system, the Polar sea ice is effecting on global climate changes through ocean surface radiation balance, mass balance, energy balance as well as the circulating of sea water temperature and salinity. Sea ice research has a centuries-old history. The many correlative sea ice projects were established through the extensive international cooperation during the period from the primary research of intensity and the bearing capacity of sea ice to the development of sea/ice/air coupled model. Based on these researches, the sea ice variety was combined with the global climate change. All research about sea ice includes the physical properties and processes of sea ice and its snow cover, the ecosystem of sea ice regions, sea ice and upper snow albedo, mass balance of sea ice regions, sea ice and climate coupled model. The simulation suggests that the both of the area and volume of polar sea ice would be reduced in next century. With the developing of the sea ice research, more scientific issues are mentioned. Such as the interaction between sea ice and the other factors of global climate system, the seasonal and regional distribution of polar sea ice thickness, polar sea ice boundary and area variety trends, the growth and melt as well as their influencing factors, the role of the polynya and the sea/air interactions. We should give the best solutions to all of the issues in future sea ice studying.

**Key words** Polar Regions, sea ice, history, actuality, Climate change

## 1 Introduction

Polar sea ice, as the insulating effect regions between sea and air, it distinguish from ice free water area by its ice-albedo feedback, adiabatic effect and other thermodynamics effects in air sea interaction process. Sea ice plays an important role in the state and variability of regional and global climate through thermodynamic and dynamic processes, and feedback mechanisms operating over a hierarchy of space and time scales (Walsh 1983, Johannessen *et al.* 1992, Wadhams 1994, 1995).

Sea ice study is more important in global change research. More and more researches on sea ice are included in international projects (Table 1). As a factor of climate systems, sea ice was discussed on many aspects by global researchers, from the Institute of Low Tem-

perature Science (ILTS) in 1950 related to ice properties, dynamics and remote sensing to Antarctic Sea ice Process and Climate project (ASPeCt) in 2000 that focused on the contribution of air/ice/sea coupling model to climate systems. Sea ice study mainly have undergone the following stages: the primary researches on sea ice intensity, bearing capacity, sea ice characteristics, dynamic process; the research on sea ice extent change, thickness distribution, mass balance; then the researches on ice dynamics and thermodynamics process, air-sea interaction, global sea ice coupling model. Based on the systematic polar ice theory, these research projects with the related work provide the sufficient evidence of sea ice role in climate. Beside the research on sea ice effects, also we should focus on its study history and present work for further knowledge about its connections with other factors of climate system. With the studying on polar sea ice, we are faced with more and more scientific questions. The presentation of the questions would be the based of its answers.

## 2 The past and present of polar sea ice research

As a significant factor of climate systems, sea ice was primarily discussed in 1550s. During the period between roughly 1550 and 1616, Russian traders, starting at the White Sea and portaging the Yamal Peninsula, had reached the Arctic sea ice for geographic reasons. In 1900s, William Scoresby, an experienced captain in England with excellent record, he understood the ice and the general environment conditions of the Arctic. He completed a paper "On the Greenland or Polar Ice" and later a book "An Account of the Arctic Regions". His understanding of sea ice and the Arctic environment qualifies him for the title of the first sea ice scientist. Scoresby's views, that there was no open ocean beyond the ice barrier and that even if ice conditions proved to be light one year, there was no guarantee that conditions would generally be favorable, were prophetic and are still considered to be true today. However, he did not prove to be a prophet in his own time. Since then, a series Arctic expeditions were taken on by John Ross (1818-1829-1833) and William Edward Parry (1819-1820, 1921-1922, 1824-1825, 1827).

