POLAR METEOROLOGY AND CLIMATE

John W. Weatherly
Cold Regions Research and Engineering Laboratory, US Army Corps of Engineers
Hanover, New Hampshire, USA

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Summary

The Polar Regions – the Arctic and Antarctic – have extremes in weather and climate, and have important interactions between the atmosphere, ocean, sea ice, glaciers, and land ice that affect the weather around the globe. Historically, people have explored and exploited the vast natural resources in both the Arctic and Antarctic, and the Arctic has been inhabited for thousands of years with people that have adapted to its extreme environment. The Arctic has also been the focus of national defenses, the Cold War, and conflicting claims of sovereignty and access to resources. The cycle of sunlight oscillating between 24-hour daylight and polar night drives the polar cycle of extreme low temperatures, ice cover, and ice sheet formation. The polar atmospheric and ocean circulation, clouds, and hydrologic cycle are all dependent on the exchanges of heat and water with the warm lower latitudes. The changes in the Arctic in temperature, sea ice cover, and permafrost are driven in part by greenhouse gases and warming of the global climate, and expected to warm by 3 to 8 C in the coming 80 years. These changes in the Arctic are not isolated and remote from us; they are an interconnected and integral part of our own habitable weather and climate.

1. Introduction

The Polar Regions are unique and extreme environments, where climate and weather have shaped history and the potential for changes in its future. For centuries the Polar

Regions have captured the imagination of writers, intrigued explorers and scientists, and enticed traders into exploiting its resources. Each generation of polar inhabitants and explorers have either learned to adapt to the extreme polar environment or have failed to survive.

Indigenous people have inhabited the Arctic since before the end of the last ice age, subsisting on the abundance of marine life, birds, caribou and reindeer herds. The Saami people of Lapland (northern Norway, Sweden, Finland and Russia) have evidence of settlements spanning 10,000 years. The Thule people in Greenland existed with little or no contact with Europeans through 1000-1600 A.D. The Norse settlers of southern Greenland may have attempted to adapt the European-style agriculture during the Medieval Warm period until the climate either cooled, or proved too harsh for their practices.

The Arctic has been the focus of European exploration since ships began transiting to North America, particularly in seeking new natural resources and a Northwest Passage for trade with the Far East. The earliest commercial resources to be sought were the sperm and right whales and Atlantic cod fisheries. Tourism in the Arctic was actually established in the early 1800’s with the advent of adventure travel, the sport of trophy hunting and fishing.

Political boundaries, territorial claims, and national defense issues have been present in the Arctic since the beginning of exploration into these regions. Defense issues in the Arctic increased in intensity during the 1950’s and the onset of the Cold War between NATO and Soviet bloc countries. The Cold War defenses included detection of long-range bombing aircraft and early warning of ballistic missiles that could be launched over the Arctic Ocean. The construction of the Defense Early Warning (DEW) Line of radar facilities across the northern coastlines of Alaska and Canada meant the expansion of airfields and associated weather observations that established our baseline data on the knowledge of the Arctic atmosphere. Today, the countries with territories in the Arctic – Russia, Canada, Norway, Sweden, Finland, Greenland (Denmark), and the United States, are competing for territorial claims for resources including oil and gas deposits beneath the Arctic Ocean seabed.

The Antarctic is almost a reverse image of the geography of the Arctic – a continental ice sheet approximately 3000 m in height, surrounded by the circumpolar Southern Ocean that is seasonally ice-covered. Although the Antarctic has been more inaccessible to exploration and inhospitable for human survival, it has not remained separate from commercial development. Commercial whaling in the Southern Ocean was active in the 19th and 20th Centuries, with whaling station such as on South Georgia Island.

Without traditional human inhabitants, there are no historical territorial claims or national boundaries in the Antarctic. Since 1959, Antarctica has not been controlled directly as a national territory, but with access shared by countries signed onto the Antarctic Treaty, (originally Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, South Africa, the USSR, the United Kingdom and the United States). The treaty excludes claims of national territories and military activities such as weapons testing or nuclear explosions, and ensuring the freedom for scientific investigation. The international cooperation on research is facilitated by the Scientific Committee on Antarctic Research (SCAR).

