

The role of the Arctic and Antarctic and their impact on global climate change: Further findings since the release of IPCC AR4, 2007

CHEN Liqi^{1,2*}

¹ Key Laboratory of Global Change and Marine Atmospheric Chemistry, State Oceanic Administration (SOA), Third Institute of Oceanography, Xiamen 361005, China;

² Chinese Arctic and Antarctic Administration, SOA, Beijing 100860, China

Received 25 March 2013; accepted 10 April 2013

Abstract Changes in the climate of the Arctic and of the Antarctic have been of great concern to the international scientific and social communities since the release in 2007 of the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4). Since then, many new findings have been reported from observations and research carried out in the Arctic and Antarctic during the fourth International Polar Year (IPY). There is evidence that global warming is inducing rapid changes in the Arctic and Antarctic, in both a quantitative and qualitative sense, and that these regional changes could be used as indicators of global climate change. Declining Arctic sea ice could affect winter snowfall across much of the Northern Hemisphere by bringing harsher winters. Projections suggest that summertime Arctic sea ice will disappear by 2037. By the 2070s, the Antarctic ozone hole will recover to the level of the early 1980s, following the ban on the production of Freon earlier this century. With the loss of the shielding effect of the ozone hole, Antarctic surface temperatures will increase, ice sheets in East Antarctica will begin to melt, and the Antarctic sea ice will retreat. Therefore, sea level rise will become an increasingly serious issue this century. As sea surface temperature rises, the Southern Ocean will become less effective as a sink for atmospheric CO₂ and the increase of surface CO₂ will be faster than that in the atmosphere. Increased surface CO₂ would lead to ocean acidification and affect ecological systems and food chains.

Keywords IPCC AR4, climate change, sea ice, ozone hole, CO₂, Arctic and Antarctic

Citation: Chen L Q. The role of the Arctic and Antarctic and their impact on global climate change: Further findings since the release of IPCC AR4, 2007. *Adv Polar Sci*, 2013, 24:79-85, doi: 10.3724/SP.J.1085.2013.00079

1 Introduction

In 2011, “Global Carbon Project” released a report on the global carbon emissions in 2010^[1]. The report stated that global carbon emission in 2010 was 10 pg C, the highest value ever, representing an increase of 5.9% compared with 2009, and the highest growth rate since 2003. The carbon emissions mainly come from fossil fuels, cement production, deforestation, and land use. About 50% of anthropogenic CO₂ is retained in the atmosphere and the rest is absorbed by the continents and oceans. This has caused the atmospheric CO₂ concentration to reach 389.6 ppm, a new

high since the Industrial Revolution or during glacial and interglacial periods with the highest value of 280 ppm. This report also brought forth a challenge during the 2011 United Nations Climatic Change Conference in Durban, South Africa, regarding climate change and the reduction and mitigation of carbon emissions.

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) recognized that human activities produce greenhouse gases, especially CO₂, which drive the rise in global temperature. Most extreme natural disasters that have happened recently on Earth could be attributed to global temperature increase. Therefore, climate change caused by greenhouse gas emissions has become a concern for society in general, but has also become an important subject for international scientific and

* Corresponding author (email: lqchen@soa.gov.cn)

political communities^[2-4]. The Nongovernmental International Panel on Climate Change (NIPCC) debates many aspects of the Fourth Report of the IPCC, which primarily concern the scientific uncertainties regarding climate change. These can be summarized as the belief that global warming is caused by natural driving forces rather than the artificial effect of greenhouse gas emissions^[5].

In 2009, at the United Nations Copenhagen Climate Change Conference, the climate change issue once again attracted the world's attention. The Copenhagen Diagnosis was published in 2009^[6] to ensure that the rapid changes in the Antarctic and Arctic, such as the continued increase of greenhouse gas concentrations in the atmosphere and the consistent rise of the global surface temperature; the accelerated melting of ice shelves and glaciers; the rapid retreat of the Arctic sea ice; and the rise of sea level became significant evidence with which to respond to the NIPCC's main questions. In addition, new evidence was obtained following the implementation of the Fourth International Polar Year (IPY) campaign during 2007–2008, which was intended to further the understanding of the role of the Arctic and Antarctic and their impact on global climate change. New findings have revealed the rapid changes and mechanisms in the Antarctic and Arctic regions, especially as indicators and driving forces of global climate change.

