PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Antarctica and the Detection of Environmental Change [and Discussion]

Gunter Weller, P. Wadhams, D. J. Drewry, J.-O. Stromberg and F. G. Larminie

Phil. Trans. R. Soc. Lond. B 1992 **338**, 201-208
doi: 10.1098/rstb.1992.0139

Antarctica and the detection of environmental change

GUNTER WELLER

Geophysical Institute, University of Alaska, Fairbanks, Alaska 99775-0800, U.S.A.

SUMMARY

Antarctica plays a critical role in global change because major interactions in this region between the atmosphere, ice, oceans, and biota affect the entire global system through feedbacks, dynamic biogeochemical cycles, deep ocean circulation, atmospheric transport of energy and pollutants, and changes in mass balance. Antarctica is also sensitive to global change and is a key area for detecting and monitoring environmental change. The parameters to be monitored in Antarctica, the deficiencies in the present measurements, and future methods and techniques were listed by the Scientific Committee on Antarctic Research (SCAR) as part of an overall global change research strategy for Antarctica and are summarized in this paper.

1. INTRODUCTION

Climate varies over a wide spectrum of timescales, from interannual changes to the much slower processes that involve the Earth's orbital parameters, continental drift, and solar aging. Concern now focuses on humanity's ability to cause additional changes through the increasing concentration of greenhouse gases and through other anthropogenically induced perturbations. Computer models have shown the likely effect on climate of increasing the amount of CO_2 and other trace gases in the atmosphere. At high latitudes, the temperature increase may be several times greater than at lower latitudes due to ice-albedo feedback effects and the stability of the polar lower troposphere, although more recent simulations with a coupled ocean model (Manabe *et al.* 1992) have shown little amplification in the Antarctic (figure 1). Snowfall is also projected to increase in coastal Antarctica in association with warmer winters. Likewise, stratospheric ozone depletion due to the introduction of anthropogenic materials, namely chlorofluorocarbons (CFCs), into the polar stratosphere is particularly pronounced at high latitudes. The antarctic ozone hole is now a well-recognized phenomenon. Ecosystems are driven mainly by phototrophic organisms which are vulnerable to changes in critical factors such as UV-B, temperature, currents, winds, and nutrient fluxes. Certain organisms are particularly sensitive to such parameters and may serve as biological indicators of environmental change. The effects of these driving forces on primary producers and other sensitive biota may affect interactions and trophic levels throughout entire ecosystems.

To answer the many questions raised by the global change issue, it is essential to detect changes in Earth systems that are occurring now and that have occurred in the past. This will allow cause–effect relationships to be established, will help to clarify the crucial feedback processes noted above that either amplify or dampen global change, and will improve the capability for predicting future change. Detection of changes in the Antarctic is an essential part of a global change strategy as various components of the Antarctic and sub-Antarctic environment may be quite sensitive to global change.

Whereas attempts to detect and monitor environmental change in Antarctica are underway now, the network of observational sites and transects (manned stations, automated systems, ship cruises, satellite observations, etc.) is still very open. Also, many of these observations are not yet fully integrated or properly coordinated for maximum benefit in fingerprinting change. The Scientific Committee on Antarctic Research (SCAR) has established a working group on global change, which has recommended a proper strategy for monitoring and detecting environmental change in Antarctica. Their recommendations (SCAR 1992, chapter 1.7) are the basis of this paper.

2. DETECTION OF ENVIRONMENTAL CHANGE IN ANTARCTICA

(*a*) *Surface temperature (ocean and land)*

Surface temperature is a key climatic variable that global climate models predict will increase strongly at high latitudes as a result of the systematic increase of greenhouse gas concentration in the atmosphere (IPCC 1990). The length of the surface temperature record in Antarctica is limited, but analysis of this data set by Jacka & Budd (1991) shows temperature increases at almost all of the Antarctic stations (figure 2). The

