Polar meteorology

Understanding global impacts

World Meteorological Organization
Weather • Climate • Water
WMO - No. 1013

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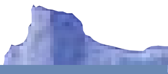

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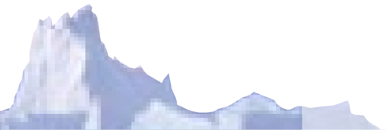


FOREWORD

World Meteorological Day (23 March) celebrates the date of the entry into force of the Convention which created the Organization in 1950.

The WMO Executive Council decided that the theme for World Meteorological Day in 2007 would be "Polar meteorology: understanding global impacts", in recognition of the importance of, and as a contribution to, the International Polar Year (IPY) 2007-2008, which is being co-sponsored by WMO and the International Council for Science (ICSU).

In recent decades, great advances have been made in our understanding of the role of the polar regions in the global climate system. Shrinking sea-ice, melting ice sheets, the discharge of glaciers and thawing of permafrost are all dramatic changes that have been taking place in those regions owing to an increase in global average temperature. It is evident that the increased average rate of sea-level rise resulting from the melting of ice of land origin would be dangerous for lowlands and some islands whatever their geographical location. Ocean circulation changes may have an impact on the distribution of temperature, salinity and organic substances in tropical areas. This would have a crucial impact on fish stocks and therefore on national economies and livelihoods and our eating habits. That is why even countries geographically far removed from the Poles have a real concern regarding changes in the polar environment and are participating in the International Polar Year (IPY) 2007-2008.

WMO, through the National Meteorological and Hydrological Services (NMHSs) of its Members, will be offering substantial contributions to the IPY in the areas of polar meteorology, oceanography, glaciology and hydrology, in terms of scientific research and observations. Ultimately, the scientific and operational results of the IPY will be offering benefits to all WMO programmes by generating comprehensive datasets and authoritative scientific knowledge to ensure the further development of environmental monitoring and forecasting systems, including severe weather prediction. Moreover, the IPY will provide valuable contributions to the assessment of climate change and its impacts, so the observing networks to be established or improved during the IPY period will be kept in operational mode for many years. This will be an important part of the IPY legacy to the world.

M. Jarraud, Secretary-General

This booklet highlights the importance of the polar regions in the entire Earth system, particularly in climate. It describes some of the major environmental changes that have taken place in the Arctic and Antarctic in recent years and considers possible changes over the next century. I wish to express my appreciation to the author, John Turner, Project Leader with the British Antarctic Survey, and other contributors.

I urge the NMHSs of all WMO Members having an interest in polar research and observations to participate actively in implementing the IPY. I would also welcome the NMHSs, international organizations, non-governmental organizations and indeed all who are interested in these unique parts of the globe to seize this ideal opportunity to provide input to the IPY and so secure a rich scientific output for the benefit of all—now and in the future.

(M. Jarraud)
Secretary-General

INTRODUCTION

In recent years, there has been an unprecedented level of interest in the climate and environmental conditions of the polar regions. The discovery of the Antarctic ozone hole, record low levels of Arctic sea ice, loss of ice from the Greenland ice sheet, the disintegration of a number of floating ice shelves around the Antarctic Peninsula and the high levels of aerosols reaching the Arctic, have all been reported by the media. Moreover, climate model predictions indicate that high-latitude areas will warm more than any other region over the next century as a result of increasing levels of greenhouse gases. It remains to be seen, however, whether the rapid climatic fluctuations in the polar regions over the last few centuries and millennia are in fact a result of natural climate variability. It is important, therefore, to try to separate the impacts of natural climate variability from those of human activity.

Although the polar regions are remote from major populated areas, they are of great significance in the global climate system; changes at high latitudes can have an impact on ecosystems and human society through factors such as sea-level rise and variations in atmospheric and oceanic circulations.

The Greenland and Antarctic ice sheets contain 9 and 90 per cent, respectively, of the world's glacier ice. If both these ice sheets melted completely, they would contribute 7 m and 70 m, respectively, to sea-level rise. While such a dramatic occurrence is not expected, even on the time-scales of hundreds of years or millennia, the melting of a small fraction of this ice would nonetheless have serious implications for global sea-level rise and ocean circulation.

The polar regions are also characterized by large areas of sea ice—the Antarctic effectively doubles in size over the year as the ocean around the continent freezes. The sea ice provides an effective thermal cap on the top of the ocean and the expulsion of salt that takes place as it forms is important for the global circulation of the ocean.

Polar meteorology in this context is considered in a broad sense with respect both to the behaviour of weather systems and its role in the global climate system.

The polar regions have warmed more significantly than other regions.

Global impacts include sea-level rise, with the risk of flooding and even the continued existence of some low-lying areas and islands.

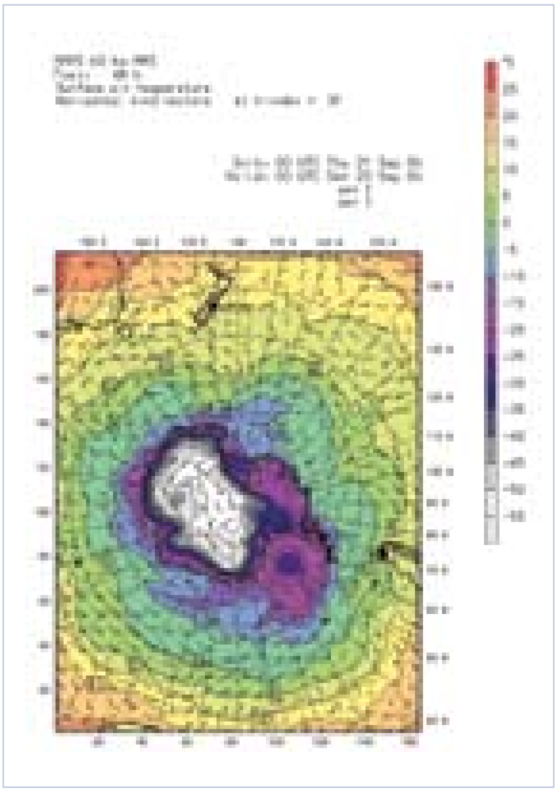
Local impacts—which are of global interest and importance—include threats to biodiversity—the survival of animal and plant species. At risk also is the traditional way of life of indigenous peoples of the Arctic, who depend on those animals and plants for their food, clothing, settlements, hunting and fishing weapons, etc.

POLAR METEOROLOGY

OBSERVING THE POLAR REGIONS

The polar regions are some of the least well observed areas on Earth, as far as in situ meteorological observations are concerned. For example, across the Antarctic, which is twice as large as the USA, there are only 44 stations making surface meteorological observations and some 14 stations launching radiosondes (instruments carried aloft, chiefly by balloon, to gather and transmit meteorological data). The more southerly parts of the Arctic are better served by observing stations because of the large number of human settlements there. Over higher latitude areas, however, few data are available from human observers because of the lack of island observing stations.

Through its Antarctic Activities Programme, WMO coordinates meteorological activities carried out by nations and groups of nations. Within the framework of the Antarctic Treaty, it focuses on the interfaces between these activities and other WMO Programmes, notably the World Weather Watch (WWW), and aims at meeting the requirements for meteorological services as well as for environmental monitoring and climate research, in particular, the upper-air soundings of meteorological variables generated by the WMO Antarctic Basic Synoptic Network. These provide vertical profiles from the surface to altitudes of about 25 km and even occasionally 35 km (the lower stratosphere). The surface and upper-air stations routinely provide coded reports that are essential for global weather forecasting. The observations are today sent from the polar regions via satellite communication systems and to the WMO Global Telecommunication System for transfer to the main forecasting centres. Specialized data and products for various users are generated by regional centres of the WMO Global Data-processing and Forecasting System.



A 48-hour forecast from the Antarctic Mesoscale Prediction System

Despite the harsh environmental conditions in the Antarctic and the problem of logistics, the Antarctic Basic Synoptic Network is well implemented, thanks to the efforts of National Meteorological and Hydrological Services

A mosaic of infra-red satellite imagery of the Antarctic and Southern Ocean on 21 August 2006

The Antarctic's massive ice cap and isolation from the rest of the planet by the Southern Ocean prevented any permanent human settlement prior to the establishment of scientific stations in the early 20th century.

The continents surrounding the Arctic Ocean have been temperate enough to be home to their indigenous populations for millennia.

An automatic weather station in the Antarctic

The Antarctic Treaty was opened for signature on 1 December 1959 and entered into force on 23 June 1961.

The Global Climate Observing System is co-sponsored by WMO, the Intergovernmental Oceanographic Commission of UNESCO, the United Nations Environment Programme and the International Council for Science.

(NMHSs) and the Antarctic programmes of the countries which are Parties to the Antarctic Treaty. Assessment of the Antarctic meteorological reports arriving at the main centres of WMO's Global Telecommunication System suggests that the percentage of reports received is close to the global average. Most of the observations from staffed stations in the Arctic and Antarctic provide a significant contribution to the upper–air and surface networks and database of the Global Climate Observing System.

Because of the lack of in situ data, polar meteorologists have always made extensive use of data from autonomous systems and polar-orbiting satellites. Since the 1960s, satellite imagery has been an important tool in identifying the locations of synoptic and mesoscale (less than 1 000 km diameter) weather systems over ocean and remote land areas. Although the early imagery was of poor quality with coarse horizontal resolution and few grey scales, many stations today have digital receivers capable of providing high-resolution images at several wavelengths.

The earliest satellite data for the polar regions consisted of visible and infra-red imagery. In recent years, however, a vast range of products has been produced from active and passive microwave instruments that allow the determination of temperature and humidity profiles (through the atmosphere in cloudy conditions), the extent and concentration of sea ice and winds over the ice-free ocean.

The lack of in situ observations from the polar regions led to the early deployment of automatic weather stations (AWSs), which provide frequent observations and require only infrequent maintenance. AWSs were first installed in the Antarctic in the mid-1980s and have proved their worth; more observations are now obtained from AWSs than from staffed stations. In the Antarctic, most research stations are located on the coast, so AWSs are essential for meteorological analysis in the interior. In the Arctic, they are installed on the land areas surrounding the Arctic Ocean in the Russian Federation, Fenno-Scandinavia, North America and Greenland. They have proved particularly valuable in Greenland, where temperatures have risen markedly in recent years.