2 Climate change and the environment in the Antarctic

The Antarctic plays a vital role in the global climate system with very sensitive essential factors, including the world's greatest cold source with the Earth's lowest recorded surface temperature of -89.2°C at Vostok Station, East Antarctica. The Antarctic sea ice will cover an area of approximately $1.9 \times 10^7 \text{ km}^2$ in the winter and retreat in summer to 20% of the winter extent. The Antarctic is a fragile and sensitive area and is a critically important part of the Earth's climate system. The climate, physical and biological properties of the continent and the surrounding ocean are closely coupled to other parts of the global environment through ocean and atmosphere circulation and CO_2 exchange. Antarctica contains 90% of the world's ice and 70% of the world's fresh water, which, were it to melt, is sufficient to raise sea level by 63 m. It also holds high-resolution records of past climate change and sensitive biological indicators of contemporary change. The Antarctic "ozone hole" was one of the most significant scientific discoveries of the last century and it has had a profound impact on the Antarctic environment. The Southern Ocean is a giant carbon pool, which can sequester more than 30% of the CO_2 in the world's oceans. In recent years, large additions of CO_2 from the air have changed the carbonate equilibrium significantly in the Southern Ocean. Owing to global warming over the last 50 years, it has increased on average by 3°C , but in the western coastal region, it has increased by 5°C , which has caused the breakup of ice

shelves on the Antarctic peninsula. The Surrounding Antarctica Circulation (SAC) is one of the world's biggest circulations and is connected with the world thermohaline circulation called the Great Ocean Conveyor Belt. The SAC prevents southerly heat transport, but in a different way to the heat exchange mechanism from low to high latitudes in the Northern Hemisphere.

Leading more than 100 international scientists who engaged in Antarctic research, John Turner from the British Antarctic Survey (BAS) published a report of Antarctic Climate Change and the Environment (ACCE) in 2009^[7]. The key findings of the report related to global climate can be included as the followings:

(1) The ozone hole shields the bulk of the Antarctic from the effects of global warming;

(2) The Southern Ocean has been warming for the past 50 years and the ecosystem has been affected, especially on the western side of the Antarctic Peninsula with warming water and declining sea ice;

(3) Sea ice has been increasing by around 1% per decade for the last 30 years and can be attributed to the effect of the ozone hole;

(4) Paleoclimate studies help to project the scale of the impact of Antarctic change on the global climate;

(5) Antarctic warming is expected to increase by around 3°C following a doubling of greenhouse gas concentrations of 280 ppm;

(6) A major contribution to sea level rise this century will be from the West Antarctic glaciers. Stronger westerly winds lead to surface oceanic water being mixed with deeper water rich in CO_2 , which saturates the carbon reservoir of the surface water and thus limits its ability to absorb CO_2 from the atmosphere. An increase in the ocean's CO_2 concentration makes the ocean more acidic. These changes seem to be linked to the increase in wind strength driven by the more positive Southern Annular Mode (SAM).

2.1 The ozone hole shielding the bulk of the Antarctic from effects of global warming

Since 1985 when Farman et al.^[8] first reported the existence of the ozone hole over Antarctica, an area below 200 DU of about $2 \times 10^7 \text{ km}^2$ has been maintained continuously over Antarctica from late winter and early spring. Based on the report from NASA^[9], in 2010 the largest area of the ozone hole over Antarctica was $2.2 \times 10^7 \text{ km}^2$, with the lowest ozone concentration of 116 DU at -61°C . However, historically, the largest area of the ozone hole reached $2.6 \times 10^7 \text{ km}^2$ in 2006, and the lowest O_3 concentration was 92 DU in 1994, which suggests that the ozone hole has been reducing gradually.

