Science Plan for a SCAR Programme on

Antarctica and the Global Climate System (AGCS)

Submitted by the SCAR Physical Sciences Standing Scientific Group

Expected Duration of programme: 6 year

Estimated SCAR Funding Required: $90,000 Over the Lifetime of the Programme. But options are presented for additional expenditure if greater levels of funding become available

Programme Summary

This proposal outlines a programme of research to investigate the nature of the atmospheric and oceanic linkages between the climate of the Antarctic and the rest of the Earth system, and the mechanisms involved therein. This work is a high priority and will require a combination of modern instrumented records of atmospheric and oceanic conditions, and the climate signals held within ice cores to understand fully past and future climate variability and change in the Antarctic as a result of natural and anthropogenic forcings. The primary time period to be considered will be approximately the Holocene (about the last 10,000 years) to 100 years in the future, but records that capture abrupt climate change over earlier periods will also be used as necessary.

The programme will make use of existing deep and shallow ice cores, satellite data, the output of global and regional coupled atmosphere-ocean climate models and *in-situ* meteorological and oceanic data to understand the means by which signals of tropical and mid-latitude climate variability reach the Antarctic, and high latitude climate signals are exported northwards. The emphasis will be on synthesis and integration of existing data sets and model output, although some new ice core and oceanographic data will be collected.

There will be four major, closely linked themes of research. (1) *Decadal time scale variability in the Antarctic climate system*, which will investigate ocean-atmosphere coupling, the role played by radiative processes and the role of the El Niño-Southern Oscillation in modulating the Antarctic climate. (2) *Global and regional climate signals in ice cores* to establish better quantitative relationships between ice core data and measures of tropical, mid- and high latitude climate variability (3) *Natural and anthropogenic forcing on the Antarctic climate system*, including the production of regional-scale estimates of expected climate change over Antarctica during the next 100 years. (4) *The export of Antarctic climate signals*, to examine the means by which climate changes in the Antarctic can influence conditions at more northerly latitudes

The programme will be a valuable contribution to the International Polar Year planned for 2007-2008, especially their Themes 1, 2 and 3 dealing respectively with environmental variability, change, and teleconnections. We plan to use the IPY as a Special Observing Period to test models and high-low latitude climate signal transfer functions.

As part of the programme we will create a new web-based inventory of data extracted from Antarctic ice cores to complement the SCAR READER data base of mean *in-situ* meteorological data. The future climate scenarios produced will be of great value to the Life Sciences SSG in their consideration of how the Antarctic biota will evolve over the next century.

1. Programme Objectives

The goals of this programme are to gain insight into the linkages between the Antarctic and the rest of the global climate system. Specifically, we will address a number of key questions concerning extra-polar/Antarctic coupling:

- How does variability in tropical and mid-latitude atmospheric and oceanic conditions modulate the Antarctic climate?
- Does variability in Antarctic climate perturb tropical and mid-latitude atmospheric and oceanic conditions?
- What are the mechanisms that transfer the tropical signals to the Antarctic?
- What are the relative roles of the ocean and atmosphere in this transfer?
- What controls the stability of coupled atmosphere-ocean phenomena, such as the Antarctic Circumpolar wave and the Southern Hemisphere Annular Mode?
- What are the quantitative relationships that reflect the non-linear linkages between climate signals in ice cores, Antarctic sea ice and the Antarctic atmospheric circulation, and the varying extra-polar signals?
- Why do the teleconnections between the tropics and the Antarctic vary on decadal timescales?
- How has the development of the Antarctic ozone hole affected these teleconnections?
- What has been the impact on the Antarctic environment of changes in the El Niño-Southern Oscillation over recent decades?
- How will Antarctic climate conditions change on regional and continent-wide scales over the next century as a result of various greenhouse gas emission scenarios and other human source emissions into the atmosphere?

Within this programme we will also:

- Work with climate modellers to improve the representation of the Antarctic atmosphere, ocean and cryosphere in global and regional models.
- Assemble a new data base of Antarctic ice core information.
- Work with life scientists to investigate the impact of recent and possible future changes in climate on Antarctic ecosystems.
- Where necessary establish linkages with the deep ice core records of pre-Holocene climatic conditions.

2. Scientific background

Our understanding of the role of the Antarctic in the global climate system has advanced dramatically in recent years as new atmospheric, oceanographic and cryospheric data sets have become available. We now know that ice-albedo feedbacks and radiative processes (mainly related to clouds) are extremely important over the continent and in the sea ice zone, explaining why the inter-annual variability of temperatures is so large at high latitudes. Great advances have also been made in our understanding of ocean processes, such as the role of the Antarctic Circumpolar Current (ACC) in linking the ocean basins, allowing the global-scale thermohaline circulation to exist.

At the time of IGY the Antarctic was thought of as rather isolated from conditions at more northerly latitudes, but studies using the new observational data sets and sophisticated Atmosphere-Ocean General Circulation Models (AOGCMs) have shown the close couplings that exist between different elements of the system and the feedbacks that are operating.

The Antarctic is the main heat sink in the Southern Hemisphere and there is a southward flux of heat in response to the radiatively-induced Equator to Pole temperature difference. The bulk of the heat (80%) is carried by the atmosphere, but with the ocean transporting the remaining 20%. The circumpolar channel is important in inhibiting the poleward flux of heat via the ocean and plays an important role in the glaciation of the continent.

In the atmosphere the transient eddies (depressions) over the Southern Ocean play a greater role in the thermal advection when compared to their counterparts in the Northern Hemisphere, as a result of the simpler orography in the Southern Hemisphere. The track and frequency of these eddies is a function of the thermal gradient over the Southern Hemisphere and provides a means for climatic signals in the tropics and mid-latitude regions to reach the Antarctic. But the more active role of the eddies complicates the southward transfer of tropical climate signals as they have to cross the belt of strong westerlies. High-low latitude teleconnections in the Southern Hemisphere are therefore less robust than north of the Equator.