Phil. Trans. R. Soc. Lond. B (1992) **338**, 201–208
Printed in Great Britain

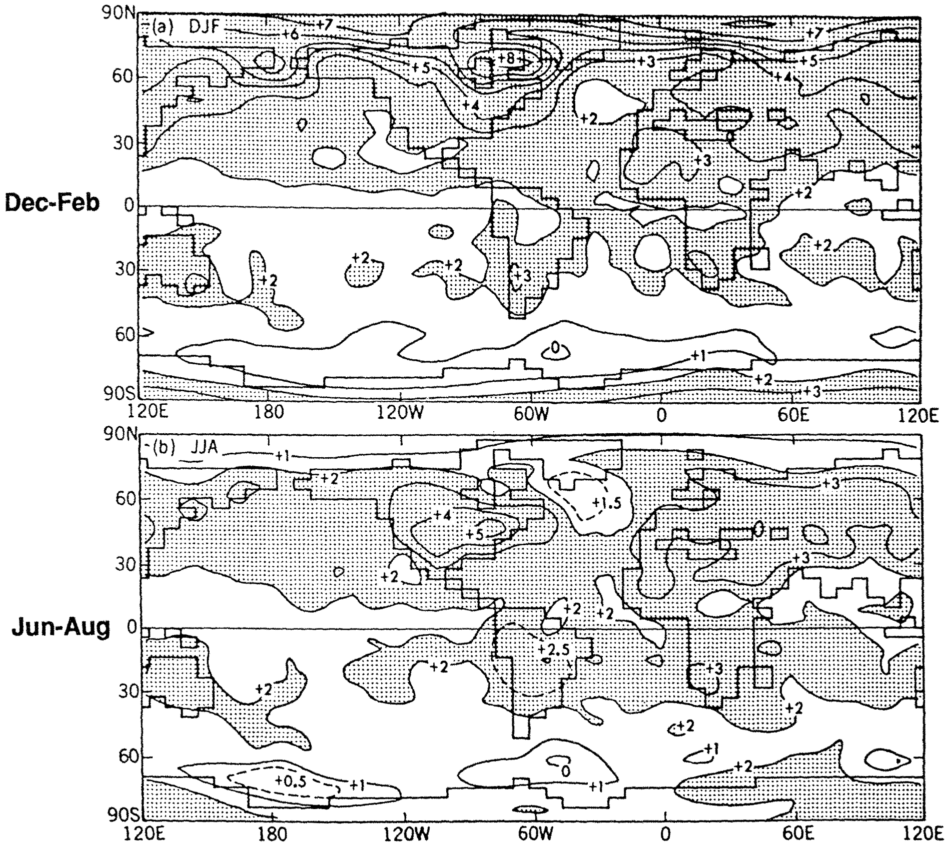

Figure 1. Climate change simulations with a coupled ocean model, showing temperature changes due to atmospheric CO_2 increases of 1% per year after years 60–80 (from Manabe *et al.* 1992). Shading covers the regions where the difference is greater than 2°C.

large gaps in the present meteorological station network preclude a definitive depiction of this fundamental parameter, however, and thus, confident verification of predicted climate change.

SCAR (1992) sees a need to establish a project on Antarctic surface temperature measurements to monitor systematically the surface temperature changes over Antarctica from satellite and surface-based measurements. The elements of such a project are as follows.

Cloud-free surface temperature estimates are presently being extracted from different satellite data sets (Temperature–Humidity Infrared Radiometer (THIR) and Advanced Very High Resolution Radiometer (AVHRR). These measurements need careful calibration and systematic analysis. Research is also needed to relate the skin temperatures measured by the satellite sensors to ground-based air and surface temperatures, especially of the Antarctic plateau, to ensure that the satellite sensors are accurately calibrated and that all sources of contamination are eliminated. This especially includes cloud detection and the correction for water vapour and aerosol attenuation.

The continuity in the temperature series needs to be ensured as changes in satellite sensors and surface-based approaches occur. The ready availability of data from diverse sources and systematic analysis needs also to be ensured. Operational meteorological agencies have an obvious role in this and can build on strong international collaboration presently manifested through the World Meteorological Organization.

Also important are borehole temperatures in the ice to reconstruct past climates. A considerable number of shallow 100–200 m core holes already exist in cold firn. These can yield a record of recent (100–300 year) temperature trends. A systematic analysis of these borehole temperatures is necessary to provide a time-integrated history of temperature and accumulation changes over the Antarctic ice sheet since the Little Ice Age. So far, analysis has been performed in a sporadic manner only. The careful collection of temperatures in additional shallow (~200 m) boreholes should be encouraged, but coordination is required to ensure appropriate precision in the collection and analysis procedures.

(*b*) *Atmospheric temperature: radiative and energy fluxes*

The radiation budget at the top of the atmosphere is the unique controlling factor of the Earth's climate. Also, atmospheric temperature changes in high latitudes and their vertical structure are a key indicator for global change studies together with the surface radiative and energy fluxes. Besides the external forcing, such as the variation of solar radiation owing

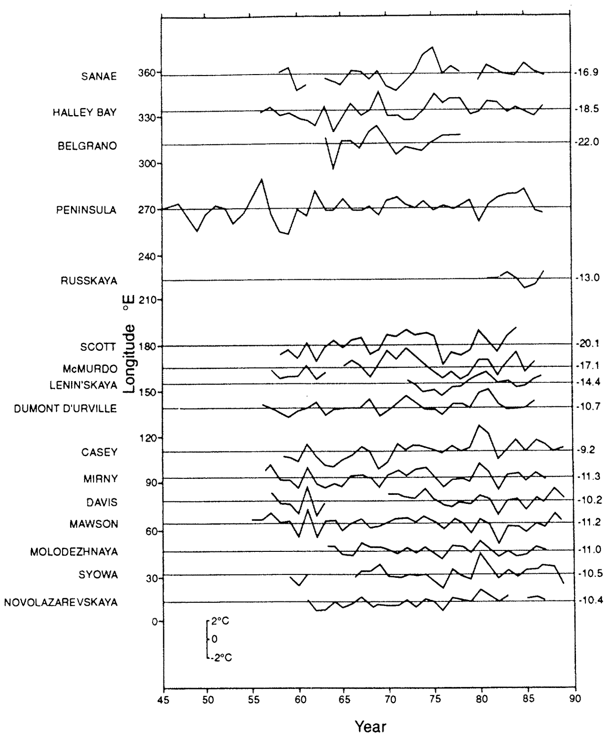

Figure 2. Mean annual surface air temperatures for coastal Antarctic stations. The time series are plotted as anomalies about a zero line. The long-term mean temperature for each station is indicated in the right hand margin. Data are plotted approximately according to station longitude (°E), indicated on the left-hand axis (from Jacka & Budd 1991).

to the change in the solar constant, greenhouse gases, particulate matters, and clouds are the major internal forcing agents.