An AWS is a stand-alone system that typically measures surface meteorological variables, such as wind speed and direction, air temperature and air pressure and may measure additional variables such as relative humidity or vertical air temperature difference. Most polar AWSs transmit data in the blind for reception by the Argos System on board polar-orbiting satellites of the US National Oceanic and Atmospheric Administration

(NOAA) series or stored on a memory module for retrieval at a later date. In the Antarctic, some 70 AWSs currently supplement the data from staffed stations.

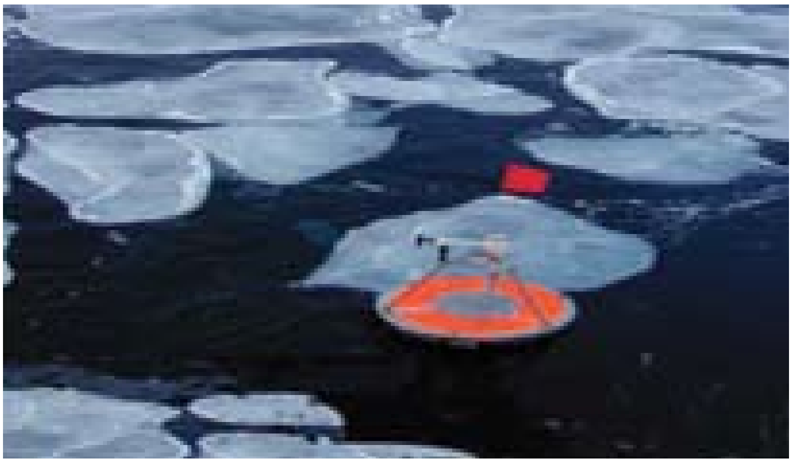
To obtain data over the Arctic Ocean or in the sea-ice zone around the Antarctic, drifting buoys are deployed on the ice. The major advance in the development and deployment of drifting buoys came with the First GARP (Global Atmospheric Research Programme) Global Experiment (FGGE) in 1978/1979, when over 300 systems were deployed in the Southern Ocean to investigate atmospheric predictability and the requirements for an optimum observing system. Since then, many different types of drifting buoy have been deployed in the Arctic by the International Arctic Buoy Programme (IABP) and in the Southern Ocean by the International Programme for Antarctic Buoys (World Climate Research Programme/Scientific Committee on Antarctic Research (WCRP/SCAR)). Currently, a number of commercial companies and research institutes manufacture buoys. These are of varying degrees of sophistication, from low-cost ocean drifters with no meteorological sensors to advanced systems making a wide range of atmospheric and oceanographic measurements.

Various instruments can be attached to the basic buoy platform, depending on the data requirements and experiments to be carried out. Measurements include atmospheric pressure, wind speed and direction, air temperature and humidity at various levels above the surface and, in the case of buoys on ice floes, the surface temperature of the snow or ice and snow thickness. Using the IABP data, significant warming of the Arctic in the 1980s and 1990s was detected.

Although some surface synoptic weather charts were prepared in the early part of the 20th century, they covered mainly the more populous regions and lacked accuracy at high latitudes. In particular, there were very few observations over ocean areas of the Antarctic; Arctic analyses were somewhat better. An increasing number of observations became available from polar-orbiting meteorological satellites in the 1970s that allowed more reliable atmospheric analyses in high-latitude areas. The atmospheric temperature sounders flown on polar-orbiting satellites since the mid-1970s were of particular importance. Similar in nature to radiosonde ascents, they provided profiles of temperature and humidity from the surface up to the stratosphere with the broad coverage provided by a satellite system.

Over the last few years, the historical archive of in situ and satellite observations have been re-processed using data-assimilation

The World Climate Research Programme is co-sponsored by WMO, the Intergovernmental Oceanographic Commission (UNESCO) and the International Council for Science.



A drifting buoy on an ice floe in the Weddell Sea, Antarctic

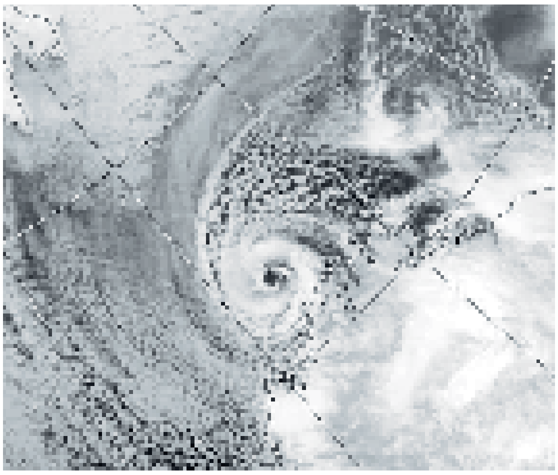
Meteorological conditions at the Poles are different. The North Pole is located over the Arctic Ocean, while the South Pole is on the high Antarctic plateau.

techniques to produce so-called "re-analysis" datasets, which provide a particularly valuable source for investigation of climate variability over the last three decades or so. The re-analysis fields for the southern hemisphere prior to 1974, when satellite sounder data became available, were poor, however, and cannot be used to investigate atmospheric circulation change.

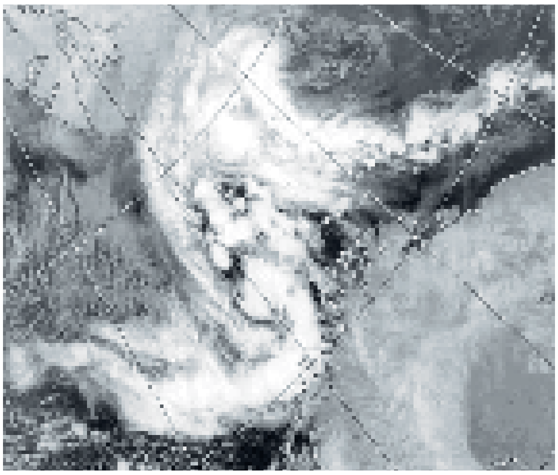
HIGH-LATITUDE WEATHER SYSTEMS

The Arctic and Antarctic are poleward of the main storm tracks in the northern and southern hemispheres and mean sea-level surface-pressure charts show climatological anticyclones in these areas. Nevertheless, care needs to be exercised in calculating atmospheric pressure at mean sea-level using measurements taken at elevated areas of the Antarctic and Greenland. Meteorological conditions at the Poles are different, as the North Pole is located over the Arctic Ocean, while the South Pole is on the high Antarctic plateau.

In the northern hemisphere, because of the major mountain ranges of the Himalayas and the Rockies, the tropospheric flow is highly meridional with many weather systems reaching high latitudes and occasionally crossing the Arctic Ocean. On the other hand, the southern hemisphere has few large, high land masses so the depressions move in a much more zonal track, spiralling only gradually towards the Antarctic coastal region. The fact that the Antarctic consists of a large, high mass of ice centred near the South Pole has a large impact on the atmospheric circulation of



An active polar low with a spiral cloud pattern



A polar low off the north coast of Norway with extensive convective cloud

The branch of physical geography which deals with the formation and features of mountains is called orography.

the southern hemisphere. Depressions moving southwards from mid-latitudes tend to become slow moving or start to track towards the east in the Antarctic coastal region as they encounter steep mountains. There are, therefore, few active depressions over the Antarctic interior, although some depressions do penetrate to Dome C, South Pole or even Vostok, where the mid-tropospheric flow is more meridional. This appears to happen as part of natural climate variability and can be detected at interior stations by a sudden, rapid rise of temperature, the presence of cloud and occasionally moderate precipitation falling in what is a cold desert.

The Antarctic coastal region between 60°S and 70°S is home to many active depressions and smaller-scale lows. The occurrence of so many storms means that atmospheric pressures are low and the zone is known as the circumpolar trough. There is no comparable feature around the Arctic, where orographic conditions are different.

Polar lows

The most violent weather systems found in the Arctic are short-lived (usually less than 24 hours), mesoscale polar lows, which are active depressions occurring over certain ice-free, maritime areas poleward of the polar front—the main boundary between polar and tropical air masses. Polar lows in the Arctic are primarily a winter season phenomenon. Most active polar lows have a horizontal scale of 400-600 km, although convective systems can have smaller vortices embedded within them. Polar lows are part of the broad category of disturbances known as polar mesocyclones, which includes the many minor vortices observed on satellite imagery of the polar regions. The definition of a polar low is that it should have a surface wind speed of 17 m/s or stronger. Observations have indicated that they can have wind speeds as high as 33 m/s. They bring some of the worst weather to Arctic coastal and island locations and can be a major hazard to maritime operations, as well as gas and oil exploration and production platforms.

In the Antarctic, the air-sea temperature differences are much less than in the Arctic and deep convection is not found close to the coast of the continent or at the latitude of the circumpolar trough. Hence, the polar lows that occur tend to be found on shallow horizontal temperature gradients, although many minor polar mesocyclones appear on satellite imagery.

Individual polar lows are obviously important in weather forecasting for the two polar regions but it is still unclear whether they are important climatologically. With the large

Mesoscale polar lows are referred to by a wide variety of names, including Arctic hurricane, Arctic bomb, Arctic instability low, cold air depression, comma cloud and polar mesocyclone.

Polar lows

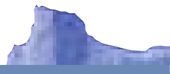
Polar lows were first investigated in the late 1960s when satellite imagery became available, but studies were hampered by the lack of in situ observations since the lows rarely crossed synoptic observing stations. Early modelling studies frequently failed to represent the systems because of their small horizontal scale and the poor parameterization of some key physical processes, such as deep convection. Recently, major advances have been made in our understanding of these systems as a result of campaigns in which dedicated aircraft fly through the lows, studies using multiple sources of satellite data, and experiments with high-resolution, limited-area models.

In the late 1960s/early 1970s, there was debate as to whether polar lows formed and deepened in the same way as mid-latitude depressions on horizontal temperature gradients or whether they were mainly associated with deep Cumulonimbus clouds, rather like hurricanes. Today, we know that there is a spectrum of disturbances ranging from the rather rare small-scale depressions, which form on shallow temperature gradients with a frontal structure that resembles a small mid-latitude cyclone, to the systems characterized by many deep Cumulonimbus clouds.

Polar lows were first investigated in the Norwegian and Barents Seas areas, where the systems affected coastal communities of Norway and produced some of the most significant snowfalls over the United Kingdom. As satellite imagery became more readily available, however, polar lows were identified in other parts of the Arctic where the air-sea temperature differences are large, including the Davis Strait/Labrador Sea, the Gulf of Alaska and the Bering Sea, the Beaufort Sea, north of the Russian Federation coast, the North-West Pacific, the Sea of Japan, and surrounding areas.