Societies, commerce, and future development in the Polar Regions are highly intertwined with the extreme climate and weather. The following sections describe the components, circulation, synoptic weather, and physical processes that define the Arctic and Antarctic, and how these regions are affected by global climate change. The observations of polar climate and numerical models of climate change provide our only reality-based predictions of what Arctic and Antarctic climate may exist by the end of the 21st Century.

2. Components of the Polar Climate System

The polar climate system can be defined as a regional subset of the global climate system that includes the atmosphere, ocean, the cryosphere (ice in many forms -- sea ice, glacial ice, snow and subsurface permafrost), as well as the terrestrial physical, hydrologic, and biological systems that relate to climate. Overall the polar climates (Arctic and Antarctic) are characterized by extremely low surface and atmospheric temperatures, the annual cycle of solar radiation, and the significant seasonal coverage and mass of ice and snow. The exchange of heat and water between these components of the system strongly influence the behavior of the polar climate: The low solar radiation and infrared energy losses to space help create the cold surface temperatures; the snow and ice cover insulate the cold atmosphere from the warmer ocean below; the shedding of glacial ice into the ocean adds fresh water that affects the global ocean circulation and the 'conveyor belt' of heat between the equator and poles. The transformation of water between gas (water vapor), liquid water, and solid ice as it moves between the atmosphere, land, ocean and ice cover is essential to the polar climate system, and may also be a common feature on other non-Earth planets that have (or once had) water on their surface.

Following section describes the general characteristics of the atmosphere in the Arctic and Antarctic that make them distinct from each other and from the lower latitudes. The entire height of the Earth's atmosphere is generally divided into four main sections: troposphere (lowest 10-12 km from surface), stratosphere, mesosphere and thermosphere. For discussing polar weather and climate, this paper will describe only the troposphere and lower stratosphere.

- **Arctic**

The Arctic lower atmosphere is affected largely by the surface of the Arctic Ocean – in winter the surface is frozen, the air (-5 to -40 ºC) is insulated from the ocean temperatures (0 to -2 ºC) by the ice cover. The near-surface atmospheric humidity is consistently at the saturation point with respect to ice (Andreas, 2000). The atmosphere boundary layer over ice regularly has an inversion layer as the surface is cold and temperatures increase in the lowest 1 km or so. Above 1 km, temperatures decrease with height, with the lowest potential temperatures being approximately -40 ºC.

In summer the ice surface is melting and the air temperatures are nearly uniform around

0 ºC. The boundary layer is also near saturation as it overlies both the areas of open ocean and melting snow and ice ponds, so the summer atmosphere has the highest frequency of maritime stratus cloud cover, along with stratus (non-convective) precipitation.

- **Antarctic**

The Antarctic atmosphere is significantly colder and drier than the Arctic, consistent with its description as a high-altitude polar desert on top of the Antarctic ice sheet. The surface temperatures year-round over the Antarctic continent can remain at-10 to -40 ºC. Strong katabatic winds are formed by cold air descending the slopes of the continental ice sheet towards the surrounding Southern Ocean. The surface visibility is frequently reduced dramatically due to blowing and drifting snow and ice crystals. The clouds over the interior Antarctic continent are generally high, thin cirrus composed of ice crystals, while closer to the coastlines there is increasing maritime cloud forms, liquid water content in clouds, and mixed ice/liquid precipitation.