Little attention has been paid to the satellite-derived radiation budgets in the polar regions, and the greatest need is to determine the interannual variability and trends in: (i) upward fluxes of longwave (terrestrial) and shortwave (reflected solar) radiation at the top of the atmosphere; (ii) upward and downward radiation fluxes and energy fluxes (sensible and latent heat transfer) at the ground surface; and (iii) the temperature of the atmospheric layer (e.g. 1000–700, 700–500 mb, etc.).

Radiative fluxes at the top of the atmosphere are derived from the satellite measurements with shortwave and longwave sensors. The ERB (Earth's Radiation Budget) experiment, conducted using the Nimbus or NOAA and ERBE satellites, is to be continued through the Earth Observing System (EOS) program, but needs a polar emphasis. Radiative forcing by clouds is one of the main subjects to be resolved in the Antarctic, as it has many uncertainties owing to the difficulty in scene identification and cloud detection. A climatology of polar clouds is also urgently needed.

Atmospheric temperature profiles can be retrieved from infrared and microwave sounders such as the Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) of NOAA satellites. Satellite-derived temperature profiles need validation through intercomparison using different sensors and conventional rawinsonde data. One problem in the Antarctic is that the satellite retrieval cannot resolve the strong surface inversion and that the high surface elevation affects the retrieval. TOVS/AVHRR should be incorporated in the successor of the NOAA satellites. For Antarctic use, the TOVS data should be the raw radiances as the routine method used for isolating cloud-free scenes is not good in polar regions.

The surface radiation budget is being measured at the ground at several sites and can be determined from satellite data. Baseline measurements of the surface radiation and energy budgets need to be made at a network of Antarctic stations, as part of the global network GBSRN (Global Baseline Surface Radiation Network of the World Climate Research Programme), to detect changes in the surface fluxes and for the intercomparison of satellite-derived surface radiation budgets.

(*c*) *Atmospheric characteristic and dynamics*

Several features of the atmosphere such as cloud cover, precipitation amount, and the general circulation will be affected greatly by any change in global atmospheric temperature. Monitoring these parameters will give an indication of how any global warming is likely to affect other parts of the Antarctic environment. Also, the processes involved in these features need to be well understood before any climate change can be explained.

The distribution of storm tracks in the southern oceans can have a large effect on the energy flux by eddy transport, the cloud amount and precipitation over the Antarctic Plateau, as well as modifying the temperature regime. These tracks should be monitored using satellite imagery and sounder data as well as using more conventional data. The variability of the position of the storm tracks in the Southern Ocean should be able to explain much of the variability seen in the temperature and sea-ice records from stations in the Antarctic Peninsula. The SCAR First Regional Observing Study of the Troposphere (FROST) has two special observing periods which should provide a baseline against which subsequent monitoring can be compared.

Precipitation represents an important input into the mass balance of ice sheets. Conventional measurements of precipitation in Antarctica are of low quality and are mostly concentrated near the edge of the continent. Passive microwave satellite measurements have been used at mid-latitudes to determine the precipitation over the ocean. The algorithms used will need further development for use at high latitudes. Also, the use of passive microwave imagery over the high Antarctic Plateau to detect the rate of accumulation should be investigated.

Routine measurements of clouds from satellite data has until now been relatively unsuccessful in high latitudes. The algorithm used by the International Satellite Cloud Climatology Project (ISCCP) has limitations during the polar night when no visible data are available. It is thought that effective algorithms have been developed in many centers and these

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

should be applied to multichannel AVHRR and TOVS data sets. Also, the future operational use of a 1.6 micrometer channel for snow and cloud discrimination is strongly recommended.

A 20-year record of meteorological analysis (pressure, temperature, winds, etc.) is now available from several centres (European Centre for Medium-Range Weather Forecasting (ECMWF) and Numerical Modelling Centre (NMC)) for climatic investigations, complemented by NOAA and other operational satellite data. These can be exploited to examine circulation variability in relation to changes in cloudiness, precipitation, and temperature. Current analyses are not a homogeneous series, however, and thus are of limited value in climate change studies. Proposals have been made for a reanalysis to produce a homogeneous series from archived data, but this is a big task.

(*d*) ***Atmospheric composition***

The Antarctic ozone 'hole', caused largely by chlorofluorocarbons, is one of the most dramatic manifestations of global change. Antarctica plays a unique role in the study of atmospheric composition and global change for at least three reasons: (i) certain atmospheric perturbations appear to be particularly pronounced in polar regions (e.g. the ozone 'hole'); (ii) Antarctica represents one of the most remote sites on the planet from which to detect and quantify global changes in atmospheric trace gases; and (iii) studies of Antarctic ice cores provide a means of documenting the variability of trace gases (such as CO_2, N_2O, and CH_4) in the near and more distant past, providing a critical framework for studies of ongoing perturbations.

