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Polar problems in climate research: some comparisons between the Arctic and Antarctic*

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Some selected processes which help to shape the weather and climate of the polar regions are briefly reviewed. Emphasis is placed on the short time scales (seasons to decades) of climate variability in which sea ice and snow demand the principal attention. The contrasting nature of the two polar regions provides an ideal natural geophysical laboratory in which comparative climate studies can be conducted and climate models can be tested.

Introduction

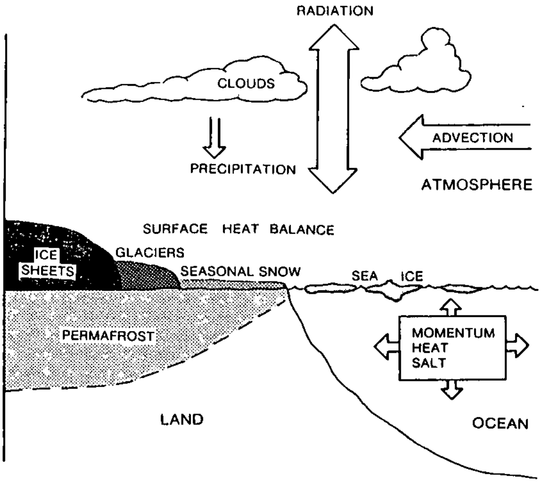
The role of the polar regions in affecting the global climate, on both short and long time scales, has long been recognised, but has come more sharply into focus in recent times, as systematic attempts are being made to understand and quantify that role. The polar regions are not only passive indicators of climatic change, but are also active participants in the dynamics of atmospheric and oceanic interactions on a global scale. Several review papers have been written on the nature of these polar atmosphere-ice-ocean interactions; one of the more recent ones is the paper by the Polar Group (1980), in which 28 scientists from the USA and USSR collaborated. It is not the intention of the present paper to produce another such review, with its usual highly condensed and abstracted style, but to select only some of the problems in polar climate research for somewhat more detailed treatment. This will be done by making comparisons between the Arctic and Antarctic, since in many instances the Arctic has been studied longer and we know more about its behaviour and responses. Moreover, as Benson (1981) has very appropriately pointed out, we are in a position to conduct comparative large-scale experiments in both polar regions, which have been set up by nature at no expense to us. These experiments can show the effects produced by having an ocean nearly symmetrical around one pole and a continental ice sheet nearly symmetric about the other. If we were to design a planet for such research we could hardly improve on the one we have.

The polar energy balance

The polar regions maintain their climatic equilibrium temperature by energy transport from the lower latitudes. The atmosphere and terrestrial surface of the polar regions have distinct and unique characteristics that control this energy transport (Fig. 1). Oort (1974) has shown that at 60°N, transient and stationary disturbances are far more effective than the mean meridional circulation in transporting energy poleward.

Although both polar regions are dominated by the presence of ice, different ice forms have different effects on climate. In the Arctic, variability in the extent of the snow cover of the land masses is probably the main factor in variations of the energy

Fig. 1 Schematic diagram of the polar regions, showing the major snow and ice forms and the exchange of heat, mass and momentum.



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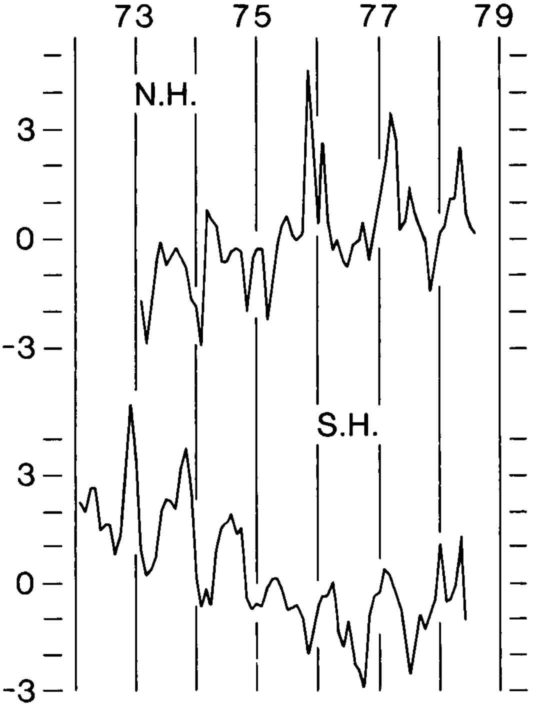
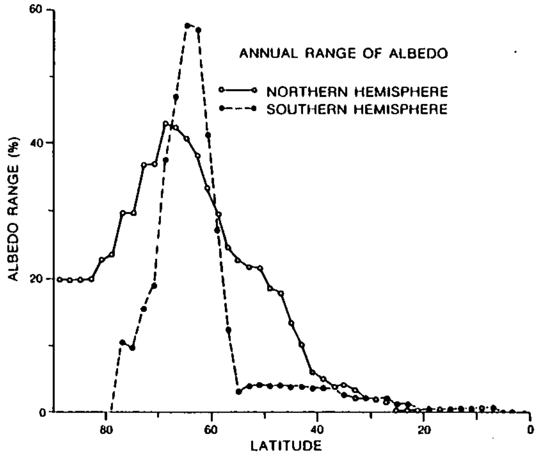
balance of the entire region. Snow cover is the critical variable of the climate system because of its high reflectivity, high emissivity, low water vapour pressure and low conductivity. The seasonal changes in the snow cover over the bare tundra regions that fringe the Arctic Ocean are abrupt, particularly in spring, and bring about rapid changes in the climate. With the break-up of the snow cover within a few days, the energy available at the terrestrial surface increases by an order of magnitude (Weller and Holmgren 1974). Interannual variations in snow extent are appreciable (Kukla 1981) and a steady increase over recent years in the albedo of the northern hemisphere (Fig. 2) is linked to increased snow extent and decreased air temperatures.