Turner et al.^[7] highlights the profound impact that the ozone hole has had on the Antarctic environment during the last 30 years, shielding the continent from many of the effects of global warming. The ozone hole occurs in the Austral spring. During this season each year, the stratospheric ozone would cool the Antarctic stratosphere, increasing the

strength of the polar vortex and the atmospheric circulation around Antarctica, such that wind speed over the Southern Ocean in autumn would increase by 15%. Strong winds isolate Antarctica from global warming and result in a decrease of surface temperature and an increase in snowfall.

2.2 Effects of ozone hole on the Antarctic sea ice increase

Based on a new analysis of passive microwave satellite data, Turner et al.^[10] demonstrated that since the late 1970s, the annual-mean extent of the Antarctic sea ice has increased at a statistically significant rate of 0.97% per decade. They suggest that the trend towards stronger cyclonic circulation is mainly a result of stratospheric ozone depletion, which has strengthened autumn wind speeds around the continent, deepening the Amundsen Sea Low through flow separation around the high coastal orography. This would be a significant force in causing the extent of the sea ice to increase in the Antarctic seas, whereas warming in the Arctic Ocean has driven a marked retreat of sea ice over recent decades.

The model also suggests that the ozone hole would recover to the level of 1980s by about 2070s, following the ban on Freon production earlier this century. By the 2070s, the shielding effect of the ozone hole to global warming will be lost and the surface temperature over the Antarctic ice sheets will increase with significant melting of the snow and ice. Therefore, the problem is whether the tipping point of the 2070s that would cause significant changes to the giant Antarctic ice sheets can be appeared.

2.3 The melting of the Antarctic Peninsula ice shelves and sea level rise

There has been significant thinning of the ice sheets in West Antarctica, especially in the Antarctic Peninsula. The losses of ice shelves along the Antarctic Peninsula, such as the Larsen B Ice Shelf, have occurred quickly. One reason for this could also be attributed to the ozone hole. The ozone hole can enhance the westerly winds across the Antarctic Peninsula, resulting in regional warming and the melting of the ice shelves. Ninety percent of glaciers across the Antarctic Peninsula have retreated over recent decades. Models project that by the end of this century, sea level will rise by 1.4 m, about 2–9 times the value of 18–59 cm^[2] estimated by the IPCC AR4, owing to the melting of the Antarctic Peninsula ice shelves. This will be a serious threat to about 0.14 billion people who live in those regions of the world that lie within 1 m above sea level.

2.4 The Southern Ocean warming and impact on the hydrological cycle and extent of sea ice

In 2010, Liu and Curry^[11] published in the Proceedings of the National Academy of Science (PNAS) a paper on the accelerated warming of the Southern Ocean and its impact on the hydrological cycle and sea ice. Based on empirical orthogonal function (EOF) analyses performed on the

area-weighted annual-mean observed SST south of 40°S for 1950–1999, they provided an explanation for the apparent paradox of increasing Antarctic sea ice in a warming global climate scenario. The first EOF mode represents variations in solar and volcanic forcing, and thus simulates natural internal variability in response to natural external forcing in the second half of the 20th century. That means that currently, as the atmosphere warms, the hydrological cycle accelerates and there is more precipitation in the Southern Ocean surrounding Antarctica. This increased precipitation, mostly in the form of snow, stabilizes the upper ocean and insulates it from the ocean heat below. This insulating effect reduces the amount of melting occurring below the sea ice. In addition, snow has a tendency to reflect atmospheric heat away from the sea ice, which reduces melting from above. The second EOF mode represents the anthropogenic driving force in the early 21st century. Increased warming of the atmosphere is expected to heat the upper ocean, which will increase the melting of the sea ice from below. Furthermore, increased warming will also result in a reduced snowfall and increased amounts of rain. Because rain does not reflect heat the way snow does, this will enhance the melting of the Antarctic sea ice. One would expect that when the switch is initiated in the Antarctic, the extent of the sea ice would begin to decline, as has occurred in the Arctic.