To document and monitor future changes of atmospheric composition, particular attention should be paid to change in stratospheric ozone, using satellite and ground-based measurements, and to monitor trace gases to provide a long-term data base for global trend studies. The continuity of ongoing satellite monitoring programs is critical to documenting future changes to the ozone layer in and around Antarctica. The recently launched Upper Atmosphere Research Satellite (UARS) contributes significantly to the monitoring of the upper atmosphere. The Earth Observing System (EOS) involving NASA, the European Space Agency (ESA), and Japan planned for the late 1990s will also greatly enhance research on ozone depletion, upper tropospheric clouds, ozone and atmospheric chemistry, and trace-gas transport.

Ground-based measurements such as the Network for the Detection of Stratospheric Change (NDSC) are also important. In addition, increasingly sophisticated balloon payloads are being used to probe the ozone hole. These include both long duration balloons (e.g. the Polar Patrol balloons by Japanese investigators) and heavily instrumented large balloons. Unmanned aircraft may be launched in Antarctica within the next decade to provide expanded spatial coverage (both vertical and longitudinal) for high-resolution in situ observations of reactive species such as NO and ClO and direct measurements of polar stratospheric clouds.

(*e*) ***Ecosystem sensitivity and indicator species***

Climatic and related environmental changes are predicted to be accentuated in the polar regions. Certain individual organisms and associations of biota in marine, terrestrial, and freshwater Antarctic ecosystems are sensitive to minor changes in specific environmental parameters. This sensitivity may be manifested as a response in their physiology, life cycle, productivity, or as an influence on ecological processes. Detection of such biological change will be an essential part of the Antarctic global change strategy. Special attention should be paid to identifying and studying representative organisms and specific processes which are sensitive to small environmental changes and to those which play an important role in the dynamics of key Antarctic ecosystems.

The primary objectives will be to identify key organisms, biological processes, and interactions that are most likely to be influenced by changes in the climatic regime of the Antarctic marine and terrestrial ecosystems. Existing data should be examined to identify key environmental parameters of major biological significance which require long-term monitoring. Primary factors will include changes in temperature, CO_2, UV-B and sea-ice dynamics. Secondary factors such as water availability, nutrient input, duration of growing season, and habitat alteration should also be considered. Evidence of past environmental changes from the palaeostratigraphic record of diatoms, pollen, and microbes in sediment, ice, permafrost, and peat cores should be examined to detect Holocene trends and generate hypotheses for future biological responses.

The present characteristics and abundance of potential indicator species should be assessed to determine an ecophysiological baseline against which to measure their metabolic resilience to environmental change and development of specific protective features. Species selected should include examples having narrow and broad environmental tolerances and ecological amplitudes. Genetic flexibility and plasmoid transfer should be considered (with particular regard to microorganisms).

Transoceanic immigration of organisms to Antarctica and their local dispersal, should be characterized and related to the potential for increased terrestrial and freshwater species diversity and ecosystem complexity resulting from climatic change. The sensitivity of the resultant propagule bank to environmental change and exploitation of newly exposed habitats should be assessed.

Primary production in the ocean is of fundamental importance for the functioning of the biosphere, but the signal derived from existing data (for example from the Antarctic BIOMASS (Biological Investigations of Marine Antarctics Systems and Stocks) programme) has a high degree of noise. Its response to environmental change is most evident in phytoplankton blooms in the marginal ice zone. It may be

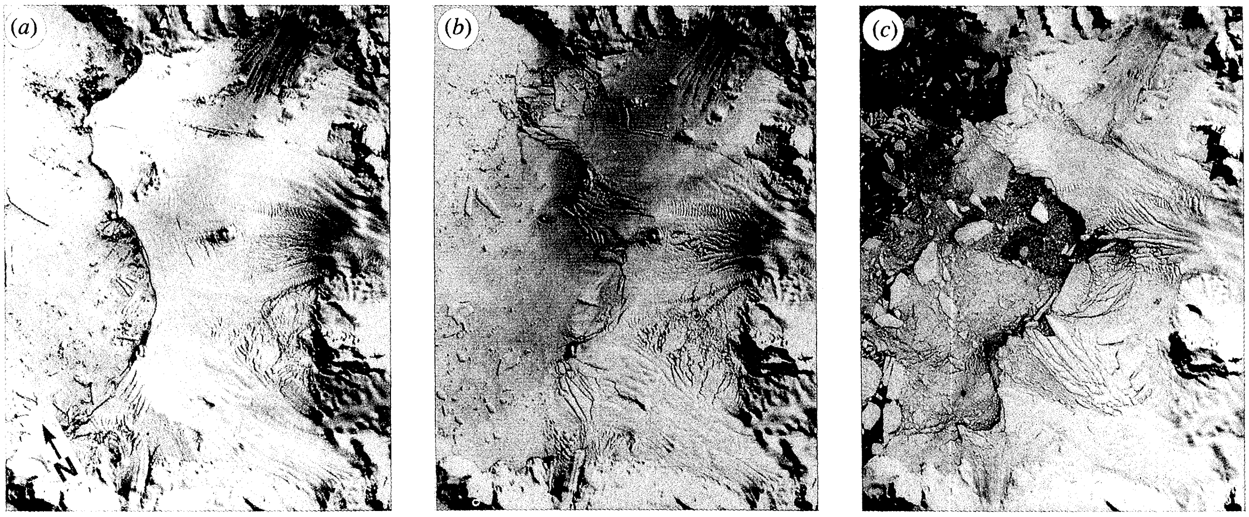

Figure 3. The disintegration of the Wordie Ice Shelf, Antarctica, observed through Landsat satellite imagery (published courtesy of EOSAT, illustration provided by D. Vaughan). (*a*) 1974; (*b*) 1979; (*c*) 1989.

desirable to monitor responses at all trophic levels to the specific effect of increased UV-B or other driving forces as they deviate from present conditions. These should be related to a predictive model that links biological and physical parameters.