In 1773, James Cook with his comrades made them way through Antarctic Circle and circumnavigated Antarctic. They encountered large area of sea ice and speculated that there has continent to the south. During 1800s, with the increased Antarctic exploration, the more considerations were paid to whaling and hunting up of seals, meanwhile, people know more about sea ice. The collection of much sea ice information data ultimately cumulated in the publication of good maps of the general sea ice distribution in both the western Arctic and Antarctic by the British Admiralty in 1866 and 1875 and of the eastern Arctic by the Russians in 1884. It should also be mentioned that in the 1870s papers began to appear in the scientific literature that discussed the properties of sea ice as well as the variations in the ice conditions (Tomlinson 1871; Pettersson 1883). In addition, papers describing experiments on both the freezing and melting of sea water as well as the properties of the resulting ice were published (Buchanan 1874, 1887, 1911). Payer and Weyprecht led an exploratory trip to Svalbard and then in 1872-74 organized the Austro-Hungarian Arctic Expedition. Although this expedition had more than its share of disaster, it led to very important results that there is absolutely no perpetual ice, if we have in mind one and the same piece of ice. Such ice cannot exist, just as there are no perpetual trees, and there are no people

Table 1 Some of the larger sea ice studies or sea ice related projects that were funded from 1950

Project	Dates	General subject
Institute of Low Temperature Science	1950-present	Ice properties, dynamics and remote sensing
Joint Services Sea Ice Physics Program	1954-1960	Strength and bearing capacity
Australian National Antarctic Research Expedition	1960-present	Mass balance, sea ice and climate, thermodynamics
Arctic SEV Program	1968-1972	Pressure ridge characteristics
(AIDJEX) Arctic Ice Dynamics Joint Experiment	1971-1976	Ice dynamics
Arctic Buoy Program (ABP)	1975-present	Ice dynamics
International Programme for Antarctic Buoys (IPAB)	1994-present	Ice motion, pressure and temperature
Passive microwave satellites	1973-76, 1978-present	Sea ice extent and type
Synthetic Aperture Radar (SAR) satellites	1991-present	Radar mapping of the ice cover
LEADEX	1991-1992	New ice properties in leads
U. S. /Russian Ice Station Weddell	1992	Ice dynamic and properties
Arctic Ocean Section (AOS-94)	1994	MY ice properties and thickness
Antarctic Sea Ice Processes and Climate (ASPECT)	1998-present	Sea ice processes and climate effects
Antarctic Ice Thickness Project (AN-SITP)	1990-present	Antarctic ice thickness seasonal and regional variability
Surface Heat Budget of the Arctic Ocean (SHEBA)	1996-present	Air-ice-sea interactions and their thermodynamics coupling
Arctic Climate System Study (ACSYS)	1998-present	Arctic sea ice boundary and its variability, heat flux
Climate and Cryosphere (CLIC)	2000-present	Cryosphere and its interactions, polar sea ice physical properties
International Antarctic Zone program (IANZone)	1992-present	Simulation Antarctic sea ice extent variability
Antarctic pack ice seals (APIS)	1992-present	Ecological interactions with prey and the environment
Study of Environment Arctic Change (SEARCH)	2001-present	Arctic environment change, in particular the recent decade

thousands of years old. Stefan (1891) examined the classic freezing problem that is now known under his name using polar ice as a model. His interest in this problem was sparked by Weyprecht's earlier field observation that ice thickness was a function of the accumulated number of freezing degree-days.

Sea ice research in the Twentieth Century can be divided into two periods separated by the Second World War with the pre-war period being described as somewhat limited and leisurely and the post-war period as more frequent and frenetic. The scientific data collected during the drift of the *Fram* (Nansen 1900-1906) vindicated Nansen's view of the general

circulation of the ice, proved that the Arctic Ocean was both deep and contained several sub-basins, served as the basis for the simple ice drift model that still proves useful today. With the expanding economy, not only had sea ice entered into the world of geophysics, it also entered the world of engineering. In the summer of 1901, Makarov carried out sea ice studies using the *Yemak* for the purpose of improving ice breaker design. This appears to be the first sea ice program that was both specifically engineering oriented and not tied to a trip of exploration. The organization of first international sea research program – Arctic and Antarctic Research Institute (AARI), which indicated that sea ice research entering the international cooperation time period. In 1921, Drygalski published descriptions of Antarctic sea ice conditions based on his expedition of 1901-1904. And also this year, Wordie published his observations on the nature history of pack ice as observed in the Weddell Sea on the Shackleton Expedition of 1914-1917 (Wordie 1921). Followed by Wright and Priestley in 1922, they published the results under the title *Glaciology*. This book is a classic that although not primarily about sea ice, contains a number of interesting observations relative to this material. It provides a good description of the geometric selection process occurring during crystal growth, the first observation on platelet ice. In 1937, the first of the Russian North Pole research station SP-1 was established on the drifting pack ice and operated successfully for significant periods of time (months to even year) for ice condition studying.