3 Climatic change and the environment in the Arctic

In 2005, following 10 years' research, Corell et al.^[12] published a report titled the Arctic Climate Impact Assessment. The report proposed that a rapid change has appeared in the Arctic climate system, and that the significant environmental factors are:

- (1) A cold source with lowest temperatures of -70°C in the Arctic as one of the heat sinks of the Earth;
- (2) The Greenland glacier comprises 9% of the global glaciers and the sea level will rise by 7 m when it melts completely;
- (3) The Arctic Ocean is a potential carbon pool; although comprising just 3% of the world's ocean area, it sequesters the atmospheric CO_2 occupied by 10% of the world's oceans;
- (4) The Arctic surface temperature has increased, on average, by 2°C during the last 30 years;
- (5) Sea ice extent in summer in the Arctic has diminished by 40%, and over the past 20 years, the average thickness has reduced from 3 m to 1.5 m.

3.1 Sea ice retreat projection and potential climate change effect

The Arctic is changing faster than anticipated in the IPCC AR4^[2]. On 26 August 2012, Arctic sea ice reached a new milestone; extreme summer minimum sea ice coverage was 4.1 M km^2 , according to the National Snow and Ice Data Center (NSIDC) (<http://nsidc.org/arcticseaicenews/>)^[13].

Based on a pattern study and by using the September 2007/2008 observed extent of the sea ice as a starting point, Wang and Overland^[14] predicted the occurrence of a nearly sea-ice-free Arctic by September 2037. The rapid and continuous melting of the Arctic sea ice will greatly affect air-sea exchange processes, principally through the high absorption of solar radiation by the open ocean, rather than its reflection because of the high albedo of sea ice. The higher potential heat content in the open ocean will delay the recovery of sea ice in late autumn and early winter, which will change the atmospheric circulation by affecting the hydrological cycle and the distribution of precipitation in the north hemisphere, which is described in more detail in the following section.

3.2 Extreme cold winter events over the Northern Hemisphere related to melting of Arctic Ocean sea ice

Petoukhov et al.^[15] published a paper in the *Journal of Geophysical Research* in 2010. They recognized that the recent overall Northern Hemisphere warming would be accompanied by several severe northern continental winters, such as the extremely cold winter of 2005–2006 in Europe, which could be linked to the reduction of the Barents-Kara (BK) sea ice. Using the ECHAM5 general circulation model, Petoukhov et al. demonstrated that lower tropospheric heating over the BK seas in the eastern Arctic caused by the reduction of sea ice might result in a strong anticyclonic anomaly over the Polar Ocean and anomalous easterly advection over northern continents. This causes a continental-scale winter cooling by as much as -1.5°C , with more than three times the increased probability of cold winter extremes over large areas, including Europe. They suggested that an anomalous decrease of sea ice concentration during winter in the BK seas could bring about extreme cold events such as the winter of 2005–2006, and they recognized that several recent severe winters did not conflict with the picture of global warming, but actually supported it.

On 27 April 2012, Liu et al.^[16] presented a paper in *PNAS* and proposed that in recent decades the Arctic sea ice reduction in summer would be a major reason for increased snowfall during winter over the Northern Hemisphere. Using data synthesizing and modeling, Liu et al. found that the large-scale reduction of Arctic sea ice during summer resulted in the delay of the sea ice recovery in autumn and winter, which causes a variation of atmospheric circulation in winter. However, this variation of the atmospheric circulation is different from the Arctic Oscillation (AO), weakening the westerly jet stream in the middle and high latitudes of the Northern Hemisphere, and increasing the amplitude of its meridional oscillation. This circulation variation will increase the frequency of blocking in the middle and high latitudes of the Northern Hemisphere, and enhance the frequency of invasion of cold air from the Arctic to most continents of the Northern Hemisphere, produc-

ing lower temperatures. At the same time, global warming will lead to warmer air, which is able to hold more water vapor. These two reasons will cause events such as the recent exceptional snows with low temperature weather experienced in most areas of the eastern Asia, Europe, and North America. Based on Liu et al.'s research, if the summer Arctic sea ice continues to diminish, then the Northern Hemisphere could expect to see more frequent severely cold weather, especially with heavy snow^[16].