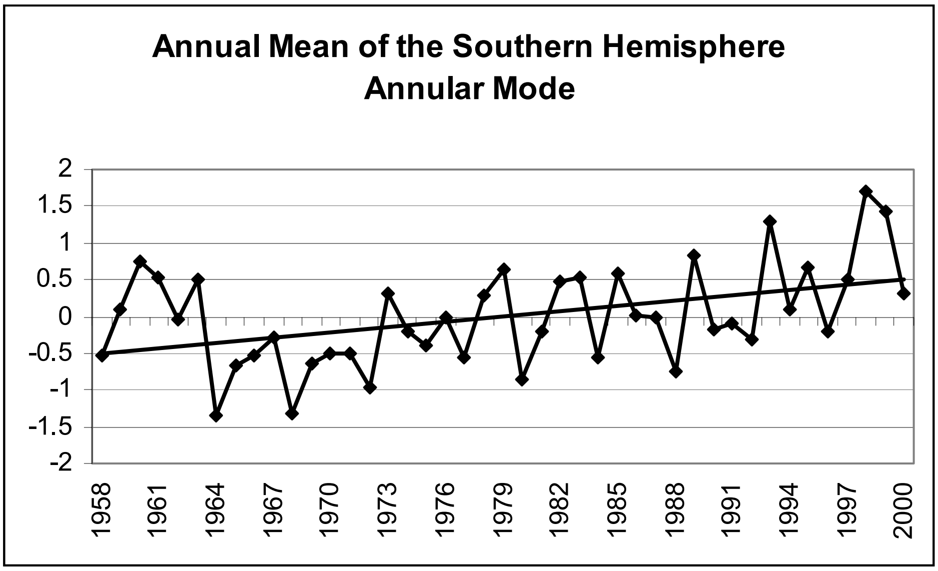

Figure 1. The annual mean value of the Southern Hemisphere Annular Mode (SAM) with linear regression line.

Ocean eddies are also of great importance in heat and momentum transport in the Southern Ocean and are likely to play an important role in controlling the strength of the Circumpolar Current. These systems typically have a horizontal length scale of 20-100 km and present challenges to modellers and those concerned with the collection of observational data.

Over recent decades part of the Antarctic have experienced major climate change, with near-surface temperatures on the western side of the Antarctic Peninsula rising faster than anywhere else in the Southern Hemisphere. This region has also experienced the disintegration of a number of floating ice shelves. Over this period significant advances have been made in understanding climatic cycles in the Antarctic and the role that extra-polar forcing and internal mechanisms, such as cloud radiative effects, plays in this variability. One of the first indications of high-low latitude coupling was the semi-annual oscillation (SAO). This was identified in the mean sea level pressure (MSLP) observations from the stations around the coast of the Antarctic and showed that pressures were at a minimum (maximum) during the autumn and spring (summer and winter) (van den Broeke, 1998). This was found to be associated with a southward movement and deepening of the circumpolar trough, which rings the Antarctic over 60-70^{o} S. The circumpolar trough is present because of the large number of storms in the coastal region, with the systems having either developed in the strong thermal gradient at the edge of the Antarctic or having moved south from mid-latitudes. The SAO, which has no counterpart in the Arctic, occurs because of the different annual cycles of surface temperature over the Antarctic continent and mid-latitudes. As well as affecting the MSLP observations, a SAO is also found in the precipitation reports from the coastal region and will therefore be reflected in the sub-annual data in ice cores. Changes in the mid-latitude conditions therefore have the capacity to alter the Antarctic environment via the SAO. The oceanic circumpolar transport also shows a pronounced semi-annual signal, as a consequence of modulation of eastward wind stress by the SAO

(Whitworth and Peterson, 1985; Meredith *et al.*, 1996), emphasizing the intimate coupling of atmospheric and oceanic dynamics around Antarctica. But the SAO is now known to exhibit inter-annual to decadal timescale variability, so complicating the investigation of Antarctic climate change.

Although the identification of the SAO was an important step in understanding the interactions between the mid- and high-latitude areas, recently it has been found that the SAO reflects, to a large extent, the Southern Hemisphere Annular Mode (SAM), which we now know is the principal mode of variability in the atmospheric circulation of the Southern Hemisphere extra-tropics and high latitudes. The SAM has a zonally symmetric or annular structure, with synchronous anomalies of opposite sign in Antarctica and the mid-latitudes, and is usually defined as the MSLP difference between 40^o and 65^o S. Over recent decades the SAM has been moving into its positive phase (Figure 1) with MSLP values decreasing across the Antarctica coastal zone and rising over the mid-latitude areas of the Southern Ocean. This has resulted in greater ascent of air around the continent and larger amounts of cloud and precipitation over the sea ice zone. The change in the SAM has also resulted in an increase in the westerly component of the wind around the continent and an increase in ACC transport. This has further given an increase in sea ice due to an increase in northward Ekman flow. There are indications that the changes in the atmospheric driving forces affect the ocean circulation and water mass properties of the source waters for deep and bottom water formation in the Weddell Sea, which contribute to the global thermohaline circulation (Fahrbach et al., 2004).

The exact reasons for the change in the SAM are not understood fully, but model experiments have shown that the SAM is affected by changing levels of stratospheric ozone (Thompson and Solomon, 2002) and increasing amounts of greenhouse gases (Fyfe *et al*., 1999). Ice core records capture annual to multi-decadal scale variability and dramatic changes in the large scale atmospheric circulation.