During 1930-1950, sea ice researches entering the new period with the more aspects to be involved, mainly included sea ice structure and characteristic, sea ice mechanical property, sea ice thermodynamic and electromagnetics characteristics, sea ice growing and melting processes, sea ice morphologic and its thickness distributions, sea ice kinematics and dynamics, the ocean wave effects both of besides the floes and between the floes. Sea/ice interaction. More and further deepgoing research works have been done by sea ice researchers during 1979-1999, mainly included sea ice characteristic studying (Allison 1989a, Allison and Worby 1994, Eicken *et al.* 1994, Gow *et al.* 1982, 1987, Jeffries *et al.* 1993, Kawamura *et al.* 1997, Lange and Eicken 1991b); sea ice drift and deformation (Ackley 1981, Allison 1989b, Geiger 1998, Worby *et al.* 1998, Agnew and Hirose 1997); polynya (Adolphs and Wendler 1995, Bromwich and Kurtz 1984, Bromwich *et al.* 1998, Gordon and Comiso 1988); mass balance (Eicken *et al.* 1994, Ackley 1979); sea ice extent changes (Masson and Comiso 1999, Enomoto and Ohmura 1990, Harangozo 1997, Hurrell and Van 1994); snow on sea ice (Eicken *et al.* 1994, Bromwich and Kurtz 1984, Eicken *et al.* 1995, Allison *et al.* 1993, Garrity 1992); sea ice and global change (Bromwich and Kurtz 1984, Sissala *et al.* 1972, Budd 1975, Kukla and Garvin 1981, Fletcher *et al.* 1982, Zwally *et al.* 1983a, Zwally *et al.* 1983b); sea ice model and other researches (Gray and Morland 1994, Hibler 1979, Holland *et al.* 1997, Hunke and Dukowicz 1997, Smith and Nelson 1985, Arrigo and McClain 1994).

Early studies, one-dimensional in space, focused on sea ice thermodynamics, introducing vertical heat transport in the floes, but these models were only run in the Arctic (Maykut and Untersteiner 1971, Semtner 1976). Parkinson and Washington (1979) extended similar formulations for physics of sea ice to the whole Arctic and Antarctic regions, with interactive air/sea ice fluxes computations and simple ice transport (Parkinson and Washington 1979). Then Hibler (1979) introduced the widely used viscous-plastic rheology and managed to improve the modeling of sea ice circulation in the Central Arctic. A global model including relatively sophisticated sea ice thermodynamics, a viscous-plastic rheology for dynamics and a mixed layer was developed by Fichefet and Marchesiello (1997). They came to the conclusion that in the Antarctic, taking snow ice formation into account is in-