Fig. 2 **Anomalies of the 1973–78 monthly means of the area-weighted surface reflectivity of land north of 30°N (N.H.), and of ocean south of 50°S (S.H.). Units in per cent albedo (Kukla 1981).**



In the Antarctic, sea ice is the largest cryospheric variable in the climate system on short time scales. There are several physical properties of sea ice that give it a role of paramount importance in the climate system. First, sea ice has a high albedo which varies, however, with ice thickness, wetness and depth of snow cover on the ice (Weller 1968). Annual mean changes in the albedo are also much higher in the pack ice regions of Antarctica than in the Arctic (Kukla and Robinson 1980, Fig. 3). Second, sea ice effectively separates the atmosphere from the oceanic reservoirs of heat and moisture. Maykut's (1978) model of energy transfer as a function of ice thickness can be applied to the Antarctic with reasonable success (Weller 1980). Third, sea ice contributes to the vertical mixing of the world's oceans through the processes of freezing, brine convection and bottom water formation. These processes are particularly intensive in areas of high annual ice production, such as the Ross and Weddell seas, and the Siberian and Alaskan continental shelves.

Fig. 3 **Annual range of zonally-averaged albedo variations in both hemispheres (Kukla and Robinson 1980).**



Unfortunately, we know very little about Antarctic sea ice. We do not understand or even know the extent of such processes as the dynamics of the open water production inside the ice edge, the relative roles of thermodynamics and advection in advance and retreat of the ice cover, or the role that frazil ice might play in heat and salt exchange processes in the southern oceans (Ackley 1981). Moreover, we do not even know how much ice there is and how it is distributed seasonally and spatially. For example, only recently has it been shown, by using satellite-mounted microwave radiometers, that sea ice in the southern hemisphere is considerably more open than thought previously (Zwally personal communication, Fig. 4). The ocean heat energy loss to the atmosphere is therefore also considerably higher, in fact by as much as a factor of 6 above previous estimates (Weller 1980). Field data on the thickness distribution of sea ice and its snow cover, ice dynamics and the energy balance are urgently needed.

Sea ice and climate dynamics

Sea ice is of special interest in forcing climatic variability in the southern hemisphere, since ice extent can fluctuate widely on short and long time scales. Seasonal fluctuations occur from about 2 to 20 x 10^6 km^2 (Fig. 5), while they vary by only a factor of two in the Arctic. Interannual variations in both hemispheres are appreciable (Kukla 1981) and

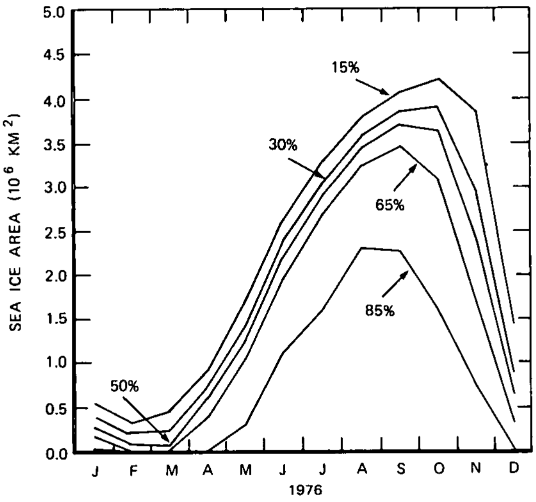


Fig. 4 **Ice concentrations in the Indian Ocean sector (20–90°E) of the Southern Ocean during 1976, derived from ESMR satellite data (Zwally, personal communication).**