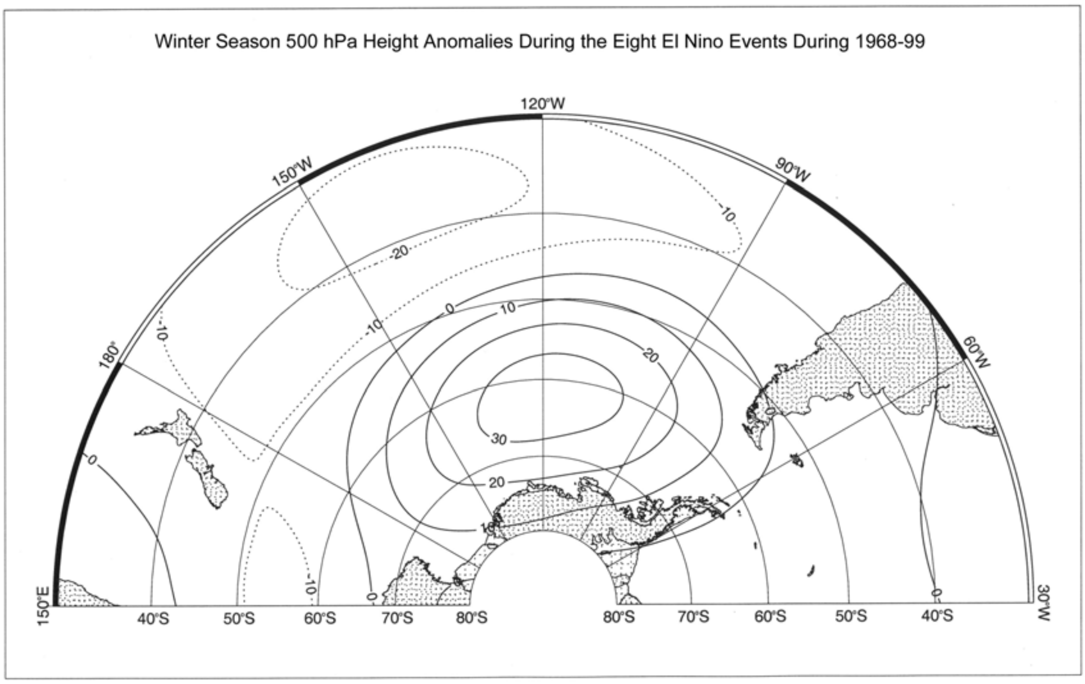

Figure 2. The 500 hPa height anomalies over the Amundsen-Bellingshausen Sea during the eight El Niño events between 1968-99.

The circumpolarity of the Southern Ocean is a key factor in the global climate system, since it forms an important link between the other major oceans; the importance of this connectivity is further enhanced by the presence of the ACC, the world's largest current in terms of transport. It has been demonstrated recently that the SAM is an important mechanism controlling temporal variability in the circumpolar ocean transport around Antarctica on timescales up to seasonal (Aoki, 2002; Hughes *et al*., 2003). The response of the ocean to the long-term trend in the SAM toward a higher index state has yet to be established, however Thompson and Solomon (2002) noted that this trend is strongly modulated by season, and recent ocean observations have revealed strikingly similar seasonal modulations in the ocean circumpolar transport (Meredith *et al.*, 2004a). This is suggestive of high latitude climate change (including possible ozone depletion) being transmitted to the ocean circulation, with possible global implications.

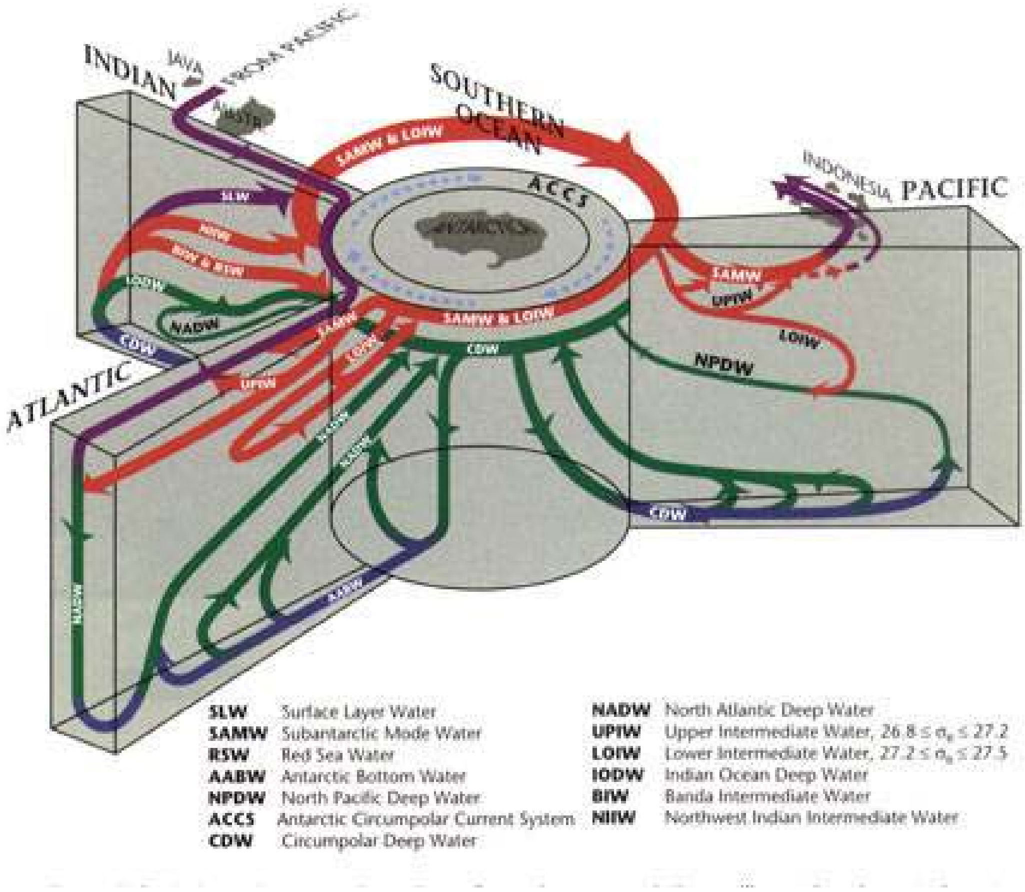

Figure 3. The thermohaline circulation. From Schmitz et al. 1995.