portant, whereas it is just the contrary in the Arctic, when the thermal inertia of the ice floes is negligible. Through the use of a coupled ocean mixed layer-sea ice model, a study by Holland *et al.* (1997) demonstrated that the ice thickness distribution plays a crucial role in determining the exchange of both heat and fresh water between the ocean and the atmosphere in the Arctic. The influence of the Southern Ocean sea ice in a global ocean model was investigated by Stössel *et al.* (1999) later, who found that the rate of Antarctic bottom water formation strongly depends on sea ice processes (particularly brine rejection). Salas (2002) described and validated the GELATO sea ice model (Global Experimental Leads and sea ice for Atmosphere and Ocean). GELATO is a dynamic and thermodynamic sea ice model with the consideration of several sea ice categories, accounts heat conduction and storage in the slab, snow layer aging and the formation of snow ice. Goosse *et al.* (2004) investigated the causes of sea-ice volume variations using two different sea-ice-ocean models. They suggested that the anomalous exchanges of sea ice, air and water between the North Atlantic and the Arctic play a large role in explaining ice volume variations. The time evolution of the ice volume appears well correlated with the low frequency variations of the North Atlantic Oscillation (NAO). Gildor *et al.* (2002) had been modeling the switch mechanism of sea ice during glacial-interglacial cycles. The further study involved sea ice physical mechanism and its effect on the atmospheric CO<sub>2</sub>. Sea ice, formed by freezing of seawater, covers much of the polar oceans. It exhibits considerable seasonal, regional, and inter-annual variability in both hemispheres. Seasonally, sea-ice extent in the Southern Hemisphere varies by a factor of 5, from a minimum of 3-4 million km<sup>2</sup> in February to a maximum of 17-20 million km<sup>2</sup> in September (Goosen *et al.* 1992). Whereas Northern Hemisphere ice extent varies by only a factor of 2, from a minimum of 7-9 million km<sup>2</sup> in September to a maximum of 14-16 million km<sup>2</sup> in March (Parkinson *et al.* 1999). Antarctic sea ice extent shows the increase trend during 1978-1996, while the Arctic sea ice cover is decreasing with the decrease rate of 2.9% every decade (Cavalieri *et al.* 1997). Wu *et al.* (1998, 1999a) used coupled sea ice model with the consideration of future greenhouse effects, human active CO<sub>2</sub> emission that led to global warming, suggested that the Antarctic sea ice cover would be decreased in the next century, the seasonal minimum and the maximum extent would be decreased 2° and 1.8° in latitude respectively. Southern Hemisphere surface temperature and global surface temperature in average would be rise 2.2°C and 2.7°C respectively. Vinnikov *et al.* (1999) used sea ice coupled model and suggested that the Arctic sea ice extent showed the decrease trend in past 30 years. This finding is in agreement with the observations. They took into account of the increment of human active CO<sub>2</sub> and aerosol emissions which results in greenhouse effect, and suggested that the Arctic sea ice cover will be decreased by 20% in average up to 2050. Keith *et al.* (2003) used coupled climate model of Geophysical Fluid Dynamics Laboratory (GFDL) (IPCC 2001) and suggested that due to the global warming, the substantial weakening of the North Atlantic overturning circulation and a large reduction in the volume of the Arctic sea ice is to occur in the 21st century (Keith *et al.* 2003; Houghton *et al.* 2001). In recent years, the researches of polar sea ice in China mainly concentrated in following subjects: sea ice and climate (Bian *et al.* 1996, 1997; Chen *et al.* 2002; Li 1996; Liu *et al.* 2003; Xie *et al.* 1994a, 1994b; Zhao *et al.* 2001); the ecology environment of sea ice cover areas (He *et al.* 1998; Wang and Dieckman 1993); sea ice spatial and temporal variability (Wang and Yang 2002; Xie *et al.* 1994c, 1998; Zhao *et al.* 2000); sea ice characteristics (Kang *et al.* 2002; Li and Kang 2001); sea ice albedo (Tang *et al.* 2003); sea ice in-situ works

(Kang *et al.* 2003, Sun *et al.* 2002, Tang *et al.* 2004); interactions between sea ice of the Arctic and Antarctic (Xie *et al.* 1994b) and sea ice effects to water mass (Dong and Liang 1993).

### 3 The role of sea ice in climate

The role of sea ice in the global climate system has been recognised and included as a study component of major international weather and climate programs such as the Polar Sub-Programme of the Global Atmospheric Research Programme and the World Climate Research Programme. Sea ice plays an important role in the state and variability of regional and global climate (Walsh 1983). This role is largely attributed to the ice-albedo feedback, the insulating effect of sea ice, and its influence on the global thermohaline circulation through salt rejection during ice growth and surface freshening during ice melt. The presence of sea ice is affecting ocean surface radiation balance, energy balance and mass balance.

**The presence of sea ice through its higher albedo has changed the polar ocean surface radiation balance** Sea ice cover can change the ocean surface albedo variability. Due to the effect of ocean surface solar radiation absorption, the presences of sea ice broken down the ocean surface radiation balance of ice cover areas. Sea ice cover area has lower surface temperature in winter than open water due to its albedo feedback. In general, ocean surface albedo is 10-15%, however, the albedo of sea ice with new snow cover can rise to 90%.

