· Review · Advances in Polar Science

doi: 10.3724/SP.J.1085.2011.00001 March 2011 Vol.22 No.1: 1–9

Review of China's scientific research progress in polar meteorology in the last 30 years

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Received July 22, 2010; accepted August 31, 2010

Abstract The Antarctic and Arctic are sensitive to global climate change; therefore, they are key regions of global climate change research. This paper, the progress in scientific investigations and research regarding the atmosphere in the polar regions over the last 30 years by Chinese scientists is summarized. Primary understanding of the relationship between the polar regions and global change, especially, the variations in time and space in the Antarctic and Arctic regions with respect to climate change is indicated. Operational weather forecasts for investigation of the polar regions have also been established. Moreover, changes in sea ice and their impact on the atmosphere of polar regions have been diagnosed and simulated. Parameterization of the atmospheric boundary layer of different underlying layers and changes in the atmospheric ozone in the polar region has also been experimented. Overall, there has been great progress in studies of the possible impact of changes in the atmospheric environment of polar regions on circulation in East Asia and the climate of China.

Keywords **Antarctic, Arctic, meteorological science, global change, research progress**

Citation: Lu L H, Bian L G. Review of China's scientific research progress in polar meteorology in the last 30 years. Adv Polar Sci，2011, 22：1—9，doi: 10.3724/SP.J. 1085.2011.00001

0 Introduction

The polar regions are critical to investigation of global climate change in multiple international scientific fields, because they play an important role in global change, especially with respect to global and regional climate. The polar regions are composed of the Antarctic and Arctic regions. The Antarctic region is located south of 60°S and includes the continent of Antarctica, island of Sub-Antarctica, and the Southern Ocean surrounding the Antarctic continent. The Arctic research plan (WCRP) and international geosphere and biosphere plan (IGBP) [1–3]. In addition, reports by the Inter-government Panel On Climate Change (IPCC) have region usually refers to the region north of the arctic circle (66°33′ N), including research into the global atmosphere research plan (GARP), paid a great deal of attention to polar regions [4]. In the earth climate system, the atmosphere, ocean sphere, cryosphere, geosphere and biosphere are uniformly integrated with interrelated effects. Accordingly, to understand global change, the polar regions must be studied [5].

The development of scientific studies of the polar regions has been closely related to international cooperative observations and research in the Antarctic and Arctic regions. Over the last 100 years, the international polar region year (IPY) has been successively executed four times (1882—1883, 1932—1933, 1957—1958 and 2007—2008). Especially the third international polar region year (1957—1958), which was extended to international geophysics year (IGY), symbolized the start of modern scientific investigation of the polar region, and promoted the founding of international organizations such as the Scientific Committee on Antarctic Research, and the drafting of the Antarctic Treaty, under the byword "peaceful utilization of the Antarctica. In the last 50 years, global meteorology has realized great progress with respect to the climate of polar regions. Specifically, the region has been found to have rapidly changing snow, ice and atmospheric environmental characteristics. The relationship between the

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polar regions and anthropogenic activities has been identified. Moreover, proxy data regarding the snow and ice climate of the polar regions has been generated, and the impact of the atmospheric environment of the Antarctic and Arctic regions on global change have been discussed [6].

In the last 30 years, field scientific investigations and research into the polar regions by China have realized fairly great progress [5–24]. In 1984, China first investigated the Antarctic, and in 1985 the Antarctic Great Wall station was established. Between 1984 and 2010, China conducted 27 investigations of the Antarctic, four investigations of the Arctic Ocean and seven investigations of land in the Arctic. In addition, four scientific investigation stations and five cooperative automatic meteorological stations (Sino-Australia and Sino-America) were constructed, preliminarily forming the hardware supporting system of polar region scientific research with manned investigation stations, unmanned automatic meteorological stations, and Snow Dragon Expedition Ship. Over 300 members of the Chinese Academy of Meteorological Sciences, National Research Center for Marine Environment Forecasts, and Institute of Atmospheric Physics of Chinese Academy of Sciences participated in these investigations.