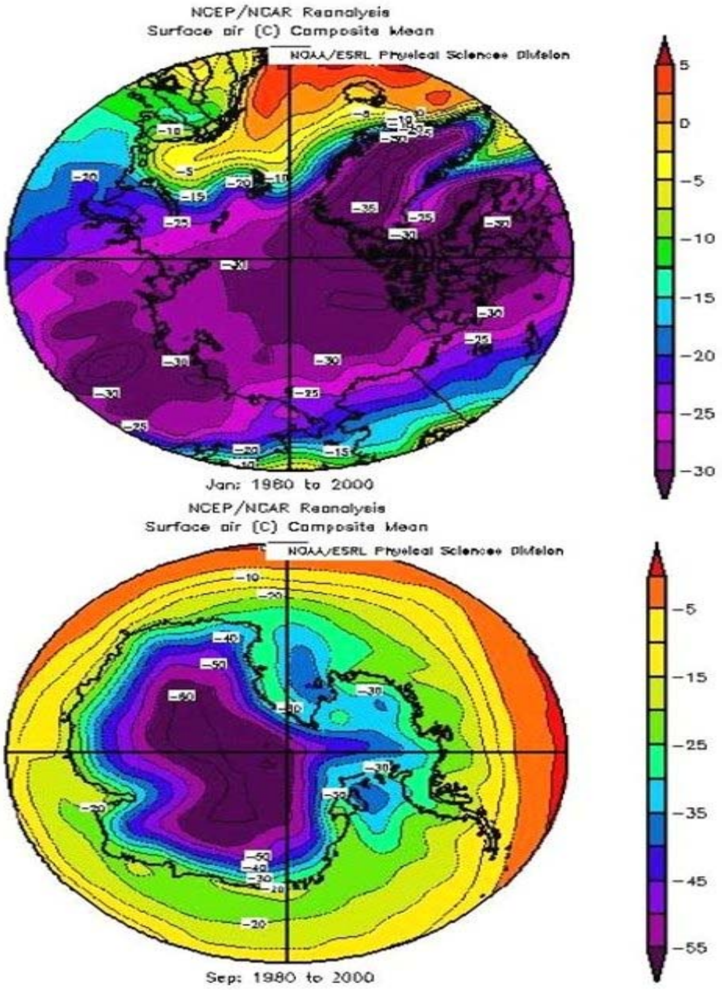

Figure 1. Wintertime surface air temperature in Northern Hemisphere in January (upper plot), and Southern Hemisphere in September (lower plot).

3. Meteorological Data Collection in the Polar Regions

Meteorological data collection in the Arctic has been pursued as part of many expeditions in the Arctic. The landmark expedition across the Arctic by F. Nansen and the crew of the *Fram* was inspired by the prevailing wind and ice drift from the Russian coast toward the North American coast in 1893-1896. One of the goals of the *Fram* was to make detailed meteorological and early oceanographic measurements. The measurements from the *Fram* were, in fact, used by Ekman to develop the theory of the turning of surface flow with friction (the Ekman spiral). The long-term observing stations in the Arctic were established at the coastal ports (such as Murmansk) and locations on rivers (such as MacKenzie River in Canada and Yenesei and Lena Rivers in Russia) that transport via shipping to the Arctic.

The Cold War provided the impetus for a large expansion in Arctic weather data collection and monitoring. With the establishment of radar sites and airfields across the northern US and Canada coastlines, balloon-borne sonde instruments were used for atmospheric profiling. Over the Arctic Ocean and ice cover, dropsondes were regularly deployed from aircraft flying between Alaska and the North Pole (called the Ptarmigan program) to monitor the atmospheric profiles over the Arctic as part of the North American air defenses. Defense concerns in the Cold War also led to missions of nuclear-powered submarines to operate under the Arctic sea ice for extended cruises, starting with the first nuclear submarine, the USS Nautilus, reaching the North Pole in August 1958. These missions were designed for mapping both the ocean bathymetry for safe navigation, perform reconnaissance missions to detect enemy vessels, and later, for preparing for defense in case of an attack on the United States. These submarines were equipped with Upward Looking Sonar (ULS) used to navigate safely under the keels of sea ice and for detecting safe thin ice and open water for surfacing. As more these data were analyzed and eventually declassified, the 1958-1979 data became our baseline for assessing the thinning of the Arctic sea ice from the 1980’s to present day (Rothrock et al. 1998).