**Polar ocean surface energy balance has been changed as the result of sea ice insulating effect** With its high albedo (the fraction of incident solar radiation that is reflected by the surface) the ice and its snow cover also reduces the amount of incoming solar radiation absorbed at the ocean surface by reflecting much of it back to space. The direct interactions between air and sea are energy exchanging and finally come to its balance. In summer, this balance is controlled by shortwave radiation and the surface albedo variability. It acts as an insulating layer between the ocean and the atmosphere, as surface turbulent heat flux exchanges affecting sea ice can be as much as two orders of magnitude less intense than those concerning the neighbouring open water area subjected to the same atmospheric conditions. Also solar shortwave absorption by an ice cover is considerably less than that of open water, and where there is sea ice, the precipitation that should otherwise directly fall into the ocean is stored at the surface of the floes, hence the strong dependence of the marine surface heat and freshwater budgets on the ice fraction (Oberhuber 1993). In the Central Arctic, the summer melting of sea ice contributes to stratify (i.e., here stabilize) the water column, which inhibits heat exchanges between the upper and deeper ocean. This lack of deep convection prevents most of the region from being ice free during the summer. Around the Antarctic, in contrast, sea ice ablation is mainly due to the release of energy from the ocean as relatively warm water masses reach the surface (Oberhuber 1993). Experiments with sea ice models have shown that models including only sea ice thermodynamics are more sensitive to changes in the thermal forcing than those that include dynamics (Hibler 1984, L€enke *et al.* 2000, Rind 1997). The inclusion of sea ice dynamics is particularly important in the Southern Ocean (Pollard 1994).

**Sea ice may transform ocean mass balance** The ice acts as a physical barrier to the exchange of gases (such as oxygen, carbon dioxide and water vapour), and as an insulating blanket between the relatively warm ocean and colder atmosphere. In geophysics area, sea



ice thickness, concentration, and other characteristics are controlled by its variable dynamics and thermodynamics processes (drifting, deformation, freezing and melting) as well as the influence of the boundary layers of air and sea. So the consequences of these interactions would determine the ice cover conditions (sea ice drifting speed, concentration, thickness) and the variability of sea/air interaction and its response to climate change.

### **Sea ice may transform the thermohaline circulation of the Polar Regions**

During winter when the temperature falls below 0°C, never falls below -1.9°C, sea water would freeze to form sea ice. Sea ice crystal is relatively fresh water at the beginning of the ice formation with the most salt reject to ocean. Sea ice is considerably less salty than sea water, and salt rejected from the ice structure during its formation and growth increases the salinity and density of the underlying water. This may induce deep vertical convection that contributes to the upwelling of nutrients and to the overall thermohaline circulation (water movement driven by salinity and temperature gradients) of the ocean. Conversely, when the ice melts in spring it releases fresher water, forming a stable low salinity surface layer. Sea ice freezing and melting would influence the formation and intensification of sea thermohaline circulation as well as of deep sea water (Martinson and Iannuzzi 1998). This occurs through “keel stirring” and the processes of sea ice formation and melts which change the density of the upper ocean layers through brine rejection during freezing and deposition of fresh water during melting. These, coupled with heat exchange through leads, directly affect the mixing of the upper ocean layers and the fluxes of salt and freshwater into the ocean, and thus the buoyancy of the upper ocean layers.

**The role of Antarctic sea ice cover in South Ocean ecosystem.** The Antarctic sea ice zone is a habitat for many species of biota. Many algal communities reside within or under the ice, and algal blooms occur in the stable freshwater “lens” that forms as the ice edge retreats in the summer. Large quantities of krill feed on the phytoplankton that in some way depend on the sea ice, and in turn provide a major food source for larger animals such as whales, seals and penguins. The sea ice is also used as a breeding platform for some seals and penguins, and may provide a refuge from predators. The presence of Antarctic sea ice shows the most important roles in South Ocean halobios and energy transform. So the ecology of Antarctic sea ice became the important part of polar sea ice research (Legendre *et al.* 1992).