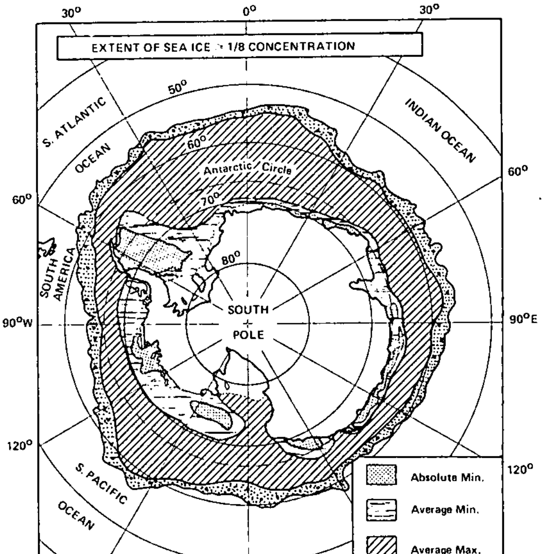


Fig. 5 **Absolute and average maximum and minimum extents of Antarctic sea ice.**

during the last glacial, sea ice was twice as extensive in the Southern Ocean during the winter than now (Hays 1978).

Several studies conducted in the northern hemisphere since the beginning of the century have shown that statistical relationships exist between ice extent in the North Atlantic and certain regional features of the atmospheric pressure field (Brennecke 1904; Meinardus 1960; etc.) and that large variations of the ice boundary in the North Atlantic are associated with fluctuations in average high-latitude temperatures (e.g. Scherhag 1936). Studies in the southern hemisphere are fewer, but Fletcher (1969), Streten (1973), Budd (1975) and Schwerdtfeger (1979) have all shown relationships between ice extent and features of the circulation or climate.

The difficulty in interpreting these observational studies stems from the fact that statistical correlation does not imply causality. Ice anomalies correlate with atmospheric anomalies but are themselves forced by the atmospheric anomalies. Modelling efforts emphasise this problem. For example, calculations with a general circulation model by Herman and Johnson (1978) showed that sea ice fluctuations in the North Atlantic and north Pacific caused statistically significant modifications of the Aleutian and Icelandic model lows, which in effect affected the intensity of the major northern hemisphere subtropical highs in the model. The model, as well as others used to date, however, had fixed sea ice boundaries which did not change as a result of changes in circulation. The approach by Walsh (1979), using empirical orthogonal function analysis, is promising in predicting ice anomalies from atmospheric anomalies. Further model development must include the various feedback processes that will be discussed in a later section.

Clouds and low-level winds

Two unique and contrasting large-scale features of the polar environment which play important roles in the weather and climate of the Arctic and Antarctic are, respectively, the Arctic stratus clouds and the katabatic winds. Both are large-scale phenomena, insofar as they occur over areas that cover millions of square kilometres, but their nature, energetics and seasonality are dictated by the quite different physical environment of the two polar regions. In energy these two phenomena are also large-scale; the katabatic winds, for example, are similar to the tradewinds in the magnitude of energy transfer (Radok 1973).

The occurrence of low-level stratus and stratocumulus clouds in the Arctic is highly seasonal, increasing from April to June, to a broad maximum of more than 70 per cent in summer, and decreasing again from October to December (Vowinckel and Orvig 1970). The heat balance of the surface of the pack ice is intimately related to the presence of these clouds, which are a complicated phenomenon. Their structure is related to eddy transports of heat and moisture into the Arctic Basin, to surface exchanges of heat and water vapour and to optical properties of the liquid water drops or ice crystals. Recent studies, including flights with the NCAR Electra aircraft, have indicated that the clouds are more transient than believed earlier, are related to cyclonic activity, and their main source of moisture probably lies outside the Arctic (Jayaweera 1981).

The Antarctic produces a different kind of large-scale phenomenon. The main feature here is a large high ice plateau; cloudiness is low, and surface and free air temperatures are considerably lower than those in the Arctic. The principal heat loss to space comes from the free atmosphere and produces a large-scale direct thermal circulation. The surface wind regime is created by intense radiational cooling and is governed more by the slope of the ice surface than by synoptic scale pressure gradients. This low-level katabatic circulation has been intensively studied by Ball (1956), Schwerdtfeger (1970), Radok (1973) and others. A recent project by Wendler and Poggi (1980) has established a number of automatic weather stations, located on a line from Dome C to Dumont d'Urville, to obtain continuous wind data. As part of this project Gosink (1981) has reviewed various katabatic flow models and has concluded that the theories of Ball (1956) and Schwerdtfeger (1975) do not account for the observed acceleration along a streamline; inertial effects may be significant.