While some polar lows are found in the Antarctic, they develop primarily on shallow horizontal temperature gradients, as there is no deep convection at high southern latitudes. This situation arises because the oceanic circulation of the southern hemisphere is much more zonal than north of the Equator, and warm water masses do not reach the Antarctic coastline. Large air-sea temperature differences can exist in the coastal polynyas (ice-free areas of water within the pack ice) (see box on page 14), but the track of air across these areas is quite short so polar lows do not have time to develop.

air-sea temperature differences associated with polar lows, coupled with the high near-surface wind speeds, surface heat fluxes of up to 1 000 W/m^2 have been recorded, although there are relatively few such systems each season at a particular location. The question has been posed as to whether the many minor vortices at high latitudes can together generate sufficient heat loss from the surface of the ocean to trigger downward convection, which may affect the thermohaline circulation, which is driven by differences in ocean water density arising from temperature and salinity gradients.



This question can only be answered using modelling experiments which are currently being carried out.

WEATHER FORECASTING IN THE POLAR REGIONS

Although most parts of the polar regions are remote from the major population centres, there is still a need for reliable weather forecasts. In the Arctic, forecasts are needed for the indigenous communities and in support of maritime operations and oil and gas exploration and production. In the Antarctic, reliable forecasts are needed for the complex air and sea logistical operations that support research programmes and for the growing tourism industry. Forecasts are also needed for field parties working in remote locations.

Forecasts of the weather over the Arctic and Antarctic have been made since the first expeditions, although they were poor in the early years owing to the few observations available and a rudimentary understanding of the workings of high-latitude climates.

This situation remained more or less unchanged until the International Geophysical Year (IGY) of 1957-1958, when a number of research stations were established at high latitudes, especially across the Antarctic, with many of these making routine radiosonde ascents. These additional data allowed more reliable surface and upper-air analyses to be prepared, although there were still few observations over the ocean areas.

Satellite imagery has been used as an aid to weather forecasting since the 1960s. For many years, the analyses were poor at high latitudes and imagery provided the only means of determining the "truth" regarding atmospheric conditions. The images were used to provide early warning of approaching weather systems, fronts and isolated cloudbanks, as well as supplementary information on sea-ice extent.

Since the late 1970s, it has been possible to determine upper-level temperature and humidity profiles through the atmosphere using data collected by polar-orbiting satellites. Such objective data allowed the implementation of

The wind scatterometer is a satellite-borne instrument which provides surface wind observations from measurements of radar backscatter from the ocean.

global numerical weather prediction (NWP) systems that could provide forecasts for several days ahead. During the 1980s, the accuracy of polar forecasts from such NWP systems was much lower than those for tropical and mid-latitude areas but, during the 1990s, there were marked improvements as a result of better analysis techniques, higher model horizontal resolution and additional data from new satellite-borne instruments, such as the wind scatterometer.

Today, the forecasting problem in the Antarctic is quite different over the ocean areas and the continent itself. Over the ocean, the NWP models have greater accuracy than in the northern hemisphere because the orography of the southern hemisphere is less complex. However, over the continent, and especially in the coastal region, sites are affected by local wind systems that many global models cannot capture. Forecasters therefore tend to adopt a nowcasting approach based on satellite imagery to predict the winds up to 24 hours ahead. High horizontal resolution, limited-area numerical weather prediction models (such as the US Antarctic Mesoscale Prediction System) are starting to predict surface winds in areas of complex orography with more success.

The forecasting problem is somewhat easier in the Arctic, since much of the region is ringed by land from which many in situ meteorological observations are provided. These, coupled with satellite sounder data, allow high-quality numerical analyses and forecasts to be prepared. The relatively low orography of the Arctic also aids predictability. The main exception is the interior of Greenland, where the same problems apply as are found on the Antarctic plateau.

The forecasting process

Weather forecasting in the Arctic and Antarctic presents a number of unique challenges compared to the extra-polar regions (see box on page 23). The great advances in observing systems and numerical weather prediction described above, however, have considerably

improved the quality of the forecasts, but the tasks of forecasting over land and ocean areas are quite different.

Over ocean areas, the large amounts of satellite sounder data that are now available mean that the meteorological analyses are of high quality, despite the lack of radiosonde data. This is turn means that the NWP fields can be used with confidence over two or three days, and give a reasonable indication of the broadscale developments to be expected up to about six days ahead. Across the Antarctic continent and in the interior of Greenland, the lack of in situ data, the problems of deriving satellite temperature soundings over a high, ice-covered surface and the complex local wind and cloud systems mean that the quality of the NWP fields drops off rapidly away from the coast.

A recent development has been that limited-area NWP models with high horizontal resolution are being run operationally across certain parts of the Antarctic. Although no additional data are as yet included in these models, the high horizontal resolution and the more realistic orography that can be included has the potential to give better short-term weather forecasts.

THORPEX

THORPEX (The Observing System Research and Predictability Experiment) is part of WMO's World Weather Research Programme. It provides an organizational framework that addresses weather forecast problems, including those in polar areas, whose solutions will be accelerated through international collaboration among operational forecast centres of National Meteorological and Hydrological Services, academic institutions and users of forecast products.

In the context of the International Polar Year 2007-2008, THORPEX has specific research goals (see box below). In order to assist in accomplishing these research goals, field campaigns will be carried out during an IPY intensive observing period.

A radiosonde is a unit for use in weather balloons that measures various atmospheric parameters and transmits them to a fixed receiver.

Radiosondes measure or calculate the following variables:

- Atmospheric pressure
- Altitude
- Geographical position (latitude/longitude)
- Temperature
- Relative humidity
- Wind speed and direction

THORPEX and the International Polar Year 2007-2008

In the context of the IPY, THORPEX seeks to:

- Address the two-way interactions of polar and sub-polar weather regimes
- Assess and improve the quality of operational analyses and research reanalysis products in the polar regions
- Address the improvement of data-assimilation techniques for the polar regions
- Assess the skill in the prediction of polar-to-global high-impact weather events for different observing strategies in higher latitudes
- Demonstrate the utility of improved utilization of ensemble weather forecast products for high-impact weather events and for IPY operations, when applicable
- Develop recommendations on the design of the Global Observing System in polar regions for weather prediction

THORPEX is a key component of the WMO Natural Disaster Reduction and Mitigation Programme. It will contribute to WMO's goal to halve the number of deaths due to natural disasters of meteorological, hydrological and climatic origin over the next 15 years.

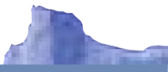
Glaciers, ice shelves and icebergs

When Antarctic glaciers reach the coast of the continent, they begin to float and become ice shelves, from which icebergs are then calved. Since 1974, a total of 13 500 km^2 of ice shelves have disintegrated in the Antarctic Peninsula, a phenomenon linked to the regional temperature rise of more than 2°C in the past 50 years.

Similar break-ups in other areas could lead to increases in ice flow and cause sea-level to rise dramatically. The final collapse of the Larsen B platform in February 2002 freed an additional 3 250 km^2 of sea bottom of an ice cover that has been estimated to have been there for at least 5 000 years.

The vanishing ice allows vegetal and animal plankton to invade and thrive. Studies will be carried out to determine the changes in ecosystems structured largely by ice in these areas. Researchers will monitor previously fished areas located in the western part of the Antarctic Peninsula to determine the state of stock recovery.

Much of the planned IPY-THORPEX research is aligned with the THORPEX focus on global-to-regional influences on the evolution and predictability of weather systems and the IPY objective of understanding polar-global tele-connections on all scales, and the processes controlling these interactions. IPY-THORPEX will address high-impact weather forecasts, the predictability, and increased knowledge of related physical and dynamical processes associated with polar and sub-polar interactions. Examples of research investigations include the role of Greenland's orography on European and African cyclonic storm systems, the interactions between tropical, middle latitude and polar processes, Rossby wave trains excited by intense cyclogenesis off the coast of Asia and whether anomalous open water in the vicinity of the Arctic and Antarctic can lead to modifications to storm



Changes in Arctic sea-ice conditions impact navigation.

THORPEX: accelerating improvements in the accuracy of one-day to two-week high-impact weather forecasts for the benefit of society, the economy and the environment

tracks, storm intensity and the Ferrel/Walker circulations.

The IPY-THORPEX will also address other core THORPEX goals in order to contribute to the development of advanced data-assimilation and ensemble prediction systems and to contribute to the design and demonstration of interactive forecasting systems. These efforts include a focused campaign over the Antarctic aimed at evaluating and improving satellite data-assimilation techniques, which will contribute to the IPY core objective of determining the present environmental status of the polar regions by quantifying their spatial and temporal variability.

The improvement in satellite assimilation over the poles afforded by this study will be an observational legacy of improving our ability to predict polar weather systems, the interactions of polar processes with lower latitudes and our ability to monitor the climate over the poles.

Many animals are at risk from global warming in the polar regions, such as penguins. It behoves all nations to preserve these unique communities for the benefit of future generations.

THE ROLE OF THE POLAR REGIONS IN THE GLOBAL CLIMATE SYSTEM

THE POLES

The global climate system is driven by energy from the Sun, most of which, at any one time, arrives at low latitudes. Over the year, the Equator receives about five times as much heat as the Poles, creating a large Equator-to-Pole temperature difference. The atmospheric and oceanic circulations respond to this large horizontal temperature gradient by transporting heat polewards. In fact, the climate system can be regarded as an engine, with the low latitude areas being the heat source and the polar regions the heat sink.

Both the atmosphere and the oceans play major roles in the poleward transfer of heat, with the atmosphere being responsible for 60 per cent of the heat transport, and the ocean the remaining 40 per cent. In the atmosphere, heat is transported by both the depressions and the mean flow. The depressions carry warm air poleward on their eastern sides and cold air towards lower latitudes on their western flanks. The atmosphere is able to respond relatively quickly to changes in the high- or low-latitude heating rates, with storm tracks and the mean flow changing on scales from days to years. Oceanic change takes place on much longer time-scales.

The different distribution of land masses in the northern and southern hemispheres has a major impact on the atmospheric and oceanic circulations, with the mean ocean and atmospheric flows in the south being much more zonal than in the north.