The El Niño-Southern Oscillation (ENSO) is the largest climatic cycle on Earth on the timescale of years to decades, and variations in the cycle have world-wide consequences. During El Niño events a Rossby wave train becomes established from the central, tropical Pacific across the South Pacific to the Bellingshausen Sea (Figure 2). On average, this results in colder, drier conditions over the Antarctic Peninsula, and warmer, temperatures and higher levels of precipitation over the coastal region of the southern Amundsen Sea during El Niño events (Turner, 2004). Ocean measurements during ENSO events are very scarce around Antarctica, however Meredith *et al.* (2004b) noted a deepened mixed layer and enhanced salinity at the western Antarctic Peninsula in response to increased ice production during the decay of the 1997/98 ENSO. This observation complements the previous observation of enhanced downslope convection of dense water from the tip of the Peninsula during 1998, again believed to be due to an ENSO-related modulation of the sea ice field (Meredith *et al.,* 2003). There is, however, considerable variability in the nature of ENSO events even in the tropics and the extra-tropical response to this forcing is rather variable. For example, the 1982-83 El Niño event was the largest of the Twentieth Century, but it had a very anomalous signature in the Antarctic. This makes it very difficult to find consistent signals of ENSO events in atmospheric, oceanic and cryospheric parameters measured in the Antarctic. For example, signals of El Niño events have been detected in ice cores collected at the South Pole via the marine biogenic sulphur species methanesulphonate (Meyerson *et al.,* 2002) and the moisture flux into west Antarctic, and therefore the precipitation in this sector of the continent, was highly correlated with the ENSO cycle (Cullather *et al.,* 1996). But this latter study highlighted a change in phase of the ENSO/precipitation relationship between the 1980s and 1990s, pointing to a decadal timescale variability in some aspects of the tropical-high latitude teleconnections.

It has also been suggested that the ocean circulation can play a role in the southward transmission of ENSO signals via the Antarctic Circumpolar Wave (ACW) (White and Peterson, 1996). This could take place as SST anomalies develop in response to ENSO events along the Equator and move south into the western subtropical South Pacific, with the signals then spreading south and east into the Southern Ocean, where subsequent eastward propagation can take place via the Antarctic Circumpolar Current. However, Connolley (2003) has shown that the ACW was most pronounced during the 1980, but was less clear in earlier and later periods, again indicating decadal variability in the atmosphere-ocean interactions.

The above studies have highlighted the non-linear nature of many of the Antarctic-lower latitude teleconnections, suggesting that simple comparisons of ENSO measures (such as the Southern Oscillation Index) with environmental quantities measured in the Antarctic are only of limited value. A sounder approach will be to combine Antarctic observational studies and ice core records with modelling experiments and numerical analysis, which will give greater insight into the processes involved.

Although many of the studies concerned with teleconnections between the Antarctic and lower latitudes have considered the southward transfer of tropical signals, there are also important linkages out from the Antarctic. These have been most investigated in the ocean, with particular attention being paid to Antarctic Bottom Water (AABW) and the thermohaline circulation. This is the densest water mass in the open ocean; as such it constitutes the abyssal layer of the global overturning circulation (Figure 3). It has been hypothesised widely that changes in the production rate and/or properties of AABW could exert a long-term influence on global climate, though the precise nature and mechanisms involved are currently undetermined. The bulk of AABW formation requires dense shelf water as a precursor, with sea ice formation being a key process in adding salt to the ocean to raise its density. Consequenty, climatically-driven changes in sea ice production could play a profound role in altering AABW formation. Similarly, changes in the mass balance of the Antarctic ice sheets could affect the glacial freshwater contribution to the adjacent ocean, again with possible consequences for the production of AABW. Once formed, the components of AABW have to negotiate various topographic obstacles before reaching the major ocean basins to the north; this circulation (which is believed to be wind driven to some extent) is likely to exhibit temporal variability (e.g. Meredith *et al.,* 2001), but the details and extent of this are presently unknown.

As well as AABW, other Southern Ocean water masses are key in the global climate system. For example, Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW) form important parts of the “upper cell” of the global overturning circulation, and show properties that depend strongly on atmospheric forcings. In addition, these water masses are responsible for around 40% of the total uptake of anthropogenic carbon dioxide, and nutrients exported from the Southern Ocean in SAMW have been shown to support around 75% of global export production It is believed that such mode waters are very susceptible to atmospherically-driven climate change, and hence are strong markers of the oceans response to such changes (Banks and Bindoff, 2003). Furthermore, changing ocean conditions can be important drivers of Antarctic and global climate change. Recent observations indicate that Circumpolar Deep Water (CDW; the most prevalent water mass of the ACC) is warming at a much greater rate than the global oceans as a whole (Gille, 2002). In regions where CDW shoals and impinges on the continental shelves of Antarctica (e.g. the western Peninsula), this could be an important additional heat source that requires consideration in studies of future climate.

It is now timely for SCAR to undertake a programme of research into the links between the Antarctic climate and the rest of the Earth system as it is only in the last few years that sufficient high resolution *in-situ* data and ice core records have become available to investigate such connections and modelling tools have developed to the point where they can represent realistically the closely coupled atmosphere-ocean processes that are clearly important in long-term climate variability.