Sea ice is known to impact on ocean and atmosphere on a wide variety of timescales. On short timescales (days to weeks) sea ice fluctuations are of most importance regionally. On longer timescales sea ice can have a wider influence on the climate system overall, in particular through the important mechanism of ice-albedo feedback which models show will enable polar amplification of greenhouse gas-induced warming over the high latitudes in winter. And also the poleward amplification of global warming in observed surface air temperature (SAT) in both hemispheres (Gates *et al.* 1996, Flato and Boer 2001). However, climate change simulations in global coupled climate models typically show a marked hemispheric asymmetry, with more warming over the northern high latitudes than the southern (Kattenberg *et al.* 1996). This asymmetry might be ascribed to simplified treatments of sea ice and ocean processes.

## **4 Key scientific questions which must be answered to meet the polar sea ice research**

What are the broad-scale time-varying distributions of the ice and snow-cover thick-

ness ice composition and other physical characteristics in the polar sea ice zone?

More and more researches show that the Arctic sea ice thickness appear the large variability. Rothrock *et al.* (1999) suggested that sea ice mean draft reduced 1.3 m at end of summer during 1958-76 and 1990 in the Arctic abyssal areas and the primary evidence show this trend would continue (Rothrock *et al.* 1999). The retreat of Antarctic sea ice balanced 38% of the global warming (Rind *et al.* 1997). Because we are ignorant of Antarctic sea ice thickness distributions and its variability, take the consideration of mass balance and energy balance, we can not confirm the results about ice thickness variability. The presence of snow cover on sea ice influences the thermodynamic properties of ice and the seasonal growth and retreat rates (Maykut and Untersteiner 1971). The modeling results indicate that sea ice zone appear the large sensitivity in response the global change (Mitchell *et al.* 1990, Wu *et al.* 1999b). The snow cover would increase this sensitivity (Eicken 1994) and further would bring on the global cooling (Ledley 1991).

What are the dominant processes of ice formation, modification, decay and transport which influence and determine ice-thickness, composition and distribution?

The characteristic of sea ice thickness, structures and compositions influence air/ice/sea interactions. The refreezing flooded snow layer and melted snow can increase the ice thickness, however, the high ocean heat flux can reduce the ice thickness and the surface water salinity through the bottom melting. The research shows that frazil ice has a much large proportion in the South Ocean sea ice region than in the Arctic (50% in Antarctic, 10% in Arctic) (Gow 1987). The frazil ice and grease ice formation controlled by intensive dynamic process that led the formation of granule ice. Under this condition, its thickness rise to 40-60 cm to form the thin pancake ice. With this thickness, it can restrain and altering the primary condition and the further thicken mainly controlled by thermodynamic process that led to the formation of columnar ice. During the ice growth, ice deformation, rafting and ridging can induce the rafting of multi-layers of both granule ice and columnar ice. The observations show that atmospheric condition and tide can influence the dynamic conditions of ice formation and deformation. Due to the regional variability of snow fall, the proportions of snow ice show the seasonal and regional variability in the Antarctic. We need more data now to explain the mainly process of ice growth and decay.

What is the role of coastal polynyas in determining total ice production, heat, salt and biogeochemical fluxes, and water mass modification?

The polynyas development can be found in both the Arctic and Antarctic sea ice cover areas. Most of them are in the South Ocean. Weddell polynya is regarded as the free ice area which results from the upwelling sensitive heat of the deep ocean pycnocline. On the other hands, coastal polynyas are regarded as the result of latent heat. As the intensive heat exchange areas, it can rapidly bring up much ice in polynyas regions. The concentrated rejection of salts when sea ice growth can also induced regional water mass changes and the increase of the continental shelf water salinity. Ice free polynyas make the key roles in controlling biology and chemical flux of the Antarctic halobios system. And also the important roles of polynyas in air-sea gas flux and biogeochemical cycle, such as carbon transmission mechanism. Whereas, few relative research work has been done till now. There are no systematic observation data.

The other scientific questions include: what are the processes that control the ice-water interactions at the ice-edge, and what about their seasonal changes? We have no data about ice-water interactions at the ice-edge.



## 5 Summaries

In the future, polar sea ice would decay. This may contribute the global warming as the result of negative feedback of sea ice. Based on the former researches, both the field observations and the modeling are needed in the future study. The wide ranges international cooperation in polar sea ice research are also necessary. In particular sea ice research in China should join in more international programs on sea ice and climate. It must contribute our research in polar ice and global change.

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