Virtually everywhere in the southern hemisphere, the atmospheric heat transport is greater than the contribution from the ocean while, north of the Equator, the ocean transport dominates from the Equator to 17°N. The peak of transport is found in both hemispheres close to 35° from the Equator. At those latitudes, the atmospheric component is about 78 per cent of the total in the northern hemisphere and 92 per cent in the southern hemisphere.

A further consequence of the different land/sea conditions in the two hemispheres is that the Equator-Pole temperature difference in the south is almost 40 per cent greater than in the north, producing stronger mid-latitude westerlies.

The poleward atmospheric transport of heat is largest during winter, when there is strong heat loss at high latitudes and the largest temperature difference between equatorial and tropical latitudes.

LINKS WITH LOWER LATITUDES

The polar regions are linked to the rest of the Earth's climate system by complex paths through the atmospheric flow and the ocean circulation. The circulation of the upper layers of the ocean can change over months to years, but the deep ocean and the global thermohaline circulation require decades

Atmospheric conditions during the positive phase (top) and negative phase (bottom) of the North Atlantic Oscillation (see pages 18-20 for more details).

The climate system can be regarded as an engine, with the low latitude areas being the heat source and the polar regions the heat sink.

The principal modes of variability in the atmospheric circulation of the extra-tropics and high latitudes are referred to as the Northern Hemisphere Annular Mode, which is closely related to the North Atlantic Oscillation and the Southern Hemisphere Annular Mode (also known as the high latitude mode or the Antarctic Oscillation).

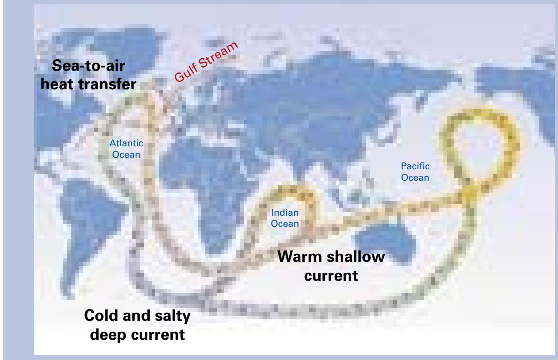
The word thermohaline is derived from the Greek words for heat (*therme*) and salt (*hals*), which, together, determine the density of seawater.

The thermohaline circulation is variously called the ocean conveyor belt, the global conveyor belt, or the meridional overturning circulation.

Thermohaline circulation

The thermohaline circulation links the major oceans. It plays an extremely important part in linking the high-latitude regions with the rest of the Earth system and provides a direct link between the Arctic and Antarctic.

It is driven by differences in the density of seawater, which, in turn, are controlled by temperature and salinity. Wind-driven surface currents (such as the Gulf Stream) head polewards from the equatorial Atlantic Ocean, cooling all the while and eventually sinking at high latitudes (forming North Atlantic Deep Water). This dense water then flows into the ocean basins. While the bulk of it upwells in the Southern Ocean, the oldest waters (with a transit time of around 1 600 years) upwell in the North Pacific. Extensive mixing therefore takes place between the ocean basins, reducing differences between them and making the Earth's ocean a global system.



On their journey, the water masses transport both energy (in the form of heat) and matter (solids, dissolved substances and gases) around the globe. As such, the state of the circulation has a large impact on the climate of our planet.

to centuries to respond (see box above). The most rapid links between high and low latitudes therefore tend to be through the atmosphere.

Over the last few years, there has been a great deal of interest in the modes of variability of high-latitude areas. These reflect the means by which high- and mid-latitude areas interact and cover broadscale changes in atmospheric pressure and the major storm tracks.

The Northern Hemisphere Annular Mode (NAM) and the Southern Hemisphere Annular Mode (SAM) have zonally symmetric or annular structures, with synchronous anomalies of opposite sign in high and mid-latitudes. They can be seen in many parameters measured at high latitudes, such as surface pressure and temperature, geopotential height and zonal wind. NAM and SAM show little variability with height. Observational and modelling studies have shown that they contribute a large proportion of the high- and mid-latitude climate variability on a large range of time-scales, with SAM being likely to drive the large-scale circulation of the Southern Ocean. SAM and NAM are usually defined as the mean sea-level pressure difference between 40° and 65°.

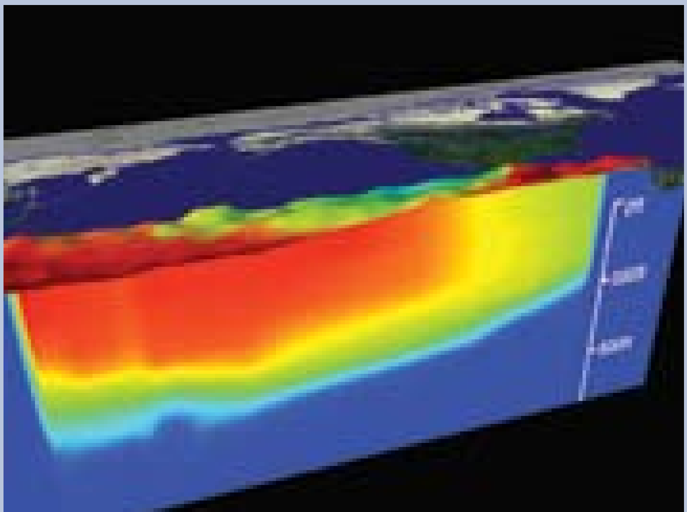
The North Atlantic Oscillation (NAO) is closely linked to the Arctic Oscillation and its variability has a major influence on the Arctic climate. NAO is the dominant mode of winter climate variability in the North Atlantic region

El Niño-Southern Oscillation

El Niño-Southern Oscillation (ENSO) is a major fluctuation of mass across the tropical Pacific associated with periods of “warm”, “cold” and intermediate conditions in the sea-surface temperatures (SSTs) of the eastern Pacific Ocean. During the more frequent “cold” periods, the tropical Pacific is characterized by strong easterly trade winds and a mean sea-level pressure distribution of high pressure over the eastern Pacific off South America and low pressure around Indonesia. This is accompanied by general ascent (descent) over the western (eastern) Pacific and a west-to-east return flow at upper levels in the atmosphere, known as the Walker Circulation.

Such a scenario tends to give extensive convective precipitation over Australasia and Indonesia (where SSTs are high), and more settled anticyclonic conditions over the eastern Pacific. The strong east-to-west trade winds induce a westward-moving ocean current, known as the South Equatorial Current, with an eastward-moving return current (the Equatorial Undercurrent) at lower levels. When these “cold” conditions are pronounced, the system is referred to as being in the La Niña phase of the cycle, when the Australasian convection can be marked with flooding in areas such as Australia and Indonesia. In the ocean, the upwelling of nutrient-rich water over the eastern Pacific can be extensive, with consequent benefits to the fisheries of South America.

During the “warm” phase of the ENSO cycle, know as El Niño, there is a reduction in the surface pressure gradient across the Pacific and a weakening of the trade winds. Convection over the western Pacific decreases and, in extreme El Niño conditions, there can be drought in parts of Australia. The main area of tropical convection moves eastwards towards the date line and SSTs rise across the central and eastern Pacific. Ocean currents are reduced in strength and there is a marked reduction in the upwelling off South America, with consequent effects on the fishing industry in the area.



Visualization of an El Niño-Southern Oscillation event (June 1997)

Teleconnections are statistically significant links between climates of different geographical areas which can be great distances apart.

El Niño-Southern Oscillation (ENSO) is the largest climatic cycle on Earth on decadal and sub-decadal time-scales. It has a profound effect not only on the weather and oceanic conditions across the tropical Pacific, where ENSO has its origins, but also in regions far removed from the Pacific basin.

The polar regions are keepers of the Earth's climate archives. They also act as a kind of early warning system of what could be expected by the planet as a whole ...

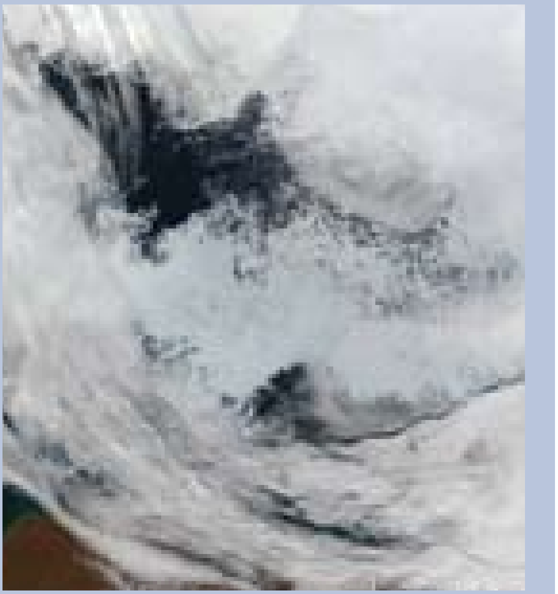
Climate changes in the Antarctic that affect the ice shelves, sea-ice production or the flow of cold, Antarctic air masses could have implications for the global ocean system.

Polynyas

"Polynya" is a Russian word meaning "an enclosed area of unfrozen water surrounded by ice". Although polynyas can be hundreds of kilometres wide, their surface area is far less than the area of sea ice which surrounds them. Some polynyas occur at the same time and place each year and certain animals adapt their life strategies to this regularity.

Polynyas teem with animal and plant life. It is only here, where the sea ice is absent, that the Sun's energy directly reaches the waters. Snow and ice ordinarily reflect much of the Sun's light energy, but the open waters of polynyas absorb it.

Phytoplankton in the polynya use this energy to produce a nutrient-rich grazing area for zooplankton. Feeding on these small animals are whales and fishes that in turn feed seals, walruses and polar bears.



A new polynya formed in the Beaufort Sea in August 2006 and continued to grow. By 11 September 2006, the area of open water had grown to some 100 000 km^2.

and its influence extends into the Arctic basin. NAO is a large-scale oscillation in atmospheric mass between the subtropical high close to the Azores and the low-pressure centre close to Iceland. The index varies from year to year but also exhibits a tendency to remain in one phase for intervals lasting several years.

During the positive phase of NAO, the subtropical high-pressure centre is stronger than usual, while the Icelandic low is deeper. The stronger pressure gradient results in more frequent and deeper winter storms crossing the Atlantic Ocean and reaching the northern parts of Europe. Europe gets warm, wet winters, but warm air is also carried into the Norwegian and Barents Seas, resulting in less sea ice than normal. On the other hand, the deep Icelandic low gives strong northerly flow down the Labrador Sea, resulting in more sea ice than usual around Greenland.