The meteorology of the polar regions is the primary part of scientific investigations of the polar regions to global change research. Executing scientific investigations of polar region meteorology has deep political implications, as well as important scientific significance to the fields of meteo-rology, glaciology, oceanography, geology, biology, geophysics and environment science, as well as the potential for economic and social benefits.

1 Polar meteorology investigations

Field investigations of the Antarctic and Arctic are the foundation of scientific development of meteorology of polar region, and there has been fairly great progress in China's scientific investigation of the meteorology of the Antarctic and Arctic over the last 30 years. The fundamental meteorological data generated by China's scientific investigations of meteorology of the Antarctic have been incorporated into the Chinese meteorology science data share service net (http://cdc.cma.gov.cn/index.jsp) maintained by the national meteorology information center of the earth system scientific data share network-data center of the Antarctic and Arctic of China (http://polar.geodata.cn:8060/Portal/index.jsp), as well as the earth science data system (WCD-D) meteorology discipline and the share database [6] as an atmospheric science database (http://www.cams.cma.gov.cn/cams_kxsy/qky_kxsy_index.htm) of the Chinese Academy of Meteorological Sciences website.

1.1 Antarctic meteorology investigation

Systematic scientific field investigations of the Antarctic by China were started in the 1980s. Since 1980, the Chinese Committee on Antarctic Research (now the Chinese Arctic and Antarctic Administration), which is the jurisdictional unit of Antarctic investigation, successively sent personnel to participate in scientific investigations of the Antarctic at stations maintained by foreign countries, which resulted in the accumulation of experience for use in the construction of independent stations by China. In 1980, Mr. Dong Zhaoqian (oceangrapher) and Mr. Zhang Qingsong (geographer) were the first Chinese scientists involved in Antarctic investigations. In 1981, Mr. Bian Lingen (Chinese Academy of Meteorological Sciences) participated in the winter investigation of the Antarctic Mawson Station of Australia, and became the first Chinese meteorologist to conduct an investigation in the Antarctic. Mr. Qin Dahe participated in the international Trans-Antarctic Expedition, and reached the Antarctic point on Dec. 12, 1989, making him the first Chinese scientist to cross the Antarctic by Foot [19]. In 1984, the national Antarctic investigation commission organized the first Antarctic investigation of China, and in Feb. 1985 the first Chinese overseas meteorological station (Great Wall Meteorological Station of Antarctica), was constructed. In Feb. 1989, Zhongshan Observation Station was constructed on the eastern portion of Antarctica. In 2005, an inland ice cap investigation team (the 21st Antarctic investigation team) reached the highest point of the dome of Antarctica (Dome A).

From 2002 to 2008, China set up five Sino-Australian and Sino-American automatic meteorological stations (LGB-69, Dome-A, Eagle, PANDA-N and PANDA-S) from Zhongshan Station to the highest ice cap of Antarctica. In 2007—2008 IPY, China executed the Antarctic PANADA plan (Prydz Bay, Amery Ice Shelf and Dome A Observatories). As part of the plan, the first business monitoring station of atmospheric constituents of the continent of Antarctica was established. In addition, ozone profile sounding and GPS low altitude detection (18 000 m) were conducted. Furthermore, in the circumference of Zhongshan Station, an ultrasonic wind temperature meter, gradient heat balance observation station, and radiation balance observation system were used to monitor the ice cap and derive detailed data regarding the interaction between the ice/gas phases of the near ground layer of the ice cap of Antarctica[15].

In Jan. 2009, China established the Antarctic Kunlun Station approximately 7.3 km southwest of the highest point (Dome A) on the ice cap of Antarctica. At present, this station is only available for summer work. However, after 5—10 years this station will be ready for use as a manned over-wintering station.

Since 1984, the general ocean climate observation and forecast service[9–12] has been conducted by various ships. In recent years, atmospheric environmental monitoring of CO_2 exchange of sea-air, ultraviolet radiation (UVB) and ground ozone, black carbon aerosols and CO concentrations have also been conducted at different latitudes using a high pressure gas collection steel cylinder to collect the air samples[15].