(*f*) *Surface hydrology and microenvironment*

A small portion (less than 5%) of Antarctica is largely ice-free. This is predominantly coastal land at lower latitudes, with the important exception of the McMurdo Dry Valleys of southern Victoria Land at 77°S and numerous inland nunataks. The ice-free areas contain numerous streams, ponds, and lakes fed by snow melt and local glaciers.

The surface hydrology of the ice-free regions represents a sensitive and important indicator of local and possibly regional climatic change in Antarctica. In particular, several readily observable characteristics of alpine glaciers, glacial meltstreams, and lakes are expected to respond to relatively small changes in local environmental conditions (e.g. temperature, wind, precipitation, etc.) over timescales of one to several years. For example, in the southern Victoria Land Dry Valleys, lake levels have been rising about 9 cm per year and the ice covers of several lakes have thinned dramatically (e.g. 20 cm per year at Lake Hoare) since the 1970s. These changes have been linked to increases in summer air temperatures over the past 20 years.

Observation and measurement of hydrological processes should be obtained on a regular basis from an appropriate network of ice-free sites in and around ice-free areas in Antarctica, and include the measurements of the annual mass balance on adjoining alpine glaciers, glacial meltstream flow, its seasonal timing and discharge, seasonal lake level and surface area, and seasonal lake ice thickness and duration. In addition, year-round climatic records of meteorological parameters should be obtained. These data will be necessary for interpreting the hydrological processes and will provide input for mathematical models used to predict their responses to climatic change.

With few exceptions, the hydrological and microenvironmental properties of ice-free areas have not been routinely monitored. A Long-Term Ecological Research (LTER) site has recently been established at Palmer Station on the Antarctic Peninsula and an additional site is planned for the McMurdo Dry Valleys. Relevant data have been collected on the glaciers, streams, and lakes of the McMurdo Dry Valleys annually since the early 1970s and data are also available from the Vestfold Hills and Syowa Oasis. An automated station for recording relevant year-round microenvironmental data will be deployed in 1992 in the Bunger Hills Oasis. Substantial climate data have also been collected in the ice-free areas of the peri-Antarctic islands and the Antarctic Peninsula. SCAR encourages the establishment and maintenance of a network of environmental monitoring sites in the ice-free regions of Antarctica. These sites could readily correspond with existing and planned sites for long-term ecological research being developed by various nations.

(*g*) *Land ice and ice shelf mass balance and sea level*

Realistic projections of changes in global sea level require knowledge of the present mass balance of the polar ice sheets. Principal elements to pursue are: (i) the measurement of ice elevation, volume, and grounding line changes by satellite laser altimetry; (ii) the detection of changes in ice-sheet extent, ice-velocity fields, and ice-stream margins by satellite imagery; (iii) determination of accumulation and quantitative relationships among moisture-transport and precipitation, ice accumulation, atmospheric temperature variations, and sea-ice extent; and (iv) surface melting by satellite passive imagery.

The antarctic topography north of 72°S was mapped with satellite radar altimetry in 1978 and