In the negative phase of NAO, both the subtropical high and the Icelandic low are weak, giving a reduced pressure gradient and fewer and weaker winter storms across the North Atlantic. There is cold air across northern Europe and in the western sector of the Arctic, causing more extensive sea ice. On the other hand, Greenland has milder winter temperatures.

During El Niño events, the intense storm activity in the tropical Pacific is close to the date line with deep convection giving divergence in the upper atmosphere. This results in long meteorological wave trains (Rossby waves) that travel polewards in both hemispheres and provide a means for the establishment of teleconnections between ENSO and the climates of mid- and high-latitude areas. In the North Pacific, a clear signal of ENSO warm events is transmitted northwards via Rossby wave trains known as the Pacific North American pattern. The northernmost limit of this wave train can affect the climate of Alaska, USA.

The most pronounced signals of ENSO in high southern latitudes are found over the South-East Pacific as a result of a Rossby wave train giving positive height anomalies over the Amundsen-Bellingshausen Sea during El Niño events and negative anomalies in the La Niña phase of the cycle. The extra-tropical signature can sometimes show a high degree of variability between events in this area, however.

The thermohaline circulation is the system that links the major oceans (see box on page 18). The seas around the Antarctic are particularly important because of the production of Antarctic bottom water—the densest water mass found in the oceans. Antarctic bottom water is formed by deep winter convection in the Antarctic coastal region, particularly in the Weddell and Ross Seas, but also in association with other ice shelves.

The water mass is formed as cold air from the Antarctic rapidly cools the surface waters, opening near-coastal polynyas (see box on page 20) and promoting downward convection. Brine rejection during the formation of sea ice on the ocean surface is also very important, as is melting under the ice shelves. Antarctic bottom water flows out into the world's oceans and is found below 4 000 m in all the ocean basins.

It flows northwards in the Atlantic Ocean, reaching the Arctic, where heat is released into the atmosphere. It can be appreciated,

Evidence of widespread sea-ice melting is corroborated by a recent three-fold increase in freshwater content of the Arctic Ocean.

Sea-ice area at the end of summer (September) has declined about 17 per cent over the last 25 years. Regionally, this is seen as a retreat in the ice edge of 300-500 km in the Beaufort Sea or the east Siberian Sea, depending on the year.

Sea ice is important for walruses during feeding as it provides a resting place between dives and enables them to fish over a wider area.

Taiga: the swampy coniferous forest of high northern latitudes

Tundra: a vast, nearly level, treeless Arctic region, usually with a marshy surface and underlying permafrost

The frozen areas of the Arctic tundra and taiga contain one-third of the world's soil-bound carbon. When the permafrost melts, it releases carbon and methane into the atmosphere and can contribute to increasing greenhouse-gas concentrations.

therefore, that climate changes in the Antarctic that affect the ice shelves, sea-ice production or the flow of cold, Antarctic air masses could have implications for the global ocean system.

Changes in ocean conditions in the Arctic can also have widespread implications. For example, ocean salinity anomalies in the central Arctic have been shown to propagate into the Greenland Sea, where they can cause major modifications to ocean stratification.

Significant advances in the understanding of the role of the Arctic in the global climate system were made during the years 1994-2003, the decade of the World Climate Research Programme's Arctic Climate System Study (ACSYS). The Arctic (and to a much lesser extent the sub-Antarctic islands) plays a further important part in the global climate system as a source and sink of important greenhouse gases, which are held in the permafrost or seasonally frozen ground. The frozen ground of the Arctic tundra and taiga contains methane, ozone and carbon dioxide. In fact, these areas contain one-third of the world's soil-bound carbon. When permafrost melts, it releases carbon into the atmosphere and can contribute to increasing greenhouse-gas concentrations.

RECENT HIGH-LATITUDE ENVIRONMENTAL CHANGES

In recent decades, there have been major changes in the polar environments, with rising near-surface air temperatures causing large decreases in perennial sea-ice extent in the Arctic, a reduction in the amount of snow cover, melting of permafrost and decreases

The polar bear is emblematic of the Arctic region. Climate warming puts at risk his habitat, his food supply and ultimately his survival — as well as that of the indigenous human population.

Weather forecasting problems specific to the polar regions

The wind field of the Antarctic is one of the most marked characteristics of the continent, with the persistent downslope (katabatic) winds in parts of the coastal region being the most directionally constant on Earth. The winds are strongest during the winter when strong radiational cooling produces a large pool of cold air on the plateau to feed the katabatic wind system. Strong katabatic winds are not found all around the coastal region but are concentrated in the main glacial valleys, particularly around the coast of the eastern Antarctic. Climatology provides a good guide to where the strongest katabatic winds are found, but excellent forecasts are provided for the coastal region by numerical weather prediction techniques.

Katabatic winds are less of a feature of the Arctic because the mountains are lower. Strong katabatic winds are found in the coastal regions of Greenland, however, where they can affect local communities.

A number of meteorological elements are of particular importance in the polar regions. One of these is surface contrast. This is the ease with which features on a snow-covered surface can be distinguished, either from the air or by a surface observer. For aviation, knowledge of surface contrast is vital so that safe take-offs and landings can be made. Surface contrast is dictated primarily by cloud cover; in cloud-free conditions, the surface contrast is usually excellent because of the small amounts of aerosol that are present in the polar atmosphere and very good visibility. The greatest problems are encountered with deep, opaque layers of cloud, often in the form of featureless Stratus, Altostratus or Nimbostratus. Under such conditions, it is often impossible for an observer to see small mounds or crevasses on the surface when only a few metres away. A forecast of surface contrast is therefore essentially one of the type and depth of cloud to be expected at a given location.

A related quantity is horizontal definition, which is the ease with which the boundary between the ground and the sky can be determined. The parameter is extremely important for flying operations on the ice shelves and in featureless parts of the polar regions, such as the interior Antarctic plateau or the centre of Greenland. In a similar way to surface contrast, horizontal definition is determined primarily by the type and nature of the cloud present. The worst conditions are experienced when there is a thick layer of Stratus, Altostratus or Nimbostratus. As with surface contrast, the forecasting of horizontal definition is carried out once a forecast has been made of the cloud to be expected. The key elements required are predictions of type and depth of cloud, plus knowledge of local orography. Together, these allow a subjective forecast of the horizontal definition to be made.

A katabatic wind is a wind that blows down a topographic incline such as a hill, mountain or glacier.

There have been contrasting trends in polar sea ice over the last couple of decades, with a large loss of ice in the Arctic and a slight increase in the Antarctic.

Satellites have revolutionized meteorological science and climate and environment monitoring. They enable scientists to observe and monitor the extent of pack ice, the volume of ice caps, the productivity of ocean waters and levels of stratospheric ozone.

Some of the largest environmental changes have taken place at high latitudes.

in river and lake ice. Melting glaciers in many parts of the Arctic are contributing to rising sea-level worldwide. In areas such as Alaska, melting glaciers can have pronounced regional effects through the contribution of their runoff to ocean currents and marine ecosystems in the Gulf of Alaska and Bering Sea. Change is less evident and less widespread in the Antarctic than in the Arctic.

Investigating high-latitude climate change presents a number of problems. The peoples of the Arctic have reported warmer and increasingly variable weather, as well as changes in terrestrial and marine ecosystems, which have had an impact on their traditional way of life.

The length of the records, however, is rather short compared to what is available in the more populous parts of the world. Around the Arctic, the climate records extend back over a century in some areas, but only about 50 years in the Antarctic. These observations provide us with the most accurate measurements of atmospheric conditions, yet the observations are widely separated in many regions, with few observations from over the oceans.

Temperature

Analyses of surface meteorological observations suggest that the near-surface air temperature of the Earth increased by approximately 0.6°C over the last century. However, the pattern of surface change across the Earth in the instrumental era is complex and sensitive to the period that is examined. Many studies highlight that some of the largest environmental changes have taken place at high latitudes.

The map of linear trends of annual surface temperature across the Earth over the last

Satellites provide invaluable environmental data, especially over areas where surface observations are sparse.

50 years indicates three "hot spots" over Alaska/northern Canada, central Siberia and the Antarctic Peninsula. These areas have all experienced annual mean temperature rises of more than 1.5°C over the past 50 years.

In the Arctic, the spatial and temporal pattern of temperature change has been complex. Time-series of seasonal surface temperature anomalies from 59 weather stations show many warm and cold periods that were often found only in limited sectors.

One of the most pronounced warm periods had its peak around 1940 as evidenced by temperature records and by the limited area of sea ice around Iceland. Experiments with climate models forced by increasing levels of greenhouse gases have not been able to reproduce this warm period, suggesting that it may have occurred because of natural climate interdecadal variability.

The warming trend across Alaska and northern Canada is primarily associated with a sudden warming around the mid-1970s. The climate of Alaska is strongly influenced by the climatological low-pressure centre located over the Aleutian Islands. When this low is deep, Alaska comes under the influence of warm, southerly air masses. When the low is weak, then cold, northerly air masses become more common and temperatures are lower. In the mid-1970s the shifted phase of the Pacific Decadal Oscillation (a major climate cycle of the Pacific region) resulted in a deepening of the Aleutian Low, and warmer conditions in the Alaskan area.

The Siberian warming on the other hand seems to be associated with the shift of the North Atlantic Oscillation/Arctic Oscillation into its positive phase over recent decades, resulting in the greater transport of warm Atlantic air across Europe and into central Asia.

While there were more regional/temporal episodic warm events from the 1930s to the 1950s, warm temperatures were more general across the Arctic during the 1990s. Surface data for 1979-1995 from the central Arctic show large warming trends for spring followed by winter, while trends are small for summer and autumn. Surface air-temperature warming trends are greater for inland regions than coastal/ocean regions. Siberia had warm anomalies around 1980 and the region from east Siberia to Canada has been warm since 1989. Many Arctic stations show positive spring anomalies for 2002–2005 and west Greenland has been warm since 1999. In addition to changes in mean temperatures, Alaska shows a substantial decrease in the number of extremely cold days.

In the Antarctic, the picture of recent climate change is quite different, with few significant temperature changes beyond the Antarctic Peninsula. Temperatures at the South Pole have dropped since the 1950s as the westerlies increased around the continent with the Southern Hemisphere Annular Mode shifting into its positive phase. There have been no significant changes at the Vostok station on the eastern Antarctic plateau, however.