4 Variability and vulnerability of carbon pools in the Arctic and Southern Oceans

4.1 Variations of the carbon pool and decrease of potential CO₂ uptake in the Arctic Ocean

The Arctic Ocean has an area of about $1.35 \times 10^7 \text{ km}^2$ and comprises about 3% of the world's ocean surface. The Arctic Ocean has great potential for taking up atmospheric CO₂ owing to the high biological production in the large ocean margin areas and the low temperature. Bates et al.^[17] synthesized historical surveyed data and suggested that the Arctic Ocean, although constituting only 3% of the world's ocean surface area and being mostly ice-covered, accounts for 5% to 14% of the total oceanic CO₂ uptake. However, this value is highly uncertain owing to small number of observations relative to a larger scale of the central Arctic Ocean and to the rapid changes in climate. Using a carbon flux and mixing model with *in situ* high-resolution data from the survey in the Canada Basin during the third Chinese National Arctic Research Expedition (3rd CHINARE-Arctic), Cai et al.^[18] reported a significant CO₂ increase in the surface water relative to earlier observations. They recognized that the rapid CO₂ invasion from the atmosphere and the low biological CO₂ drawdown are the main causes for the higher CO₂ in the surface water of the Canada Basin. This situation also acts as a barrier to further CO₂ invasion and they predicted that the Arctic Ocean basins would not become a large atmospheric CO₂ sink under ice-free conditions.

The decreased capacity of CO₂ uptake in the Canada Basin can be evidenced from a comparison of four CHINAREs-Arctic (the 1st to 4th CHINARE-Arctic). China initiated the first CHINARE-Arctic from July to September in 1999^[19], the second in 2003, the third in 2008, and the fourth in 2010. The R/V *XUE LONG* icebreaker was the Chinese polar icebreaker used to carry out all four voyages. The most northerly latitude reached by the first expedition was 75°N , the second reached 80°N , the third reached 85°N , and the final expedition reached 88°N , implying that during each summer, the sea ice retreated at a much faster rate of $\sim 1^{\circ}$ per year. Table 1 lists the decadal variations of carbon sinking in the western Arctic Ocean from the four surveys of CHINARE-Arctic (negative numbers in Table 1 express CO₂ uptake by the seawater). A strong CO₂ sink can be found in the Chucki Sea by a pri-

mary control mechanism of a biological carbon pump process^[20] owing to the high productivity in the marginal sea with the support of water rich in nutrients continuously inflowing from the Bering Sea. However, in the Canada Basin with a shallow depth and strong stratification, there appeared a relatively quick re-equilibration with the atmosphere. The rapid increase in surface $p\text{CO}_2$ slows any further CO_2 uptake by decreasing the air-sea $p\text{CO}_2$ gradient, the driving force for gas exchange. Table 1 shows the CO_2 uptake capacities in the Canada Basin, which exhibit a continuously weakening trend: $14.0 \text{ mmol C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in 2003, $10.4 \text{ mmol C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in 2008, and $7.15 \text{ mmol C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in 2010, decreasing by a rate of about $1.0 \text{ mmol C}\cdot\text{m}^{-2}$ per year.