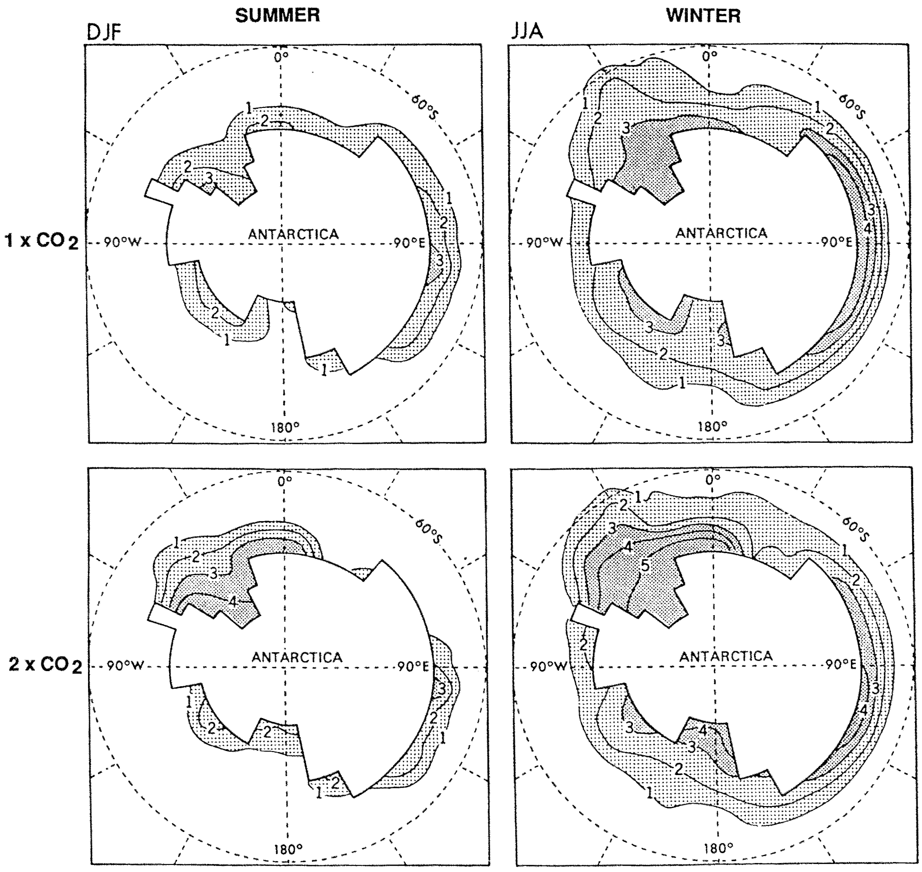

Figure 4. Simulations of sea-ice changes using a coupled ocean model (from Manabe *et al.* 1992). Note thicker ice in some sectors after CO_2 increases, caused by higher precipitation stratifying the ocean surface layer and decreasing ocean heat convection.

1985–1989 and north of 82°S commencing in 1991. However, the accuracy of radar altimetry is only about 50 cm on the smoother and flatter areas and degrades to 5 to 10 m over slopes of about 0.7 degrees. Furthermore, current radar altimeters are effectively limited to slopes of less than about 0.7 degrees, thereby excluding most of the critical ice sheet marginal areas. A satellite laser altimeter system with an accuracy of 10 cm has been designed for the EOS, but will not be available for several years yet.

Satellite imagery has also been increasingly used for mapping ice margins, flow patterns, and ice velocities. Major changes in ice margins have been observed in some areas such as the Wordie Ice Shelf (figure 3). Much of this work has been enabled by the acquisition of satellite imagery coordinated by the SCAR Working Group on Glaciology. Monitoring of surface melting has been initiated with passive microwave data, which has been nearly continuous since 1978.

(*h*) *Sea-ice conditions and ocean circulation*

The sea-ice cover in the Southern Ocean undergoes a five- to sixfold variation in extent between its annual maximum and minimum. There are also irregular decadal and long-term fluctuations that are poorly defined and understood. Ice concentration changes, including such intermittent features as the large Weddell Sea polynya, are poorly known. Reliable hemispheric information exists only from the 1970s. There is little information on ice thickness and ice decay mechanisms.

Sea ice is a major component of the ice and albedo feedback process, which is largely responsible for the projected amplification of global warming in high latitudes. Associated ice growth and decay affects the ocean salinity and density structure and deep-water formation. Ice also largely isolates the atmosphere from the underlying ocean heat and moisture fluxes. Recent climate modeling with a coupled ocean model (Manabe *et al.* 1992) has shown surprising increases in ice thickness after greenhouse warming, due to a more stratified ocean resulting from increased precipitation (figure 4).

One of the most vigorous and dynamic parts of the World Ocean is Southern Ocean around Antarctica. In this region, the seasonal sea-ice cover makes the understanding of interactions even more difficult. Considerable water mass modification is largely responsible for the rather cold character of the deep and bottom waters of the world ocean. The circulation and vertical fluxes not only influence the overall characteristics of the deep ocean and thus the global climate, but also affect sea ice, providing the physical setting for a unique ecological system, and perhaps influencing the stability of the ice sheet of Antarctica. Oceanic circulation affects life cycles and marine organisms on various temporal and space scales. Large-scale pro-

Table 1. *Parameters to detect and monitor change in Antarctica*

parameter	future planned programme[a]
1. surface temperatures (ocean and land)	EOS
land temp. (surface obs. and satellites)	
ocean temp. (surface and satellites)	
palaeotemp. (ice cores, sediments, etc.)	ITASE, EPICA
2. atmospheric temperature, radiative and energy fluxes	EOS
upward fluxes at top of atmosphere	
energy balance at the surface	
temp. profile of the atmosphere	
UV spectral irradiance	
3. atmospheric characteristics and dynamics	GEWEX
storm tracks	FROST
cloud cover (troposphere and stratosphere)	ISCCP
moisture flux and precipitation	GEWEX
4. atmospheric composition	
total ozone (from ground and satellites)	IGAC, NDSC
trace gas species	
aerosol concentrations	
5. ecosystems and indicator species	
target organisms	RISE
effects of UV-B	LTER, RISE,
population dynamics	RACER, SO-GLOBEC
key environmental parameters	SO-JGOFS, LTER
6. surface hydrology and microenvironment	GEWEX
alpine glacier mass balance	
glacial meltstream flow	
lake characteristics (level, area, ice cover)	
7. land-ice and ice-shelf mass balance and sea level	SAR
ice elevation, volume and grounding line changes (satellite altimetry)	WAIS
ice-sheet extent, ice-velocity fields and ice-stream margins (satellite imagery)	
accumulation	
surface melting	
sea level	
8. sea-ice conditions and ocean currents	SAR, EOS
ice and open water extent	PELICON
ice thickness	
ocean circulation	WOCE