Across the Antarctic peninsula, temperature changes have been quite different on the eastern and western sides. The eastern warming has been most pronounced during the summer and autumn seasons, and has been linked to the stronger westerlies, which are a consequence of the changes in the Southern

Over the next century, near-surface air temperatures are expected to rise more in the polar regions than in any other parts of the Earth. This will have serious implications for the cryosphere, oceanic and atmospheric circulations, the terrestrial environment and the indigenous peoples of the Arctic.

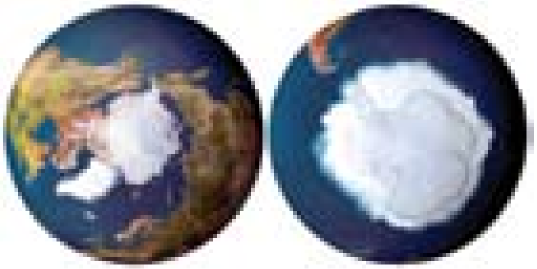
Shrinking pack ice in the Arctic has caused a reduction in the number of seals which are the principal food for polar bears.

Hemisphere Annular Mode. During these seasons, more warm air masses are crossing the peninsula compared to earlier decades, raising temperatures by several degrees. Since temperatures were previously close to freezing point, this has had a major impact on the environment, including contributing to the break-up of several ice shelves. Of course, the loss of the ice shelves does not directly affect sea-level since they were already floating on the ocean but their disintegration may result in glaciers on the eastern side of the peninsula flowing more quickly.

Temperatures on the western side of the Antarctic peninsula have risen by more than anywhere else in the southern hemisphere, with in situ data indicating warmings of 3°C in the annual mean and 5°C in winter temperatures over the last 50 years. In this area, there is a close association between winter season temperatures and the extent of sea ice off the coast, with years of extensive ice resulting in cold temperatures and years of little ice yielding high temperatures. The large warming trend in the area suggests more extensive sea ice in the 1950s and 1960s, although the reasons for this are not yet understood. The higher temperatures have been accompanied by a greater number of precipitation events, with a large increase in the number of reports of summer rainfall.

Sea ice

Prior to the 1970s, our knowledge of sea-ice extent and concentration was mostly based on ship and aircraft observations, with some information from coastal stations. The majority of these data are from the Arctic, where it has proved possible to prepare ice analyses for the Eurasian Arctic that extend back to 1930. Some Norwegian ice charts also exist for the North Atlantic going back to the 1500s, although the data on which they are based are extremely sparse in the early years. Drawing largely on this source, the WCRP ACSYS project was able to produce a climatology of Arctic Ocean sea-ice edge dating back as far as 1553.



Polar ice cover as seen by satellite

Reliable, high horizontal resolution sea-ice extent and concentration data are available for the polar regions from 1978, when the scanning multichannel microwave radiometer instrument was first flown on the Nimbus-7 polar-orbiting satellite. Such data showed that, over the period 1978-1996, Arctic sea ice decreased by 2.8 per cent per decade or 34 300 km^2 per year. These reductions took place in all seasons and over the year as a whole, but the losses were greatest in the spring and smallest in the autumn. The greatest losses were in the Kara and Barents Seas with decreases of 10.5 per cent per decade. Smaller levels of ice loss have taken place in the Seas of Okhotsk and Japan (greatest in winter) and the Arctic Ocean. Lesser ice loss occurred in the Greenland Sea, Hudson Bay and the Canadian Archipelago.

Since the mid-1990s, there have been several years with record low summer-ice extents. Data from the US National Snow and Ice Data Center indicate a September decline of more than 8 per cent per decade from 1979 to 2005. Based on the frequency of near-record low ice extents, it is likely that the Arctic Sea is on an accelerating, long-term decline. In addition, the recent ice minimum was believed to be lower than the Arctic ice minima of the 1930s and 1940s.

The winter of 2004/2005 was remarkable in that sea-ice recovery during the season was the smallest in the satellite record. As temperatures dropped over the winter, sea ice formed but, with the exception of May 2005, every month from December 2004 set a new record low ice extent for that month. September 2005 saw a new record minimum in Arctic sea-ice extent surpassing the previous record low in 2002. On 21 September 2005, the five-day running mean sea-ice extent dropped to 5.32 million km^2, the lowest ever observed in the satellite record, starting in 1978. All four years 2002-2005 had ice extents approximately 20 per cent less than the 1978-2000 mean, with the loss of sea ice amounting to approximately 1.3 million km^2.

The extent and concentration of Antarctic sea ice are known with confidence only since the 1970s, when reliable satellite passive microwave observations became available. These data show that, for the period 1979-1998, Antarctic sea ice as a whole increased by 11 180 km^2 per year or 0.98 per cent per decade. Regionally, the trends in extent were positive in the Weddell Sea, Pacific Ocean and Ross Sea sectors, slightly negative in the Indian Ocean sector and strongly negative in the Bellingshausen-Amundsen Seas. This is consistent with the ongoing warming on the western side of the Antarctic Peninsula, which is closely coupled with the oceanic conditions of the Amundsen-Bellingshausen Sea. For all sectors, the sea-ice increases occurred in all seasons, with the largest increase during the autumn. From region to region, the trends are different across the seasons.

There are only limited data available on sea-ice thickness, but data from a 1 000 km transect in two summer cruises in 1958 and 1970 suggested that the draft had decreased by 0.2 m in the transpolar drift stream and the Eurasian basin and by 0.7 m in the Canadian Basin. There is also evidence of sea-ice thinning of 0.8 m over 1976-1987 between Fram Strait

The Antarctic has no permanent human residents and has never had an indigenous population. Only certain plants and animals can survive there, including penguins, fur seals, mosses, lichens and algae.

The Arctic is mostly a vast, ice-covered ocean, surrounded by treeless, frozen ground. It teems with life, including organisms living in the ice, fish and marine mammals, birds, land animals and human societies.

Rising temperatures are affecting penguin populations with growth occurring in some parts and decline in others, especially where the food supply—krill— is disappearing.

Oil pipelines across areas of permafrost have fractured, resulting in significant pollution and environmental damage.

and the Pole and of 2.2 m north of Greenland. Upward-looking sonar measurements of sea-ice draft from submarines provide a record extending back into the 1950s. These have provided the first persuasive evidence of large-scale thinning over the entire Arctic basin. Such data showed that, between 1958 and 1976 and between 1993 and 1997, the mean ice draft at the end of the melt season had decreased in most deep water parts of the Arctic Ocean, from 3.1 m in the early period to 1.8 m in the 1990s, i.e. by about 1.3 m or 40 per cent.

Permafrost

Loss of permafrost in the Arctic is already having a profound effect on the environment because of the severe damage that can be caused to buildings reliant on permafrost for solid foundations. The trans-Arctic pipeline, which runs for some 1 287 km across Alaska, was a hugely expensive enterprise, but breaks in the pipeline and other repair costs due to melting permafrost could become significant. The near-term risk of disruption to operations of the pipeline is judged to be small, although costly increases in maintenance due to increased ground instability are likely. We can expect to see increases in such potentially damaging slumping of land in the coming decades.

The ice sheets and sea-level

The altimeters that have been flown since the early 1990s on polar-orbiting satellites allow us to determine the height of major ice sheets and therefore to investigate the question of mass balance—whether the ice sheets are growing or shrinking. The mass balance of an ice sheet is dependent on a number of factors, including the snow that falls on it, the amount of snow that is blown into the ocean, the loss of mass via iceberg calving and the isostatic adjustment.

Between 1992 and 2002, the Greenland ice sheet showed a mixed pattern of thickening and thinning. Above 1 200 m elevation, there has been thickening of 4 cm per year and ice growth of 53 gigatonnes (Gt) per year. Below that elevation, there has been thinning of 21 cm per year and a shrinkage of 42 Gt per year. This has resulted in a small overall mass gain of 11 Gt per year, which is equivalent to a drop of -0.03 mm per year in sea-level.

The west Antarctic ice sheet is losing mass at a rate of -47 Gt per year, while the ice sheet in the eastern Antarctic shows a small mass gain of +16 Gt per year. The combined net change has been -31 Gt per year or an increase in sea-level of +0.08 mm per year.

This is of particular interest, since much of it is grounded below sea-level. A complete loss of the west Antarctic ice sheet would result in a 5 m sea-level rise so there is obvious concern over the disintegration of even a small section. Satellite data have recently revealed a thinning of part of the ice sheet in the vicinity of Pine Island glacier. This is the largest glacier in the western Antarctic. It is up to 2 500 m thick and is grounded over 1 500 m below sea-level. In the eight years from 1992, the glacier retreated inland by over 5 km with the loss of 31 km^3 of ice. The loss of ice from the Pine Island and Thwaites glacier basins are probably ice-dynamic responses to long-term climate change and maybe also to past removal of their adjacent ice shelves. If the present rate of thinning continues, it is thought that the whole Pine Island glacier could be lost to the ocean within a few hundred years. An important research target must be to understand why this glacier is currently shrinking, whether this is a result of anthropogenic activity and whether, in a warming world, the thinning of other glaciers could start to accelerate and drain more ice from the interior of the ice sheet with consequent impacts on sea-level.

Since 1992, global mean sea-level has been rising at a rate of 3.2 ± 0.4 mm per year, compared to 1.7 ± 0.3 mm per year in the previous century. This is faster than the rate of 1 mm per year that has characterized the last 5 000 years. Sea-level rise is a result of thermal expansion of the ocean, increased river flow into the ocean, changes in precipitation/evaporation and loss of ice from the ice sheets. The exact reasons for the current rise in sea-level are not known and are a major topic of research.

The Antarctic ozone hole

Ozone is an extremely important gas in the stratosphere as it absorbs solar ultraviolet (UV) light, protecting humans and other elements of the biosphere. The total amount of ozone through the depth of the atmosphere was first measured in the Antarctic during the IGY (1957-1958) by surface-based instruments. These showed that typical values for the total ozone amount were around 300 Dobson Units (DU), which corresponds to a layer of ozone 3 mm thick at the surface.