1.2 Arctic meteorological investigation

In 1991, Gao Dengyi participated in an Arctic investigation together with scientists from Norway, the USSR and Iceland. In 1994, the Chinese Academy of Sciences cooperated with the USA to conduct a scientific inves- tigation of Alaska, and in 1995 the China Association of Sciences and Technologies organized a walking expedition of the Arctic and reached the north pole. In 1997, the Institute of Atmospheric Physics of the Chinese Academy of Sciences, and the Chinese Academy of Meteorological Sciences cooperated with Norway to conduct test research regarding atmospheric boundary layer structure and turbulent flux transmission on the sea ice of the Arctic [11].

China organized four Arctic Ocean scientific investigations (Jul.—Oct., 1999; Jul.—Sep., 2003; Jul. —Sep., 2008, Jul.—Sep., 2010) in the Bering Sea and Arctic Ocean, in which an expedition ship, helicopter and floating ice station were used as observations stations to conduct multidiscipline integrated observation of ocean-sea ice-atmosphere-biology. In addition to observations of ocean meteorology, ground ozone, UV-B and ozone sounding, these investigations also included near ground layer atmospheric physics (gradient and ultrasonic), boundary layer atmospheric layer structure (TMT soft meteorological tower), high altitude atmospheric detection (GPS sounding and ozone sounding), collection of polar region atmospheric chemistry, sea water micro element evaluation, atmospheric aerosol evaluation and low layer atmospheric greenhouse gas evaluation. These investigations reached 78°N, 80°N, 85°N [16–18] and 88°N, respectively.

From 2001 to 2003, the scientific expedition to Chinese Arctic Yellow Station, in the Longyearbin region of Svalbard archipelago, integrated investigation of related disciplines of atmosphere, glacier, geology and flora, etc., were carried out [11–13].These investigations promoted the execution of scientific investigation research in the Arctic and the construction of Chinese research stations in the region.

In Jul. 2004, China established the first Arctic land scientific investigation station, the Chinese Arctic Yellow River Station, in the Ny-Alesund of the Svalbard archipelago, to conduct investigations regarding high altitude atmospheric physics, ocean biology, meteorology, GPS tracking and observation, and ice and snow. Since its establishment, investigations have been conducted each year.

2 Polar meteorological studies

China's Antarctic Great Wall Meteorological Station and Zhongshan Observation Station were built in 1985 and 1989, respectively, which created conditions enabling execution of field meteorological investigations and research in Antarctica. After establishment of the Antarctic Zhongshan Station, the key point of Antarctic investigations and research by China shifted toward execution of scientific research in the polar regions. Additionally, based on the principle of global change, the Chinese Committee on Antarctic Research (now the Chinese Arctic and Antarctic Administration) organized related units to jointly investigate key problems for the following national scientific research project, of which China's meteorological science research of polar region was the integrated part and in the rapid development [8, 21, 24]. Prior to 1999, China had not conducted national Arctic field scientific research, and all related Arctic research was organized by each unit via a decentralized mode [11–13]. China organized the Arctic Ocean scientific research project, which executed a multi-disciplinary study of the mutual effects of the ocean environment and sea air of the Arctic in 1999.Then in 2003, 2008 and 2010, three Arctic Ocean scientific investigations were conducted, while the Arctic Yellow River Scientific Research Station was constructed in 2004. Together, these projects created conditions enabling further understanding of the Arctic region [14, 17, 18].

In the last 20 years, the natural science fund commission of China has supported over 300 projects related to the polar regions, including over 130 projects related to atmospheric science, and over 70 and 60 projects related to atmospheric science research in the Antarctic and Arctic regions, respectively. Of these, more than 10 projects related to atmospheric science research in the polar regions received at least [6–8].

3 Main progress in polar meteorological science research

Scientific investigation and research regarding the meteorology in the polar regions is the scientific field in which China has shown the greatest advances in the last 30 years. Through this research, a primary understanding of the relationship between the polar regions and global climate change was derived [5–137].