[a] List of acronyms: EOS, Earth Observing System [NASA/Europe/Japan]; EPICA, European Polar Ice Coring in Antarctica; FROST, First Regional Observing Study of the Troposphere; GEWEX, Global Energy and Water-Cycle Experiment; IGAC, International Global Atmospheric Chemistry; ISCCP, International Satellite Cloud Climatology Project; ITASE, International Trans-Antarctic Scientific Expedition; LTER, Long-Term Ecological Research; NDSC, Network for the Detection of Stratospheric Change; PELICON, Project for Estimation of Long-Term Variability in Ice Concentration; RACER, Research on Antarctic Coastal Ecosystem Rates; RISE, Ross Ice Shelf Ecosystem; SAR, Synthetic Aperture Radar; SO-GLOBEC, Southern Ocean-Global Ocean Ecosystems Dynamics Research; SO-JGOFS, Southern Ocean-Joint Global Ocean Flux Study; WAIS, West Antarctic Ice Sheet Initiative; WOCE, World Ocean Circulation Experiment.

cesses are related to Antarctic krill distribution, while small-scale circulation affects coastal populations of fish and planktonic organisms. All of these attributes influence the global heat, freshwater, and CO_2 budgets as well as sea-level changes.

The principal elements to determine the long-term variability and trends in sea ice and ocean circulation are: (i) continued measurements of ice extent and open water within ice pack by satellite microwave imagery; (ii) monitoring of sea-ice thickness with moored sonars; (iii) addition of Antarctic receiving stations of the Global Acoustic Transmission Experiment (GATE) to detect changes in the antarctic circumpolar and coastal currents; and (iv) the definition of key parameters and methods of measurement for future monitoring of antarctic bottom-water production.

Some of these measurements are underway. For example, satellite passive microwave measurements have been nearly continuous since 1973 and are expected to continue. Synthetic aperture radar (SAR) data will be collected by the ERS-1 satellite and other future satellites for large parts of Antarctica. Ship cruises have provided valuable ground-truth data for the validation and calibration of the satellite data. The Antarctic Ice Drifting Buoy Programme

(AIDBP) for ice dynamics and thickness has been initiated. The Global Acoustic Transmission Experiment (GATE) has also been initiated, but there are as yet no plans for antarctic receiving stations.

3. CONCLUSION

Table 1 lists major parameters needed to detect and monitor change in Antarctica and future programmes being planned which will aid in this pursuit. Measurements are being made now of practically all of the listed parameters, but many deficiencies exist, which have been outlined in some detail in this paper. These deficiencies presently prevent an adquate overall assessment of environmental change in Antarctica. SCAR has outlined a coordinated strategy for a regional research program in Antarctica, which in part has been described here. If put into action it will be a major step in learning about and understanding the changes in Antarctica expected as part of global change.

I am indebted to the members of the SCAR group which met on 18–21 September 1992, at the Alfred Wegener Institute in Bremerhaven, Germany, and helped to compile the material used here as part of a larger SCAR report on the role of Antarctica in global change (SCAR 1992). The members of the group were R. Barry, T. Lachlan-Cope, B. Luchitta, R.Lewis-Smith, T. Yamanouchi, T. Viehoff, R. Wharton, D. Wynn-Williams and J. Zwally.

REFERENCES

IPCC 1990 *Climate change: the IPCC scientific assessment.* Intergovernmental Panel on Climate Change. World Meteorological Organization/United Nations Environmental Programme. Cambridge University Press.

Jacka, T.H. & Budd, W.F. 1991 Detection of temperature and sea ice extent changes in the Antarctic and Southern Ocean. In *Proceedings of International Conference on the Role of the Polar Regions in Global Change* (ed. G. Weller, C. Wilson and B. Severin), pp. 63–70. University of Alaska.

Manabe, S., Spelman, M.J. & Stouffer, R.J. 1992 Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2. Part II: Seasonal response. *J. Climate* **5**, 105–126

SCAR 1992 *Antarctica and global change: An international regional research plan.* Scientific Committee on Antarctic Research: ICSU Press. (In the press.)

Discussion

P. Wadhams (*Scott Polar Research Institute, Cambridge, U.K.*). There is good reason to expect an improvement in the quality and quantity of sea-ice thickness data from the Antarctic. Although submarine operations, the mainstay of synoptic data gathering in the Arctic, do not occur, there are a number of moored upward sonar systems in the Weddell Sea, deployed by Alfred-Wegener-Institüte für Polar- und Meeresforschung, Bremerhaven and also a number of drifting buoys which measure ice thickness using thermistor chains. Both the drifting buoy and the upward sonar programmes are being coordinated by WCRP (World Climate Research Programme).

In the future, an answer to the problem of synoptic ice thickness measurement could come from the use of autonomous underwater vehicles (AUVS) equipped with upward sonar, and airborne laser profiling has shown great promise in the Arctic.

D. J. Drewry (*British Antarctic Survey, Cambridge, U.K.*). The Antarctic Global Change programme being planned by SCAR is ambitious and multifacetted with six major core projects. Each of these will be responsible for generating considerable volumes of data, and will be combined with other globally relevant programmes. What mechanisms are being considered for the processing, archiving and overall coordination of these data so that a coherent pattern of environmental change can be discerned?