The climate of the Antarctic varies on a very wide range of time scales from the annual and sub-annual to the major ice ages. In order to keep the scope of the project manageable, the focus on recent and future climate variability and change, and to be able to examine atmospheric/oceanic processes in some detail, we propose to have the primary focus of the programme over the period of the Holocene out to the next 100 years. The second half of the Holocene was when the solar forcing was essentially the same as today and natural climate variability over this period will provide a reference against which we can compare variability and change in the period of anthropogenic influence. This is also a period during which the modern configuration of the Antarctic ice sheet began to evolve (Conway *et al.,* 1999), and it is upon these evolving boundary conditions that modern climate is superimposed. The next 100 years is also the period of interest to the Intergovernmental Panel on Climate Change (IPCC) and we propose to use some of the model data created as part of this activity in AGCS. The programme will also benefit from the involvement of several Antarctic deep ice core records that cover one or more glacial/interglacial cycles. These records offer case histories of a wider range of climate change than available over the Holocene and as such offer important opportunities for modelling climate extremes and abrupt climate change scenarios. We will also investigate the mechanisms controlling the duration and the variability of the warm periods.

We propose that the programme has four major, closely linked themes reflecting significant gaps in our knowledge:

a. Decadal time scale variability in the Antarctic climate system

This activity will focus on explaining the mechanisms responsible for variability in the Antarctic climate system on the scale of several years to a century. This is the timescale on which much of the ocean variability takes place and the changes observed in the atmospheric conditions and sea ice environment reflect the close coupling between the atmosphere and ocean in the high southern latitudes. Key targets will be to understand the variability of Southern Ocean water masses, including the warming of CDW, and the expression of the low frequency variability of ENSO in the Antarctic. Sea ice extent and concentration will also be examined, along with the reasons for changes in the SAM. The relative importance of the radiative processes in modulating the climate system will also be investigated.

b. Global and regional signals in ice cores

A large investment has been made in the collection of shallow and deep ice cores from the Antarctic, yet we still have an imperfect understanding of the means by which the signals of regional and global climate variability reach the coring sites and are locked into the ice record. To date most investigations of global and regional climate signals in ice cores have been based on the assumption that there will be linear relationships between measures of climate variability outside the Antarctic and quantities measured in ice cores. In this theme we will use diagnostic information from models and the re-analysis fields to establish better quantitative relationships between ice core data and measures of tropical and mid- high-latitude climate variability.

c. Natural and anthropogenic forcing on the Antarctic climate system

Elements of the Antarctic climate system have experienced major changes in recent decades, such as the marked warming on the western side of the Antarctic Peninsula since the 1950s. In addition, during the 1970s the total extent of Antarctic sea ice decreased; a change that was frequently attributed to humankind's activity. However, the ice extent recovered during the 1980s and the temperatures on the Peninsula have not changed significantly since about 1980. It has therefore proved difficult to separate natural climate variability from anthropogenic activity. As Antarctic sea ice is predicted to decrease over the coming century as a result of increases of greenhouse gases it is important to be able to distinguish natural variability from anthropogenic activity and to understand how global climate change will be expressed in the Antarctic.

d. The export of Antarctic climate signals

This theme will examine the means by which climate changes in the Antarctic can influence conditions at more northerly latitudes. Much of this is believed to happen via the ocean, with AABW escaping the subpolar gyres and traversing topographic obstacles to spread out into the world's ocean. The processes which control the transfer and spreading of the AABW require investigation, to determine the extent to which changes close to the Antarctic continent can influence the larger-scale ocean and climate. Processes close to the Antarctic can influence the production rate and properties of AABW and other water masses, such as intermediate and mode water. For example, removal of sea ice and glacier melt can both influence water mass production in the Antarctic coastal zone, thus influencing the shelf water properties that are key to the formation of AABW. Atmospheric changes that affect the ocean surface (heat and freshwater fluxes, wind-driven Ekman transports) are known to be important in setting the properties of intermediate and mode waters, and hence need to be included in the analyses. The long-term warming of CDW will have consequence fore formation and spreading of other water masses, since it is the oceanic source for all other waters that form around Antarctica. Thus consideration of this warming is important if our understanding of the Southern Ocean's role in global climate is to be usefully advanced.

3. Programme rationale/justification

The research proposed here is necessary in order to interpret correctly the climate signals in ice cores and to understand past and future climate variability and change in the Antarctic as a result of natural and anthropogenic forcing factors. As described above, the linkages between the different elements of the Antarctic climate system are highly non-linear and it is necessary to understand the atmospheric, oceanic and cryospheric elements of the system if past change is to be explained and we are to have confidence in future predictions.

SCAR is well placed to lead this activity as it has representatives from all the nations with major Antarctic research programmes and now has the structure of SSGs that brings together scientists with the necessary skills to undertake such a cross-disciplinary programme of research. It also has excellent links into the planning of Antarctic operations via COMNAP.

The work described here will build on successful SCAR activities that have already raised the profile of SCAR in the international community. The International Trans-Antarctic Scientific Expedition (ITASE) has the goal of understanding the last 200-1000 years of Antarctic climate and change in the chemistry of the atmosphere using ice core data. The ongoing collection of ice cores through ITASE will provide vital, high-resolution climate data extending back into the pre-industrial period. The SCAR REference Antarctic Data for Environmental Research (READER) project will continue to develop its high quality data base of mean *in-situ* mean meteorological data for investigation of climate variability at the research stations over the last 50 years. The Antarctic Tropospheric Aerosols and their Role in Climate (ATAC) Action Group is determining the influence of Antarctic tropospheric aerosols on the radiation budget and characterising and classifying the nature of Antarctic aerosols. Aerosols are transported to the Antarctic via the meridional atmospheric circulation and provide information on the sources of airmasses. ATAC will therefore become part of AGCS and contribute to the investigation of high-low latitude linkages.