The seasonal cycle of ozone in the Antarctic is linked to the development and breakdown of the winter circumpolar vortex, which is the strong circulation around high southern latitudes. Historically, ozone values within the vortex were around 300 DU at the beginning of the winter and similar at the end. During the winter, ozone amounts build up in a circumpolar belt just outside the vortex, due to transport of ozone from source regions in the tropics. Since the mid-1970s, an increasingly different pattern of behaviour has been observed—the Antarctic ozone hole. At the end of winter, values were found to be around 10 per cent lower than they were in the 1970s and they then dropped about 1 per cent per day to reach around 100 DU at the end of September. Values then slowly began to recover as the stratosphere warmed. Because the spring warming in the stratosphere is often delayed to the end of November or into December, the ozone hole can last several months.

The Antarctic ozone hole developed because of emissions, mainly in the northern hemisphere, of chlorofluorocarbons (CFCs) and halons. These gases were widely used in refrigeration, as industrial solvents and for fire control. If the provisions of the Montreal Protocol on Substances that Deplete the Ozone Layer of 1987 are strengthened and followed, and according to the UNEP/WMO "Scientific Assessment of Ozone Depletion: 2006", the ozone layer over the mid-latitudes should recover by approximately the middle of this century. Over the Antarctic, the recovery would take approximately 15 years longer. Currently, it seems to have stabilized, with some variation from year to year, depending on atmospheric conditions.

While the Antarctic ozone hole is present, there are increased levels of ultraviolet radiation at the surface of the continent, which can be a hazard to humans and biota. Reduced levels of ozone can also have an impact on lower latitudes. The polar vortex can frequently become elongated and extend over the southern part of South America and Australia, resulting in increased UV at the surface there. Many newspapers in these regions provide reports and predictions of UV levels to alert the community to take precautions and use sun block.

Four million indigenous peoples live on eight million square kilometres of the habitable Arctic landmass.

Many studies highlight the vulnerability of the Greenland ice sheet in a world of increasing air temperatures.

If sea-level continues to rise at its present rate or more, it will pose a very significant problem for low-lying areas across the world.

The ozone layer protects life on Earth by blocking harmful ultraviolet rays from the Sun. The "ozone hole" is a severe depletion of the ozone layer high above the Antarctic.

The 1987 Montreal Protocol to the Vienna Convention for the Protection of the Ozone Layer (1985) banned ozone-depleting chemicals, but the long lifetime of those chemicals means that the ozone layer will not recover for several decades.

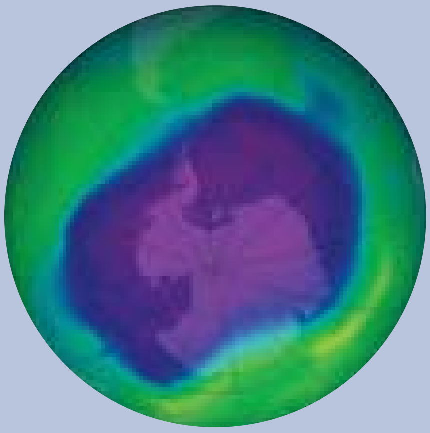
The annual assessments of the state of the ozone layer over the Antarctic and Arctic are based on data collected by WMO's Global Atmosphere Watch. During the Antarctic ozone hole season from late August through November, WMO issues bi-weekly bulletins on the state of the ozone layer. More information can be found at: http://www.wmo.int/web/arep/ozone.html.

The Antarctic ozone hole in 2006

From 21 to 30 September 2006, the average area of the Antarctic ozone hole was the largest ever observed, breaking records for both area and depth. A little over a week after the ozone hole sustained its new record high for average area, satellites and balloon-based instruments recorded the lowest concentrations of ozone ever observed over the Antarctic, making the ozone hole the deepest it had ever been.

The new record set in 2006, by contrast, was for the largest average area over an 11-day period, indicating that the hole stayed larger for longer than it ever has before.

While human-produced compounds break down the ozone hole by releasing chlorine and bromine gases into the atmosphere, the temperature of the Antarctic stratosphere causes the severity of the ozone hole to vary from year to year. Colder-than-average temperatures result in larger and deeper ozone holes, while warmer temperatures lead to smaller ones. In 2006, temperatures plunged well below average, hovering near or dipping below record-lows. These unusually cold temperatures increased the size of the ozone hole.



The Antarctic ozone hole on 24 September 2006. The blues and purples indicate low ozone levels, while greens, yellows and red point to higher ozone levels.

Depletion of the Arctic ozone layer has also been observed, albeit to a lesser extent, because the temperatures in the lower stratosphere there usually remain higher than those over the Antarctic. Ozone depletion is a concern in the Arctic, however, because of the human settlements there and the risk to the fish and animal life which is their traditional source of food.

HOW WILL THE POLAR REGIONS CHANGE IN THE FUTURE?

Possible consequences for the rest of the globe

The main tools we have for predicting how the climate of the Earth will evolve are coupled atmosphere-ocean climate models. Yet current climate models do not work well in the polar regions in trying to simulate the climate of the 20th century. For example, they failed to predict atmospheric conditions that led in recent years to the dramatic break-up of Antarctic ice shelves. Furthermore, the various models have a high degree of variability in their predictions. Research is needed to refine their outputs.

Atmospheric circulation

Model predictions suggest that, with increasing levels of greenhouse gases, the Southern Hemisphere Annular Mode and the Northern

Hemisphere Annular Mode may be in their positive phase for a greater length of time. This will result in lower atmospheric pressures over the Arctic and Antarctic and higher pressures at mid-latitudes. With the greater pressure gradient between the mid-latitudes and the Poles, there will be an increase in the strength of mid-latitude westerly winds.

Temperature

The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (2001) estimated that, over the period 1990-2100, globally averaged surface temperatures will rise by 1.4-5.8°C. This range of estimates comes from the outputs of 35 greenhouse-gas emission scenarios and a number of climate models.

The model runs for the IPCC's Fourth Assessment Report suggest that, with an increase in greenhouse gases of 1 per cent per year, annual mean surface temperatures in the Antarctic sea-ice zone over the 21st century would increase by 0.2-0.3°C per decade. There would be a corresponding decrease in the extent of sea ice. Large parts of the high interior of the Antarctic would experience surface temperature rises of more than 0.3°C per decade. This would weaken the katabatic winds, especially in the summer season.

For the Arctic, a major focus of research has been the Arctic Climate Impact Assessment, which involved hundreds of research scientists. Based on the results from an average of the output from five climate models, which were also used for the IPCC, temperature projections were produced for the next century. The models all predicted a steady rise in annual mean temperature with, on average, temperatures being 4°C higher by 2100.

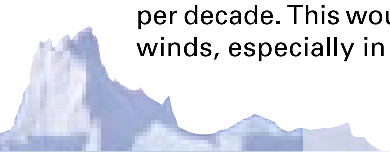
The models suggest the largest temperature increases will be in autumn and winter after much of the Arctic's sea ice has either gone or thinned. The albedo feedback associated with retreating sea ice dominates the signal of high-latitude climate warming.

With rising temperatures, there will be a northward shift of the Arctic climatic zones with a poleward extension of the boreal forests and the treeline. This will result in a transformation of Arctic landscapes, with the northern edge of the boreal forest advancing into the area now covered by tundra. In areas such as Alaska there are fears that there will be a loss of the moisture needed for forest growth, a rise in tree mortality caused by invasions of insects, increased risk of large fires and detrimental changes to the reproduction of some trees, such as white spruce.

The IPCC has estimated that, over the period 1990-2100, globally averaged surface temperatures will rise by 1.4-5.8°C.

It has also estimated that, by 2100, sea-level may have risen by between 0.09 and 0.88 m.

Albedo: the ratio of the outgoing solar radiation reflected by an object to the incoming solar radiation incident upon it.



The Arctic Council is a grouping of the eight countries that have territory in the Arctic: Canada, Denmark (Greenland, Faeroe Islands), Finland, Iceland, Norway, the Russian Federation, Sweden and the USA.

The focus of the Arctic Council is the environment and sustainable development.

http://www.arctic-council.org/

Across the Antarctic, many mammals and plant species require specific climatic conditions in which to flourish, with temperature and the amount of liquid precipitation being particularly important, although the level of UV-B radiation is also a significant factor. The amount of UV-B radiation received in the spring has increased markedly in recent years with the appearance of the Antarctic ozone hole, with consequent impact on the biota. Increasing temperatures would extend the active season, boost development rates and reduce the life cycle duration. In addition, there would be reduced stress tolerance, altered distribution of species and exotic colonization. An increase in water availability would create an extended active season, further the local distribution of species and expose new ground for colonization. Meanwhile, an increase in UV-B radiation could alter resource allocation, damage cellular structures and impact the food chain.

Sea ice

Because sea-surface temperatures are increasing, the extent of both Arctic and Antarctic sea is expected to decrease over the next century. It is thought that this process will be amplified by feedbacks in the Arctic, with some climate models predicting that all summer season sea ice will disappear by the second half of the 21st century.

Sea-ice retreat will allow larger storm surges to develop in larger areas of open water, increasing erosion through greater wave activity. There would also be sedimentation and the risk of flooding in coastal areas.

Although loss of Arctic sea ice could have serious implications for the ocean circulation, there could be some benefits in terms of navigation around the northern parts of the Russian Federation and Canada. A longer ice-free summer season could provide substantial

benefits for marine transport and offshore gas and oil operations, which could have major implications for international trade.

Loss of sea ice around the Antarctic threatens large-scale changes in marine ecosystems, including threats to populations of marine mammals, such as penguins and seals. Of the six species of Antarctic seal, four breed on the sea ice during spring and may be affected by major reductions in sea-ice extent. At present, the Antarctic sea ice shelters the larvae of the vast krill population that feeds countless seabirds, seals and whales; serious reductions in the extent of sea ice would diminish the krill population, with subsequent effects on higher predators.

Permafrost

Permafrost is highly sensitive to long-term atmospheric warming, so there will be a progressive thaw of the permanently and seasonally frozen ground around the Arctic. The IPCC has estimated that, under some greenhouse-gas emission scenarios, 90 per cent of the upper layer of Arctic permafrost may thaw.

The loss of permafrost will bring destruction of trees and loss of boreal forests, the release of thaw water and the expansion of thaw lakes, grasslands and wetlands. This will result in changes to habitats and ecosystems, such as loss of habitat for caribou and terrestrial birds and mammals—but there will be additional habitat for aquatic birds and mammals.