3.1 The temporal and spatial characteristics of polar climate change

The actual measurement data was mainly collected to investigate the climate and circulation characteristics of the polar regions, especially the climate characteristics of the Antarctic Great Wall Station and Zhongshan Station, and the section from Zhongshan Station to Dome A of the ice cap of Antarctica. Besides, the Yellow River Station and areas in the circumference, and the meteorological factors characteristics of the floating ice area of Arctic Ocean, and the time space variety of polar region climate change [25–40] were researched.

Climate change in polar regions is diversified by time and space, and the changes in climate with respect to temperature and sea ice are not consistent [29–30]. In the last 50 years, the changes in temperature in Antarctica and its neighboring regions have not been consistent with changes in global temperatures. China's Great Wall Station and Zhongshan Station are located in west and east Antarctica, respectively. In the last 20 years, the temperature at the Great Wall Station rose, while no change in temperature was observed at Zhongshan Station [5]. The warming phenomenon of Antarctica primarily emerges in the peninsula region, while in the main body of the continent of Antarctica the warming phenomenon has not been apparent, and a decreasing temperature has been observed over the last 10 years [29, 30, 34]. In recent years, the western portion of Antarctica has frequently undergone ice shelf thawing and collapse, while this has not occurred in the east portion of Antarctica.

The climate system of Antarctica and the Arctic is very complicated, and it is difficult to demonstrate that some changes are simply caused by anthropogenic activities. Moreover, there is currently no sufficient reference to demonstrate that the changes in temperature that have occurred in Antarctica and its neighboring regions over the last 50 years have been caused by the greenhouse effect. Indeed, these changes may have been caused by internal variations in the climate system [29–30, 34].

3.2 Research regarding polar weather forecasting and polar disaster climate

The natural conditions in the polar regions are severe, and the climate conditions are variable. From the Chinese first cruise to the Antarctica(1984), the Chinese polar ships and Chinese Antarctic and Arctic stations of China are all set up by business weather and ocean meteorological forecast system [7, 12, 43] serving for investigation of polar region, and this provided the meteorological guarantee for compiling and executing investigation plan.

The research that has been conducted to date has also included evaluations of gale weather, circulation type, and forecast key points of various gale climate type of the region of the Great Wall Station and Zhongshan Station with fairly great impact on the polar region; the activities of sea fog, cyclones, cold air activity, snow storm disaster climates and methods of forecasting weather in the Antarctic and Arctic [12, 41–49]. In the Prydz Bay area of the Antarctic, there are great changes in sea ice with seasons, which results in a circumpolar current and eastward wind. Accordingly, at the northeast part of Prydz Bay an ice dam usually forms, resulting in the shore by Zhongshan Station generally containing a large amount of ice. Indeed, only when the westward wind emerges, the sea ice drifts away from the station. Zhongshan Station basically suffers eastward wind in the whole year with minor opportunity of westward wind, When the expedition ship reached the circumference of Zhongshan Station; the near ground wind situation had great impact to investigation activity[12, 43].

3.3 Diagnosis and simulation of polar sea ice change

The sea ice of the polar regions is the underlying surface that undergoes the largest seasonal change and attracts the most attention from atmospheric scientists. Accordingly, the diagnosis and simulation of changes in the sea ice is the main topic of scientific research in the polar regions [50–64]. Similar to temperature, changes in the sea ice of polar regions also has obvious effects on regional characteristics [30, 51, 62, 64]. In the last 30 years, seasonal changes in the sea ice of Antarctic have been asymmetrical and the thawing speed of sea ice has been much greater than the condensing speed, while the seasonal changes in sea ice in the Arctic have basically been symmetrical. As a result, the sea ice of the Antarctic appears to be increasing, while the interannual variation in the sea ice of the Arctic is decreasing. On the west side of the Antarctic peninsula, the periphery of the Bellinsgauzen Sea and Ross Sea are key regions characterized by high board characteristics that are closely related to ENSO, and the defined Antarctic sea ice oscillation indicator (ASOI) is closely related to changes in the SOI and Nino3 indicator, and thus can be used as a key indicator of variations in Antarctic sea ice [58–59, 62, 64]. The oscillation indicator of sea ice in the Antarctic can be used to investigate the sea ice situation and activity of key areas of sea ice in the region. The establishment of a sea ice oscillation indicator for the Antarctic provides new possibilities for further recognizing the impact of changes in sea ice on the atmosphere and climate of China, as well as short term climate forecasts for China [58–59].