This programme is also timely in that many of the tools, models and data analysis procedures required to carry out the work have only just become available. The ECMWF 40 year atmospheric re-analysis project (ERA-40) is just coming to a close and has produced the best time series of atmospheric conditions yet created, extending back to IGY. Although there are some questions regarding the quality of the analyses in the period before the mid-1970s when satellite sounder data became available, the fields are of high quality since that time. The data will be vital for investigating atmospheric variability, and will also allow the production of back trajectories for the investigation of signals arriving at the ice coring sites.

Early climate models were simple atmosphere-only models with poor horizontal and vertical resolution and no interactive ocean or sea ice. With prescribed ocean conditions they were not able to simulate the natural climate variability of the Earth. Later models were coupled to ocean models and had sea ice that simulated successfully the interactions between floes. The current generation of AOGCMs have developed to the point where they have sufficient horizontal and vertical resolution to successfully simulate most of the orography of the Antarctic, although they still have problems in handling areas such as the Antarctic Peninsula, which is a high, narrow barrier. A very recent innovation is the development of coupled atmosphere-ocean regional climate models that are better able to simulate the small-scale processes that are found in the Antarctic, and these will be used within AGCS. The results of AGCS will be of value to the modelling community and it is hoped that they will result in improvements to the high latitude element of global climate models.

There have also been great advances in the analysis of ice cores so that annual, and in some areas of high accumulation sub-annual, information can be retrieved. A broad range of environmental indicators are now available from ice cores allowing reconstruction of past content of gases, major and trace chemistry, radionuclides, isotopes, organics etc. These measurements allow reconstruction of past physical (temperature, precipitation, atmospheric circulation) and chemical climate through calibration with *in-situ* observations. That said, the opportunities and complexities inherent in such calibrations require significantly more focus and tighter connections between communities represented by SCAR, notably meteorologists, atmospheric chemists, solar physicists, biologists, and glaciologists. ITASE has dramatically advanced the number, quality, and calibration potential of ice core records. Further, through ITASE, ice core records can now be traced from site to site through tracking of time synchronous radar reflectors and into the atmosphere through aerosol collections. Deep ice cores collected by several SCAR nations have now successfully penetrated back 800, 000 years in the Antarctic revealing changes in the long term behaviour of climate and through comparison with Arctic deep ice cores reveal the global structure of abrupt climate change events. Efforts will be made with the International Partnerships in Ice Core Sciences (IPICS) to extend the record in time and to investigate during IPY where the longest records can be retrieved. With IPICS, surveys will be carried out of the best places on the edges of the Antarctic to establish a network of intermediate drillings with the aim of investigating the stability of this region over the last 20,000 years.

The International Polar Year (IPY) will be a major focus of Antarctic research, survey and logistical coordination during the period 2007-9. Over this time there will be additional observing systems deployed across the Antarctic and the Southern Ocean. The operational meteorological analyses, which will assimilate these data, will therefore be of high quality. But the enhanced observational data provides an ideal opportunity to carry out case studies of high-low latitude oceanic and atmospheric linkages. We will therefore use the IPY as a Special Observing Period within AGCS to test models and high-low climate signal transfer functions. We see AGCS as being a valuable SCAR contribution to the IPY, especially its Themes 1 “To determine the present environmental status of the polar regions by quantifying their spatial and temporal variability”, 2 “To quantify, and understand, past and present environmental and human change in the polar regions in order to improve predictions” and 3 “To advance our understanding of polar – global teleconnections on all scales, and of the processes controlling these interactions”.

We also see the results of this programme being of value to the IPCC. Work is already well underway to produce the Fourth IPCC Assessment, which will be published in 2007. However, the trend is clear that users of the IPCC assessments require regional information on change rather than indications of global change. We see this programme as providing advise to IPCC for the Fifth Assessment, which we anticipate will need input towards the end of the programme. This may be one means for SCAR to have input to the assessment process. The long-term ice core record will also provide significant information for the chapter on palaeoclimatology in the next IPCC report.

Within SCAR itself we see the outcomes of this programme as being of great value to the SCAR Life Sciences SSG who require information on the climate evolution of the Antarctic over the next century based on various greenhouse gas emission scenarios. This will allow them to investigate possible changes in terrestrial and marine biota. We will also work closely with the proposed CACE programme, which will be concerned with the Cenozoic period.

4. Methodology and preliminary implementation plan

This programme of research will be carried out through a close collaboration between meteorologists, climatologists, glaciologists, oceanographers and ice chemists, and will involve integration of observational and modelling activities. Such an approach will be essential as the programme will deal with subjects that are highly cross-disciplinary.

Preliminary implementation plans for the four research themes are presented below:

a. Decadal time scale variability in the Antarctic climate system

- Existing long, 1,000 year control runs of the pre-industrial climate from AOGCMs will be used to examine the natural climate variability of the Antarctic atmosphere and the oceanic conditions around the continent.
- As part of the above activity the ability of such models to represent Antarctic and Southern Ocean conditions will be verified thoroughly against existing atmospheric observations and analyses, and oceanographic ship and float data.
- Selected model parameters, such as precipitation and temperature across the Antarctic, will be compared to the available ice core records to further assess the performance of the models. Such runs will provide an indication of atmosphere/ocean variability on a range of time scales and allow the determination of the robustness of high-low latitude teleconnections. Diagnostic information from the runs will provide insight into the mechanisms that are important in maintaining the teleconnections and the reasons for changes on the decadal timescale.
- The high quality re-analysis data sets, such as ERA-40, will be used to investigate atmospheric variability over recent decades. Case studies will be carried out of low-latitude – Antarctic linkages during different stages of recent ENSO events.
- Changes in water mass variability and other ocean properties will be carried out using existing cruise and float data. This work will also make use of the output from ocean and AOGCM runs.