Loss of permafrost will also result in increased erosion and soil instability, especially on the coast and along the banks of rivers. This could result in the blocking of streams that are important for salmon spawning. There could also be increased occurrence of landslides and development of talik (a year-round thawed layer of what was formerly permafrost) and increased water table depth. Some of the major impacts on the community could be through damage to buildings, roads and other infrastructure.

The melting of Arctic permafrost has serious implications for the carbon cycle and the levels of greenhouse gases in the atmosphere. In the past, permafrost has been a sink of carbon, which is locked into the frozen ground. However, with melting and the resulting warmer soils, there will be an increase in speed of decomposition and the release of the greenhouse gases carbon dioxide and methane into the atmosphere.

The WCRP Climate and Cryosphere (CliC) Project, the International Permafrost Association, and the Global Carbon Project of the Earth System Science Partnership are currently undertaking a study aimed at assessing more exactly the carbon pools in permafrost and the potential impacts of their release into the atmosphere in a warmer climate.

The oceans

Predicting how the ocean circulation will evolve in the next century is extremely difficult. Because the ocean is seriously undersampled compared with the atmosphere, we still have a poor understanding of recent ocean variability. Nevertheless, some reasonable predictions can be made. In the Antarctic, with the Southern Hemisphere Annular Mode being in its more positive

Indigenous peoples of the Arctic include the Aleut, Athabaskan, Gwich'in, Inuit and Saami.

Indigenous leaders have called on the Arctic Council to develop an impacts and adaptation programme that would include community-based pilot projects on adaptation, and that would stress work on education, outreach and communications, and capacity-building.

Salekhard (Russian Federation) is the only city in the world situated on the polar circle.

In October 2006, the Russian Association of Indigenous Peoples of the North told the Arctic Council that development pressures and pollution were threatening reindeer pastures, hunting and fishing activities and sacred sites.

phase and the westerlies being stronger, it is expected that the Antarctic circumpolar current will strengthen.

The Antarctic coastal region is one of the primary areas for the production of bottom water by the sinking of cold dense water on continental shelves. These dense cold waters carry abundant oxygen into the ocean deeps, thereby cooling and ventilating deep ocean space. With the production of less sea ice being likely over the next century, it seems probable that less bottom water will be produced, raising the concern that the deep oceans may warm.

In the Arctic the loss of sea ice, increased river runoff, precipitation, melting of the Greenland ice sheet and the attendant freshening of the waters in the upper layer of the ocean will similarly mean less production of the North Atlantic deep water that feeds the Antarctic region through the global thermohaline conveyor belt. Thus both Arctic and Antarctic processes will combine to reduce the intensity of the thermohaline circulation. That reduction may, in turn, weaken the Gulf Stream and North Atlantic Drift. This has the potential to seriously affect the climate of northern Europe, possibly lowering surface temperatures by several degrees.

The ice sheets and sea-level

With rising surface temperatures over the next century, it is estimated that glaciers, ice caps and snow cover will all contract. The extent to which they will do so, and how fast it will happen in different regions, is still a matter for calculation and debate. It is very unlikely that there will be a major disintegration of the main Antarctic ice sheet during the next few centuries but some parts of the Antarctic have shown rapid glaciological changes over the last few years, indicating a sensitivity to climatic factors. Most of the main Antarctic ice sheet is too cold for widespread surface melting and it is expected that it will gain ice through increased snowfall over the next century, which will act to reduce global sea-level by about 10 cm. In response to further loss of the ice shelves by ocean warming or to surface melting at the margins, however, there could be an acceleration of the ice flow from the interior, which is currently dammed by coastal ice shelves. The impact of such effects could offset or outweigh greater snowfall across the continent.

The loss of ice shelves around the Antarctic peninsula in recent years has often been reported and attributed to anthropogenic activity. There is certainly evidence that the warming during the summer on the eastern

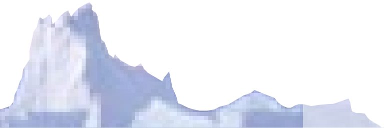
side of the peninsula is, at least in part, a result of atmospheric circulation changes associated with "global warming". If greenhouse gas levels continue to increase, we may well see further loss of ice shelves in this region. Of course, ice shelves are already floating on the ocean and their loss does not contribute to sea-level rise. It is at present unclear whether the ice streams that flow into the ice shelves will accelerate once the shelves have disappeared, so leading to a more rapid draining of ice from the interior of the Antarctic. There is evidence from the peninsula that some 87 per cent of the glaciers there have shown signs of retreating over the past 50 years. This pattern seems likely to continue with continued warming.

Over the next century, major changes in the Greenland ice sheet are expected. Higher air temperatures are likely to trigger greater snowfall over the high, interior parts, increasing surface elevations. At lower levels, on the fringes of Greenland, warmer conditions will melt the ice and prompt increased runoff. In addition, there could be a greater amount of iceberg calving. At the edge of the ice sheet it is expected that the loss of mass through runoff will exceed the gain from greater precipitation. Experts also predict an overall loss of ice, which will result in a change of sea-level of -0.02 to 0.09 m. This compares to the contribution to sea-level rise from the Antarctic, which is estimated at -0.17 to +0.02 m.

As near-surface air temperatures increase worldwide, a thermal expansion of the oceans will lead to a rise in sea-level estimated at 0.11-0.43 m. This will be augmented or mitigated by contributions from the ice caps, as discussed above. There will also be contributions from melting glaciers, which have been estimated at 0.01-0.23 m. Overall, the IPCC has estimated that, by 2100, sea-level may have risen by between 0.09 and 0.88 m.

If sea-level continues to rise at its present rate or more, it will pose a very significant problem for low-lying areas across the world.

The peoples of the Arctic have reported warmer and increasingly variable weather, as well as changes in terrestrial and marine ecosystems, which have had an impact on their traditional way of life.



INTERNATIONAL POLAR YEAR 2007-2008

Despite a great deal of research into the polar regions over recent decades, there are still large gaps in our knowledge about how polar climate operates and its interaction with ecosystems, polar environments and societies. We therefore need a better picture of conditions at the Poles and how they interact with and influence the atmosphere, oceans and land masses. This will be obtained during the International Polar Year (IPY), 2007-2008, a major international focused research programme that was initiated by the International Council for Science (ICSU) and the World Meteorological Organization.

The fundamental concept of the IPY 2007-2008 is as an intensive burst of internationally coordinated, interdisciplinary, scientific research and observation in the Earth's polar regions. The main geographic focus will be concentrated on the high latitudes, but studies in any Earth region relevant to the understanding of polar processes or phenomena will also be encouraged. To ensure that researchers have the opportunity to work in both polar regions in summer and winter if they wish, the Polar Year will actually run for two years from March 2007 to March 2009.

The first International Polar Year took place in 1882/1883. Since that time, there have been a number of major international science initiatives at high latitudes, including the second International Polar Year (1932/1933), all of which have had a major influence in improving our understanding of global processes in these important areas. These initiatives have all involved intense periods of data collection, interdisciplinary research and the establishment of archives that indicate the state of the polar regions. The last major initiative was the International Geophysical Year (IGY) in 1957/1958, in the pre-satellite era, which involved 80 000 scientists from 67 countries. The IGY involved unprecedented exploration and produced unexpected discoveries in many fields of research. It was during this period that many of the Antarctic research stations that exist today were established. The IGY also gave rise to the formulation of the Antarctic Treaty in 1959 and its ratification in 1961.

Today, technological developments, such as polar-orbiting satellites, automatic weather stations and autonomous vehicles offer great opportunities for further increase in our understanding of polar systems. The upcoming IPY 2007-2008 also offers an opportunity to engage the next generation of young Earth system scientists and to raise the profile of research in the polar regions with the public.

IPY 2007-2008 has attracted great interest from scientists working in many disciplines and nationalities. In response to a call by the ICSU/WMO Joint Committee for IPY, scientists have already planned and proposed more than 200 complex, international, interdisciplinary projects addressing a wide range

The International Polar 2007-2008 will emphasize the central importance of the polar regions as integral and sensitive components of the Earth system.

The IPY will also address historical weather and climate records, human health impacts and community sustainability; and human and ecosystem vulnerability to extreme weather events and natural disasters.

"Remote and harsh, polar regions are nonetheless the barometers of global warming and the water stored in their vast amounts of ice has significant implications for the entire planet. The launch of International Polar Year 2007–2008 comes at a propitious time and will provide a vital heritage of scientific knowledge for generations to come."

(Michel Jarraud, Secretary-General, WMO)

African involvement in International Polar Year (IPY) 2007-2008

The Regional Workshop on African Involvement in IPY 2007-2008 and International Heliophysical Year was held in Cape Town, South Africa, in October 2006 with the support of the ICSU Regional Office and the South African National Foundation for Research. The representative of the International Programme Office for IPY made a presentation on International Opportunities from the IPY.

The audience was primarily South African scientists and research council representatives but also included representation from several other African countries, including Kenya, Nigeria, Malawi, the United Republic of Tanzania and Zambia. There was obvious enthusiasm for the IPY and outcomes from the meeting included the intention to establish a Website for IPY that could represent the interests of African countries.

(IPY IPO Newsletter, November 2006, Issue No. 2)

"The scientific community stands ready ... to gather as much data about the effects of global warming on polar areas as quickly as possible—changes in these regions will have a massive influence on the well-being of the rest of the planet."

(David Carlson, Director of the International Polar Programme Office (IPO) for IPY)

of physical, biological and social research topics in the polar regions.

The National Meteorological and Hydrological Services of countries having an interest in the Arctic and the Antarctic are actively involved in the IPY preparation and implementation. It is envisaged that the IPY will involve more than 50 000 individuals from more than 60 nations. Climate change research, weather forecasting and establishing better observing systems are some of the priorities. Moreover, IPY will develop a unique legacy of discovery, data, observing systems and international cooperation among the geophysical, biological and social sciences.

The urgency and complexity of changes in the polar regions demand a broad and integrated scientific approach. These collaborations and coalitions will stimulate new data access and exchange practices, new academic courses and new forms and forums for scientific discourse. In its total science and outreach effort, IPY will represent a large step forward in making science available and accessible to the general public.

For more information, please contact:

World Meteorological Organization

7 *bis*, avenue de la Paix – P.O. Box 2300 – CH 1211 Geneva 2 – Switzerland
Tel.: +41 (0) 22 730 83 14 – Fax: +41 (0) 22 730 80 27
E-mail: cpa@wmo.int – Website: www.wmo.int