To investigate the sea ice in polar regions and its effects on the ocean, an ice-ocean coupling model has been established for the Bohai Sea and Baltic Sea [54–55]. The sea ice thermodynamics model has been shown to simulate changes in the sea ice of polar regions in the vertical direction fairly well [57].

3.4 Physics of polar boundary layer and interaction between sea ice and air

The polar region is an important unit of the global climate system, including the effects of several circle layers of atmosphere, ocean, land, ice snow and biology, etc., and many processes emerge in the boundary layer of atmosphere. Studies have employed field investigation data to investigate the near ground surface radiation and heat balance characteristics of different underlying layers of the polar region, boundary layer structure characteristics of the atmosphere, physics of the boundary layer of the polar region, and mutual effects of the sea ice and gas phase, and provided important physical parameters describing the boundary layer for the climate model [65, 68−69, 78, 82, 87, 91]. A primary simulation test was also conducted for the boundary layer of the atmosphere of the polar regions [90], and a multi-scale theory based on turbulent flow has been developed to explain the heat antigradient transmission phenomenon observed at the Zhongshan Station [81].

The results of NCEP/NCAR and EC near ground data and the availability of the Arctic tundra and sea ice region are recognized. Generally speaking, reanalysis data can reflect changes in many factors; however, since consideration of the underlying surface situation and the characteristics of the boundary layer are not perfect in the tundra of the Arctic and the sea ice region, the simulated value of each component of radiation and heat quantity balance of the reanalysis data differs greatly from the actual measured value. Accordingly, during the operation, the measured values should be used whenever possible[37−39]. To investigate the interaction of sea-ice-air of the polar regions, the measured data was used to calculate the turbulent flux by the method of aerodynamics, and general universal function methods. The results are compared to obtain the new turbulent parameters[88].

3.5 Polar atmospheric impact on the circulation of East Asia and climate of China

The changes in the atmospheric environment of the polar regions, especially in the temperature and ice/snow, circulation and oscillations in the polar region influence circulation in East Asia and the climate of China [94–119].

The change in temperature, snow and ice and circulation in the Arctic as well as their impact on the global and Chinese climate are of great concern to meteorologists in China. The oscillations of the north Atlantic and the Arctic can impact the climate of East Asia [105–107]. In addition, changes in the sea ice of Barents Sea in the winter and the Kaka Sea in the winter are closely related to inter-annual and interdecadal changes in the climate of China, as well as changes in the winter monsoon and ESON event of East Asia [102–106]. The subtropic high pressure of the northern hemisphere is related to the sea ice in the Arctic [95]. Moreover, the sea ice in spring is related to precipitation associated with the summer monsoon in East Asia [109].

The summer oscillation of temperature and sea ice in the Antarctic are related to the summer circulation of the northern hemisphere, summer precipitation and temperature of China [96, 98, 113]. The Antarctic sea ice is also related to the polar vortex indicator, sea temperature of the equator, subtropic high pressure of the western Pacific Ocean, and typhoon activity [98]. The Antarctic atmospheric environment and Antarctic oscillation are closely related to ENSO, typhoon and subtropic high pressure in the western Pacific Ocean, and summer precipitation in China [31, 58, 105, 114].

Fluid physical turntable simulation has shown that the formation of atmospheric circulation and climate characteristics in the circumference of Antarctica are the result of the joint effects of topography and coldest environment of Antarctica [26]. The simulated results have shown that the atmospheric characteristics, sea temperature and the Antarctic sea ice is the characteristic of the latitudinal direction circulation of the equator first, and then a series of vortex street being activated at the north west Pacific from south to north, impacting the climate of China, and this may be the mechanism by which the temperature and ice of the Antarctic region impact atmospheric circulation [22, 99−100].

The polar region also impacts the regional climate of China [8, 11, 13, 111]. Specifically, sea ice and oscillations in the polar region influence the atmospheric circulation of East Asia, which can alter China's climate. The strong signal for climate forecast can be presented in the process.