b. Global and regional signals in ice cores

- Existing and new ice core data will be used in conjunction with re-analysis fields and selected lake sediment data to investigate how signals of change reach the cores. Back trajectory analysis will indicate the source regions of precipitation falling at the drilling sites.
- Blowing snow models will be used to investigate the mixing of snow on the surface, which provides a limit on the resolution of the data that can be identified in the cores. Output from the high resolution models that are becoming available will provide insight into the role of mesoscale processes in affecting the core data.
- A study will be carried out to determine the extent to which quantitative relationships can be developed between parameters measured in ice cores (or determined from ice core data) and measures of the atmospheric and oceanic circulation.
- The role of sea ice variability in modulating the atmosphere/ocean signals in ice cores will be determined.
- Study of the actual vertical aerosol distribution in the Antarctic troposphere, their transport pattern and life cycle, including air-snow transfer of aerosol in general, will be carried out to improve the ability to decipher the signals in the Antarctic ice core records of past climate (part of the ATAC project).
- The IPY will be used as a Special Observing Period for tracking airmasses arriving at ice core sites.
- A special focus will be ENSO variability as reflected in the cores.

c. Natural and anthropogenic forcing on the Antarctic climate system

- Using measures of the natural climate variability of the Antarctic climate system produced by Theme 1, we will use all available data to determine if the observed climate changes that have taken place over the last 50 years in certain sectors of the Antarctic are a result of anthropogenic activity. We will concentrate our investigation on the warming across the Antarctic Peninsula, the recent changes in

sea ice extent and the role of the ozone hole in influencing tropospheric and oceanographic conditions and circulation. Regions of recent glacier change in East Antarctica will also be investigated notably Northern Victoria Land and the Lambert Glacier region. Throughout Antarctica evidence of changes in physical and chemical climate will be sought.
- Predictions will be produced of how the Antarctic climate is expected to evolve over the next century under different greenhouse gas scenarios. We will specifically use the predictions from the new generation of high resolution regional climate models that are becoming available.

d. The export of Antarctic climate signals

- Variability in AABW, AAIW, SAMW and CDW will be determined from cruise data and profiling float data.
- These data will be compared to such variability as represented in AOGCMs.
- The role of atmospheric and cryospheric forcing and variability on water mass production will be examined. Special emphasis will be placed on processes close to the Antarctic continent, including sea ice variability, iceberg calving and changes in freshwater release via glacial melt.
- The role of changing ocean abyssal circulation in regions of complex topography will be examined, with particular emphasis on understanding the mechanisms that control the northward export of AABW into the global overturning circulation.

In support of the above themes a **central archive of ice core data** will be created. Data derived from short and long ice cores will be essential to this programme with meteorologists, climatologists, sea ice experts, and ice chemists requiring access to these data. Projects such as ITASE, PAGES and EPICA have all produced extremely valuable paleoclimate data, but the data are scattered across institutes and data centres and not readily available to the broader research community. As a first step towards bring these data together, we will establish a web-based inventory of paleoclimate data derived from ice cores. Maps showing the locations where cores were collected will be created linking to information on who holds the data, the data derived and published papers that draw on these data.

5. Programme management and governance

We propose that the programme be managed and directed by a Steering Committee consisting of the chair of SSG/PS and leaders of the four themes. These will be distinguished scientists from the international community. The Steering Committee will meet for several days each year and review progress of the programme. Other scientists will be invited to the meetings of the Steering Committee as necessary in order to have external input to the planning and implementation of the programme. They will also meet at the biennial SCAR Science Meeting and present progress reports to the full SSG. Biennial reports will also be presented to the SCAR Delegates Committee on Science and the full Delegates meeting.

Each theme will be led by a distinguished scientist who will be responsible for coordination of the research within the theme. If approved a full implementation plan for the programme will be developed.

The Steering Committee, and particularly those involved in the themes will work closely with JCADM over the data management and data stewardship aspects of the programme.

With a programme of this scope it will be essential to maintain liaison with a number of international organisations and groups, and this will be the responsibility of the Steering Committee. We wish to stress that we see AGCS as being complementary to many existing programmes and not in competition with them, nor duplicating their activities. Programmes we will work closely with include:

- The WCRP CLIVAR programme
- CliC, and in particular the CLIVAR/CliC/SCAR Southern Ocean Panel, possibly by directly involving a member of the panel.
- IPCC
- SCOR

6. Deliverable outcomes from the programme, including public awareness

We anticipate that this programme would deliver:

- Greater insight into high/low latitude climate linkages.
- Papers in peer reviewed journals.
- Insight into Antarctic decadal timescale climate variability that will be of value to CLIVAR
- Advances in the representation of high latitude processes in climate models.
- High visibility for SCAR science to workers in tropical and mid-latitude climate studies.
- Valuable information for biologists attempting to understand how Antarctic biota are affected by tropical conditions.
- Insight into the relative roles of the ocean and atmosphere in coupling the Antarctic and lower latitudes.
- Future climate predictions for the Antarctic under various greenhouse gas emission scenarios will be of value to other groups within SCAR, such as the marine and terrestrial life scientists.
- An AGCS web site will be created to describe the goals of the programme to scientists and the public, and to present research results.
- Data sets of Antarctic climate variability that will be of value to other workers.

7. Biennial milestones against which progress can be evaluated

Assuming that the programme starts in 2005 we would identify key biennial milestones as:

By the end of 2006

- Determine the natural climate variability of key elements of the Antarctic climate system from long climate model runs
- Preliminary assessment produced of atmospheric, and especially Southern Ocean, conditions in AOGCMs.
- Production of data on airmass origins reaching ice core sites

By the end of 2008

- Complete analysis of water mass variability from historical cruise and float data
- Study completed on quantitative relationships between ice core data and atmospheric/oceanic indices.
- Determine whether anthropogenic activity was responsible for the climate changes noted across the Antarctic over the last 50 years
- Complete study of atmospheric and cryospheric forcing on water mass production
- Initial data base of ice core data available
- Quantification of the Antarctic aerosol budget.
- Preparation of initial atmospheric and oceanic analyses for use within IPY

By the end of 2010

- Provide input to the Fifth IPCC assessment
- Completion of study on relationship between ENSO and Antarctic climate
- Complete analysis of Antarctic-tropical/mid-latitude links during IPY
- Output from high resolution models will provide insight into the role of local, regional and global signals in ice cores
- Production of regional and Antarctic-wide climate predictions for the Antarctic covering the next 100 years
- Supply regional climate scenarios covering the next 100 years to Life Sciences SSG

8. Success factors

- Obtaining funds for this work from the primary funding bodies.