Table 1 Decadal variations of carbon sinking in the western Arctic Ocean

Year	Chucki Sea/ ($\text{mmol C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)	Canada Basin/ ($\text{mmol C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)
1999	-18.9 ± 6.8	No data
2003	-18.2 ± 7.0	-14.0 ± 2.7
2008	-16.5 ± 4.4	-10.4 ± 1.6
2010	-26.8 ± 9.2	-7.2 ± 2.8

4.2 Annual variations and vulnerability of carbon in the South Ocean

The Southern Ocean has an area of about $3.8 \times 10^7 \text{ km}^2$ and represents about 10% of the world's ocean surface. However, it has a potential carbon pool to absorb atmospheric CO_2 of about 25%–30% of the world ocean's carbon uptake capacity. Turner et al.'s report^[7] indicated that at latitudes poleward of 40°S , CO_2 in the ocean increased faster than it did in the atmosphere, suggesting that the ocean becomes less effective as a sink for atmospheric CO_2 . The stronger westerly winds lead to surface oceanic water being mixed with deeper water rich in CO_2 , which saturates the carbon reservoir of the surface water and thus limits its ability to absorb CO_2 from the atmosphere.

To estimate the monthly air-sea CO_2 flux in the southern Atlantic and Indian Oceans, we use remotely sensed data and *in situ* parameters of $p\text{CO}_2$ in the sea water and atmosphere, Chl-*a*, and SST measured underway along cruise tracks between Zhongshan Station in East Antarctica and Great Wall Station on the Antarctic Peninsula. These data were obtained in December 1999, January 2000, December 2004, and January 2005 during the sixteenth and twenty-first Chinese National Antarctic Research Expeditions (the 16th and 21th CHINAREs) respectively. Empirical relationships were established between surface water $p\text{CO}_2$, Chl-*a*, and SST, and applied to datasets of remotely sensed Chl-*a* and SST to estimate the monthly air-sea carbon flux and uptake of atmospheric CO_2 in the southern Atlantic and Indian Oceans. The results show significant spatial and temporal variability of carbon flux in the southern Atlantic and Indian Oceans. The monthly uptake of at-

mospheric CO_2 in the region from 50°S to the ice edge between 60°W and 80°E are 3.55 Tg C , 5.73 Tg C in December 1999 and January 2000, and 3.61 Tg C , 5.25 Tg C in December 2004 and January 2005, respectively.

Table 2 lists the monthly and annual variations of air-sea CO_2 fluxes and the related parameters in the Southern Ocean^[21]. The monthly variations of air-sea CO_2 fluxes in ice zones show a remarkable increase in the same season from December to January in 1999/2000 or 2004/2005. This can be attributed to the biological pump because of the higher values of Chl-*a* in January than in December. However, the yearly variations of air-sea CO_2 fluxes present a significant decrease in the capacity to absorb CO_2 in January 2005 compared with 2000 with an increase of 0.11°C (Table 3), suggesting that a major driving force for yearly changes would derive from the physical pump relative to temperature. This also means that CO_2 uptake capacity will decrease when surface water temperature increases in the Southern Ocean.

Table 2 Monthly and annual variations of air-sea CO_2 fluxes and related parameters in the Southern Ocean

Date (YYYY-MM)	Chl- <i>a</i> / $\text{mg}\cdot\text{m}^{-3}$	Wind speed/ $\text{m}\cdot\text{s}^{-1}$	Sea surface temperature/ $^\circ\text{C}$	Fluxes/ ($\text{mmol C}\cdot\text{m}^{-2}\cdot\text{m}^{-1}$)
1999-12	0.387	5.956	0.951	-84.237
2000-01	0.42	6.092	1.439	-132.639
2004-12	0.367	5.756	0.917	-96.583
2005-01	0.4	5.653	1.548	-115.601

Table 3 Relationships between air-sea CO_2 flux and temperature

Date (YYYY-MM)	Sea surface temperature/ $^\circ\text{C}$	Fluxes/ ($\text{mmol C}\cdot\text{m}^{-2}\cdot\text{m}^{-1}$)
2004-12—1999-12	-0.03	-12.35
2005-01—2000-01	0.11	17.04

In 2012, Bednaršek et al.^[22] reported in Nature Geoscience and recognized an extensive dissolution of live pteropods in the Southern Ocean. They highlighted that in the upper layers of the Southern Ocean, aragonite—a metastable form of calcium carbonate with rapid dissolution kinetics—might become undersaturated by 2050. Aragonite undersaturation is likely to affect aragonite-shelled organisms, which can dominate surface water communities in the polar regions. Using a scanning electron microscope to compare the shell structure with samples from aragonite-supersaturated regions from elsewhere, they found severe levels of shell dissolution in the undersaturated region and concluded that upper ocean regions where aragonite-shelled organisms are affected by dissolution are likely to expand.