3.6 Observation research of atmospheric chemistry in the polar regions

Atmospheric chemistry is an interdisciplinary science developed in modern times, and is one of the main methods used to investigate the atmospheric environment and atmospheric pollution. Over the last 30 years, China has made progress in investigation of the atmospheric chemistry of the polar regions, especially with respect to the atmospheric ozone of the Antarctic [120–137].

China's field investigations and research into the atmospheric ozone of Antarctica began in the 1980s, when Chinese scholars participated in an Antarctic investigation conducted at a foreign station. The data from radio sounding in Antarctic was used to discuss the relationship between the sudden temperature increase and ozone changes in the stratosphere during spring [120–122]. From 1988 to 1989, a solar spectrograph made by the geophysics department of Beijing University was used to observe the total quantity of the ozone of the atmosphere, and the daily changes in the quantity of ozone were discussed[121]. In 1993, at Zhongshan Station on the eastern portion of

Antarctica, a Brewer ozone spectrograph was used to observe the quantity of ozone of the atmosphere, and related research was conducted [124–127].

The generation of the ozone hole over Antarctica is closely related to the emission of pollutants into the atmosphere by humans, especially compounds such as Freon that contain chlorine and bromine. Under the low temperature condition of stratosphere, ozone loss is closely related to photochemical reaction of the surface of ice cloud (PSC) of the aerosol [128]. In the atmosphere, the existence of the substances that damage the ozone layer result in the formation of an ozone hole over the Antarctic in spring; however, the low temperature of the polar vortex of the stratosphere over Antarctica is also necessary for formation of the ozone hole [132, 137], which explains why it only emerges in the sky over Antarctica during spring [137]. During autumn, the relatively low level of ozone over Antarctica is primarily related to the reduced amount of sunlight, and its generation mechanism is different from that of the ozone hole that forms during spring [128].

In addition to the total quantity of atmospheric ozone, during the polar region investigation of the Xuelong vessel the surface ozone observation data for the 75°N—70°S polar region navigational line were derived, and the distribution characteristics of the ozone concentration on the ground along the navigating line was investigated [129]. The distribution of the source of CO_2 and the sea-gas flux of the sea ice in the polar region showed that the sea ice area of the Southern Ocean between 80ºE and 60ºW is always the clean gathering area of CO_2 from the atmosphere, and that the high productivity of sea ice area of the Southern Ocean in summer has apparent impact to carbon flux of Southern Ocean [34]. In the investigation area of the Arctic Ocean, except for a weak source area of CO_2 from the atmosphere in east part of the ocean during summer, most sea areas are sink of atmospheric CO_2. During summer, the Arctic Ocean has a relatively active carbon cycle process that involves a biological pump with fairly high operation efficiency. Over the Chukchi Shelf it is also an organic carbon sinking area with high efficiency [136]. The investigations of the aerosols concentrations and the sulfate, phosphate and nitride in the aerosols have been conducted [7]. In addition, the research of ancient climate environment and atmospheric physics of the polar regions [7, 10, 19, 24]. have been advanced in the fields of high altitude ice caps and ice free area.

4 Summary

The scientific investigation of the meteorology in the polar regions has made great progress over the 30 years, from above the brief. Primary understanding of the relationship between polar regions and global climate change has resulted. The important progress are shown on the temporal and spatial variations in climate change of the Antarctic/Arctic region, and establishment of a operational weather forecast system for polar regions, characterized the boundary layer in different underlying layers of the polar region, and the variations in the quantity of the atmosphere ozone at Zhongshan Station, and the simulated the sea ice change. Specifically, study on the atmospheric environment of polar regions impacted on the circulation of East Asia and climate of China is very meaningful for future prediction of climate change.

The 2007/2008 IPY provided a very good opportunity and challenge for China to push forward its large scale earth science investigation and research.

Acknowledgments This work was supported by the National Natural Science Foundation of China (Grant no. 41076132), the National Science and Technology Infrastructure Program of the Ministry of Science and Technology of China (Grant no. 2006BAB18B05) and China's Action Plan for the International Polar Year (IPY).

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