G. Weller. There is a SCAR ad-hoc Group on Coordination of Antarctic Data which has begun to address this problem, and the New Zealanders have recently opened an International Centre for Antarctic Information and Research which could become the focus for Antarctic data management. Also, the BIOMASS Data Centre could be a useful model. The SCAR global change programme in Antarctica will have to address this issue in some detail in the near future.

J.-O. Strömberg (*Kristinebergs Marinbiologiska Station, Fiskebäckskil, Sweden*). During investigations in the Greenland Sea, it has been found that the convection of cold surface water is not as deep as formerly believed. If this trend continues it would possibly influence the so called conveyor belt. Now Professor Weller has shown in one of his scenarios that much less sea ice may be formed in the future which would threaten the existence of the conveyor belt.

F. G. Larminie. In the debate on the processes of environmental change the rates of change seem to me to be seriously neglected. The graphs depicting climatic change tend to be smooth low angle curves showing trends and are at odds with the results of palaeoenvironmental studies which are strongly suggestive of quite large changes (of the order of 5°C+) over relatively short periods of time. Would Professor Weller care to comment on the fashion for emphasizing trends rather than sharp, short-duration events in the processes of environmental change?

G. Weller. I agree that sharp, short-duration events should be looked at more closely. Some global change scenarios in fact suggest that these might become more frequent than now. In predicting future changes we are tied to existing models, however, which are capable of showing trends but do poorly on these short events. When we talk about 'relatively short' periods of time in the palaeoenvironmental record (e.g. ice cores) these are still on the order of 50–100 years, comparable to the predicted climate change at high latitudes over the next century.

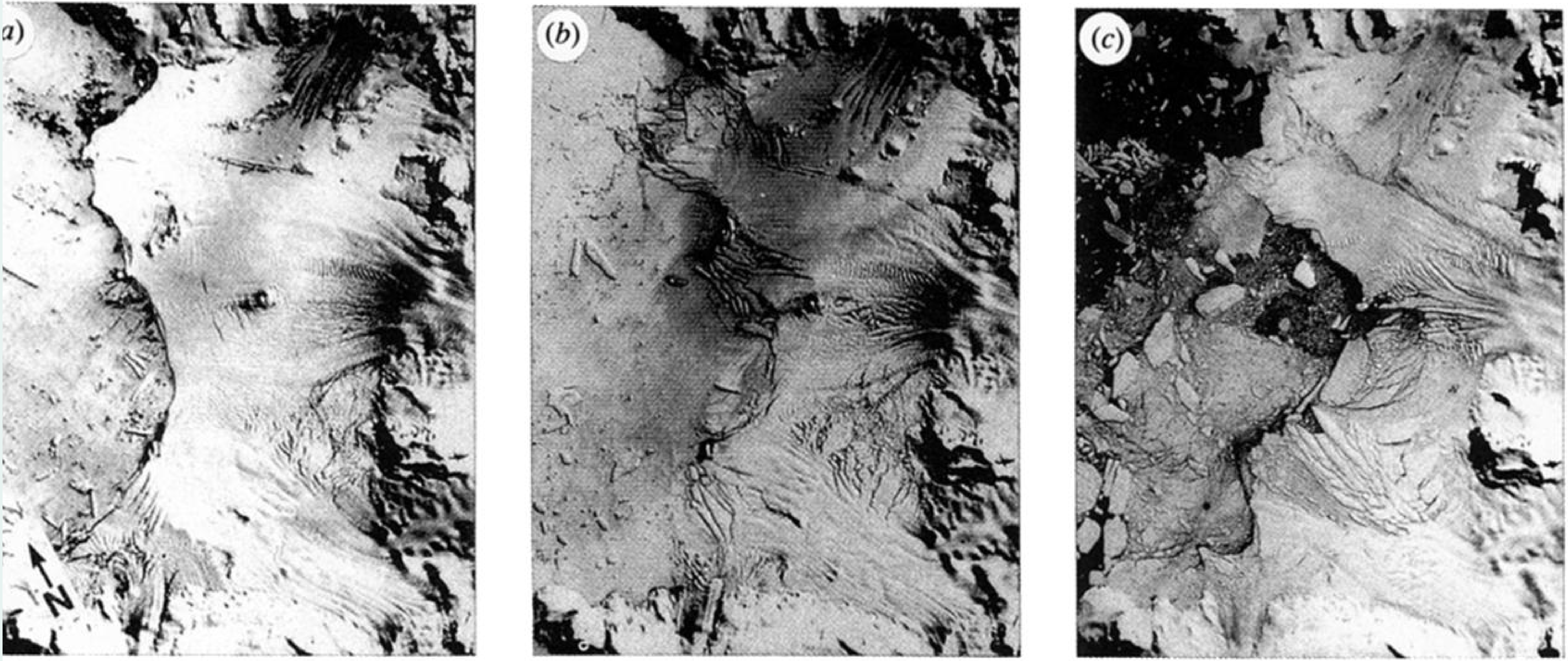

Figure 3. The disintegration of the Wordie Ice Shelf, Antarctica, observed through Landsat satellite imagery (published courtesy of EOSAT, illustration provided by D. Vaughan). (*a*) 1974; (*b*) 1979; (*c*) 1989.