5 Discussions

Global warming has driven a rapid temperature increase in the Arctic Ocean, which means that summer sea ice has

retreated more quickly and larger areas of open water are available to retain more radiation heat in the surface layer. The potential heat increase in the Arctic Ocean will result in delaying the sea ice recovery in autumn and winter, allowing the transfer of large amounts of local water vapor from the surface water to the atmosphere, to be transported south over the Northern Hemisphere. As the summer sea ice retreats more significantly and larger areas of open water appear, the relationship between the concentration of winter sea ice and the frequency of cold winters in the Northern Hemisphere should be examined. The trend of summer sea ice melting raises the question of whether harsher winters would present more often until 2037 when the summer sea ice is expected to disappear completely.

The double functions of ozone hole shielding over Antarctica and snow-form precipitation over the Southern Ocean would drive an increase of the extent of sea ice in the Antarctic seas. However, when the double functions become weak or disappear, such as the ozone hole shield disappearing by the 2070s, the issue is then whether a rapid temperature increase in the Antarctic would cause the melting both of the ice sheet in East Antarctica and of the sea ice in the Antarctic seas. Sea surface temperature increase has an important role in promoting rapid air-sea re-equilibration of CO₂, especially in the cold waters of the Arctic and Antarctic Oceans^[23]. As larger amounts of atmospheric CO₂ enter the surface waters in the Arctic and Antarctic Oceans, the question is at what point a saturated state of surface water CO₂ would occur and what would be the impact on ocean acidification, ecosystem response and climate change.

All these key scientific issues and new findings are very important to help understand the role of the Arctic and Antarctic and their impact on global climate change. However, there are still further uncertainties, even though some of them have been evidenced from *in situ* observations or from modeling. We need to take an intention including how changes of the ocean structure will develop from ocean acidification and sea ice melting, and what will be the effect on the carbon cycle following the permafrost carbon release in the Arctic? Therefore, to address these uncertainties, further observations, research, and evidence or corrections should be given time and effort by the scientific communities of the world, through the implementation of the Arctic Ocean Observation System (AOOS) and Southern Ocean Observation System (SOOS).

Acknowledgments This work was supported by the National Natural Science Foundation of China (Grant nos. 40531007, 41230529), the National High-tech Research & Development Program of China (Grant no. 2008AA121703), the International Cooperation Project supported by Ministry of Science and Technology of China (Grant no. 2009DFA22920), the International Cooperation Project supported by Chinese Arctic and Antarctic Administration (Grant nos. IC201013, IC201114, IC201201, and IC201308), the Chinese Polar Environmental Comprehensive Investigation and Assessment Programs (Grant nos. CHINARE2012-01-04-02, CHINARE2012-02-01, and CHINARE2012-03-04-02) and the Ocean Public Welfare Scientific Research Project of China (Grant no. 2004DIB5J178). Data were issued by the Data-sharing Platform of

Polar Science (<http://www.chinare.org.cn>) maintained by PRIC and Chinese National Antarctic & Arctic Data Center.