Observations and data collection by the Soviet Republics during the Cold War have also contributed substantially to our knowledge of Arctic meteorology, oceanography, and hydrology. Russia deployed manned, drifting ice camps on the Arctic sea ice between 1937 and 1991, with one to four drifting stations each year from 1954 to 1991 to collect observations of meteorology, snow depths, ice drift and ocean currents (*Rigor et al 1999*). The Russian’s Stevenson-screen 2-m air temperature measurements are considered the most accurate record of Arctic air temperatures made over the 20th Century, and are used for validation of other buoy-measured temperatures.

With the end of the Cold War and reduced operations of submarines in the Arctic, the Arctic ice cover is being monitored with other methods. *In situ* methods for measuring ice thickness have always included the direct method of drilling holes manually and with gas-powered ice augers. Ice mass balance (IMB) buoys have been deployed into sea ice floes that include thermistors (thermally sensitive resistors) to measure ice temperature and the changes in thickness, the heat flux from the underlying ocean, and acoustic sensors to measure snow depth and under-ice keel depths as the floes drift across the Arctic. These buoys have been deployed as part of the North Pole Environmental Observatory between 2000 and 2008 in conjunction with atmospheric and oceanographic profile measurements.

Other measurements of sea ice thickness are collected by upward-looking sonar from moored under-ice buoys, anchored to the ocean floor, which measure ice keels as they drift over the buoy. As these moored buoys are difficult to deploy and to retrieve with ships in the moving ice pack, other approaches have been developed to measure ice thickness remotely from aircraft and satellites. Measurements of ice thickness from satellites have been developed using both laser and radar altimetry instruments that use the differences between open-ocean and snow/ice surface heights to assess ice thickness. NASA’s ICESat mission launched in 2003 uses pulsed laser altimetry to measure the time and distance between the satellite and the surface. The European Space Agency’s (ESA) CryoSat satellite was designed with Synthetic Aperture Radar (SAR) altimetry to measure ice heights. The original CryoSat mission was lost due to its rocket failure during launch in October 2005, and the replacement CryoSat 2 satellite is under construction for launch in 2009 or later.

Antarctic meteorology has been progressing with the historical exploration and establishment of observing stations. After the initial base stations established at McMurdo Sound, most Antarctic stations were set up by along the coastlines during the International Geophysical Year (IGY) in 1957/58 by multiple participating countries. The United Kingdom, Norway, Japan, China, Chile all established their coastal stations. For the interior ice sheet, the U.S. established the Scott-Amundsen station at the South Pole during IGY, and Russia (during the Soviet Union era) established observations at Vostok in the vast East Antarctic Plateau which continue today. Because of the need for additional observations over the ice sheet, ASOS (Automated Surface Observing Stations) systems have been deployed to relay some meteorological variables back to the base stations.

One of the critically important Antarctic measurements made to ensure the safety of personnel is the monitoring of ice thickness and ice temperatures at the sea ice runway accessing the McMurdo station. Through the winter to spring seasons (Sept. to Dec.), the temperatures in the ice increase from near -20ºC in September to near 0ºC in December as the sun remains above the horizon. The runway’s ice thickness increases during this period from between 2 m in September to about 2.5 m in December, before the warming air and surface melt make it unsafe for use as a runway.

Observations over the moving and seasonal sea ice are difficult to obtain, however, surface observations from the ice-breaking ships that supply McMurdo and other stations are the most frequent source of data. In addition, automated drifting buoys have been deployed around the Antarctic to give some pressure data and tracking the drift of sea ice when possible.

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Biographical Sketch

Dr. John Weatherly is a Research Geophysicist at the Cold Regions Research and Engineering Laboratory, which he joined in 1998 after a postdoctoral research position at the National Center for

Atmospheric Research in Colorado. He received his Ph.D. in atmospheric sciences in 1994 from the University of Illinois at Urbana-Champaign. His research includes developing model simulations of the Arctic and Antarctic sea ice cover and their response to changing climatic conditions like greenhouse gas-induced warming. He has collaborated on global climate models that have been used in the Intergovernmental Panel on Climate Change assessments, and is currently researching the different impacts of climate change on society, infrastructure, and natural resources.