Aerosols and carbon dioxide

Atmospheric aerosols occur in both polar regions but play different roles in the weather and climate of the Arctic and Antarctic. In the Arctic, the relative proximity to the large industrial centres of Europe and North America leads to very high atmospheric aerosol loadings of the troposphere, creating the so-called Arctic Haze (Rahn and McKaffey 1980). Tropospheric and stratospheric aerosols affect the vertical temperature structure in the atmosphere, and numerical studies by Shaw and Stamnes (1980) have indicated that the heating to be expected with increased aerosol concentrations cannot be ignored in the mass balance changes of the pack ice. In the Antarctic, aerosol loadings are an order of magnitude lower than in the Arctic and the origin of the aerosols is not from industrial sources, but from the earth's crust and the sea (Shaw 1979). In both polar regions sulphur is the predominant element but carbon is also high in concentration in the Arctic. When comparing aerosols from industrial sources only, the Arctic has about two orders of magnitude more aerosols than the Antarctic.

Another atmospheric constituent, CO_2, is also presently receiving increased attention because of the possible disastrous consequences of world-wide increasing CO_2 levels; these consequences include melting of the polar ice sheets. Recent papers on the effects of increased CO_2 levels in the polar regions have been published in volumes edited by Pearman (1980) and Bentley (1981). Numerical modelling experiments have indicated that atmospheric warming due to an increased CO_2 content of the atmosphere will be highest in the polar regions, especially in the Arctic (Manabe and Stouffer 1979). At the present, however, any effects of CO_2 increases on the global climate cannot be detected against the natural background variations due to causes other than CO_2 increases. These effects can probably best be monitored in the polar regions, but the problem is complicated by the fact that CO_2 will affect cryospheric processes through numerous feedback mechanisms, which presently cannot be adequately quantified. These feedback processes are the topic of the next section.

Cryospheric feedback mechanisms

The climate is largely determined by complex interactions within the total system made up of the atmosphere, the oceans, the solid earth, and the cryosphere. No complete model of this total system has been constructed so far, but it has been useful to investigate feedback mechanisms in which the response of some part of the system to a change is influenced by the response of other parts. Some feedback mechanisms in the polar regions are apparently very powerful, and there are others which are still to be evaluated properly (Kellogg 1975).

The heat balance of the polar regions is determined by the transport of sensible heat by the atmospheric and oceanic circulation, by the infrared emission to space from the atmosphere and the surface, and by the solar radiation absorbed. The last factor is greatly influenced by the extent of snow and ice with their high albedo (Kukla 1981). A shrinking of the snow and ice cover due to a warming trend (as caused by increased CO_2 levels, for example) will result in the absorption of more solar radiation at the surface (assuming that the cloud cover does not change appreciably), and this extra heat will further warm the region. This is a classical example of a positive feedback mechanism (Kellogg 1975) and has been included in virtually all of the current latitude-dependent climate models, starting with those of Budyko (1969) and Sellers (1969, 1973).

An example of a negative feedback loop in the polar regions is the albedo-polar cloud cover-temperature loop, which results since the albedo of the clouds is generally less than the underlying snow, and assuming that cloud amount increases when the temperature falls. Sea ice also enters into several feedback loops. Sea ice tends to maintain itself in the face of fluctuations in mean temperature due to the layer of stable low-salinity water that it protects, but it also has a self-limiting effect as it grows thicker due to its poor thermal conductivity. The positive loop in this case predicts that sea ice will tend to persist, but once removed it will not form until temperatures fall very low. This can be thought of as a polar ice flip-flop in the climate system. Another well-known polar feedback mechanism is the one proposed by Ewing and Donn (1956). It has been criticised on theoretical grounds and on the basis that there is evidence that the Arctic Ocean has been ice-covered for the last 100 to 200 thousand years. Nevertheless it is a hypothesis that retains great appeal and may be applicable on other time and space scales.

These polar feedback mechanisms are important because they may serve to amplify small climate change and, since the polar regions respond more dramatically than mid-latitudes to climate change, they are part of a potential early warning system of climatic changes.

Conclusion

This brief review has singled out some, but by no means all the important processes involved in shaping the weather and climate of the polar regions. Emphasis has been placed on the short time scales of climatic variations, in which sea ice and snow demand the principal attention, but glaciers and ice sheets also need to be studied and modelled. The two polar regions respond more rapidly to climatic change than the mid-latitudes, although they may not necessarily be in phase with each other. Monitoring the behaviour and extent of the various ice forms of the polar regions therefore does provide one of the best indicators of climatic change. The two polar regions also are active participants in shaping the global climate, and their contrasting nature provides an ideal natural geophysical laboratory in which future climate studies should be emphasised and climate models should be tested.

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