References

- 1 GCP. Global Carbon Project. <http://www.globalcarbonproject.org>, 2011.
- 2 Intergovernmental Panel on Climate Change (IPCC). Climate Change 2007: IPCC Fourth Assessment Report-The Physical Science Basis // Solomon S, Qin D H, Manning M. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2007.
- 3 Ding Z L, Duan X N, Ge Q S, et al. Control of atmospheric CO₂ concentrations by 2050: A calculation on the emission rights of different countries. *Sci China Earth Sci*, 2009, 52(10): 1447-1469, doi:10.1007/s11430-009-0155-3.
- 4 Ding Z L, Duan X N, Ge Q S, et al. On the major proposals for carbon emission reduction and some related issues. *Sci China Earth Sci*, 2010, 53(2): 159-172, doi:10.1007/s11430-010-0012-4.
- 5 Craig I, Singer S F. Climate Change Reconsidered: Report of the Non-governmental Panel on Climate Change (NIPCC), Chicago, IL: The Heartland Institute, 2009.
- 6 Allison I, Bindoff N L, Bindschadler R A, et al. The Copenhagen Diagnosis: Updating the World on the Latest Climate Science // The University of New South Wales Climate Change Research Centre (CCRC), Sydney, Australia, 2009.
- 7 Turner J A, Bindschadler R, Convey P, et al. Antarctic Climate Change and the Environment. Cambridge: SCAR, 2009.
- 8 Farman J C, Gardiner B G, Shanklin J D. Large losses of total ozone in Antarctica reveal seasonal (ClOx/NOx) interaction. *Nature*, 1985, 315(6016): 207-210.
- 9 National Aeronautics and Space Administration (NASA) Goddard Space Flight Center. Ozone Hole Watch, <http://ozonewatch.gsfc.nasa.gov>, 2011.
- 10 Turner J, Comiso J C, Marshall G J, et al. Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. *Geophys Res Lett*, 2009, 36(8), doi:10.1029/2009GL037524.
- 11 Liu J P, Curry J A. Accelerated warming of the Southern Ocean and its impacts on the hydrological cycle and sea ice. *Proc Natl Acad Sci*, 2010, doi:10.1073/PNAS.1003336107.
- 12 ACIA. Arctic Climate Impact Assessment. Cambridge: Cambridge University Press, 2005: 1042.
- 13 National Snow and Ice Data Center (NSIDC). Arctic sea ice extent breaks 2007 record now, <http://nsidc.org/arcticseaicenews/>, 2012.
- 14 Wang M Y, Overland J E. A sea ice free summer Arctic within 30 years? *Geophys Res Lett*, 2009, 36(7), doi:10.1029/2009GL037820.
- 15 Petoukhov V, Semenov V A. A link between reduced Barents-Kara sea ice and cold winter extremes over northern continents. *J Geophys Res*, 2010, 115(D21111), doi:10.1029/2009JD013568.
- 16 Liu J P, Curry J A, Wang H J, et al. Impact of declining Arctic sea ice on winter snowfall. *Proc Natl Acad Sci*, 2012, doi:10.1073/PNAS.1114910109/.
- 17 Bates N R, Mathis J T. The Arctic Ocean marine carbon cycle: Evaluation of air-sea CO₂ exchanges, ocean acidification impacts and potential feedbacks. *Biogeosciences*, 2009, 6(11): 2433-2459.
- 18 Cai W J, Chen L Q, Chen B S, et al. Decrease in the CO₂ uptake capacity in an ice-free Arctic ocean basin. *Science*, 2010, 329(5991): 556-559.
- 19 Chen L Q. Study on Marine Environment and Sea-Air Interaction in the Arctic. Beijing: Ocean Press, 2003(in Chinese).
- 20 Chen L Q, Gao Z Y. Spatial variability in the partial pressures of CO₂ in the northern Bering and Chukchi seas, *Deep Sea Res II*, 2007, 54(23-26): 2619-2629.

- 21 Chen L Q, Xu S Q, Gao Z Y, et al. Estimation of monthly air-sea CO₂ Flux in the southern Atlantic and Indian Ocean using *in-situ* and remotely sensed data. *Remote Sens Environ*, 2011, 115(8): 1935-1941.
- 22 Bednaršek N, Tarling G A, Bakker D C E, et al. Extensive dissolution of live pteropods in the Southern Ocean. *Nature Geoscience*, 2012, 5: 881-885.
- 23 Chen L Q, Gao Z Y, Zhang L Y, et al. Rapid change in Arctic and Antarctic oceans and their feedbacks to global climate change. *J Appl Oceanogr*, 2013, 32(1): 138-144 (in Chinese).