- Papers published in peer reviewed journals
- Provide input to IPCC
- Influence the development of AOGCMs
- Develop methods that give insight into ice core data
- Outputs of AGCS used by other SCAR SSGs
- Obtain a higher profile for SCAR

References

Aoki, S., Coherent sea level response to the Antarctic Oscillation. Geophys. Res. Lett., 29, 2002.

Banks and Bindoff, J. Climate, 2003.Mayewski, P.A., K. A. Maasch, J.W.C. White, E. Meyerson, I. Goodwin, V.I. Morgan., T. van Ommen, J. Souney, and K.

Kreutz, , in press 2004, A 700 year record of Southern Hemisphere extra-tropical climate variability, Annals of Glaciology 39.

Conway, H., B.L. Hall, G.H. Denton, A.M. Gades, and E. Waddington, Past and future grounding-line retreat of West Antarctic Ice Sheet, Science, 286, 280-283, 1999.

Connolley,W.M. (2003), Long-term variation in the Antarctic Circumpolar Wave, J. Clim. 108, 8076-doi.

Cullather,R.I., D.H.Bromwich, and M.L.Van Woert. (1996), Interannual variations in Antarctic precipitation related to El Nino southern oscillation, J. Geophys. Res. 101, 19109-18.

Fahrbach, E., M. Hoppema, G. Rohardt, M. Schröder, and A. Wisotzki, Decadal-scale variations of water mass properties in the deep Weddell Sea, Ocean Dyn., 54, 77-91, 2004

Fyfe,J.C., G.J.Boer, and G.M.Flato. (1999), The Arctic and Antarctic oscillations and their projected changes under global warming, Geophys. Res. Lett. 26, 1601-4.

Gille, S.T., Warming of the Southern Ocean since the 1950s. Science, 295, 1275-1277, 2002.

Hughes, C.W., P.L. Woodworth, M.P. Meredith., V. Stepanov, T. Whitworth III and A. Pyne. Coherent fluctuations in Antarctic sea level, the Southern Hemisphere Annular Mode and the transport through Drake passage. Geophys. Res. Lett, 30(9), 10.1029/2003GL017240, 2003.

Meredith, M.P., J.M. Vassie, K.J.Heywood and R.Spencer. On the temporal variability of the transport through Drake Passage. J. Geophys. Res., 101(C10), 22485-22494, 1996.

Meredith, M.P., A.C.Naveira Garabato, D.P.Stevens, K.J.Heywood and R.J.Sanders. "Deep and Bottom Waters of the Eastern Scotia Sea: Rapid Changes in Properties and Circulation". Journal of Physical Oceanography, 31(8), 2157-2168, 2001.

Meredith, M.P., C.W. Hughes and P.R. Foden. Downslope convection north of Elephant Island, Antarctic Peninsula: Influence on deep water and dependence on ENSO. Geophysical Research Letters, 30(9), 10.1029/2003GL017074, 2003.

Meredith, M.P., P.L. Woodworth and C.W. Hughes. Changes in the oceanic circumpolar transport around Antarctica during the 1980s and 1990s in response to the changing nature of the Southern Annular Mode. In preparation; for submission to Science, 2004a.

Meredith, M.P., I.A. Renfrew, A. Clarke, J.C. King and M.A. Brandon. Impact of the 1997/98 ENSO on upper waters in Marguerite Bay, western Antarctic Peninsula. J. Geophys. Res., accepted, 2004b.

Meyerson,E.A., P.A.Mayewski, S.I.Whitlow, L.D.Meeker, K.Kreutz, and M.S.Twickler. (2002), The extratropical expression of ENSO recorded in a South Pole glaciochemical time series, Ann. Glaciol. 35, 430-436.

Schmitz, W. J., 1995. On the interbasin-scale thermohaline circulation. Rev. Geophys., 33, 151-173.

Thompson,D.W.J. and S.Solomon. (2002), Interpretation of recent Southern Hemisphere climate change, Science 296, 895-99.

Turner,J. (2004), The El Nino-Southern Oscillation and Antarctica, Int. J. Climatol. 24, 1-31.

Van den Broeke,M.R. (1998), The semi-annual oscillation and Antarctic climate. Part 1: Influence on near surface temperatures (1957-79)., Antarct. Sci. 10, 175-83.

White,W.B. and R.G.Peterson. (1996), An Antarctic circumpolar wave in surface pressure, wind, temperature and sea-ice extent, Nature 380, 699-702.

Whitworth III, T. and R.G. Peterson. The volume transport of the Antarctic Circumpolar Current from bottom pressure measurements. J. Phys. Oceanogr., 15, 810-816, 1985.

Supporting information

Programme proposers

Dr. John Turner, Chief Officer, SCAR Physical Sciences SSG

John Turner is a researcher at the British Antarctic Survey in Cambridge, UK where he leads a project investigating the climate of the Antarctic. He has a BSc in Meteorology/Physics and a PhD in Antarctic Climate Variability. From 1974 to 1986 he was employed by the UK Meteorological Office where he was in involved in the development of numerical weather prediction models and satellite meteorology. Since 1986 he has been at BAS working on high latitude precipitation, polar lows, teleconnections between the Antarctic and lower latitudes and weather forecasting in the Antarctic. From 1995 to 2003 he was the President of the International Commission on Polar Meteorology. He is currently the Deputy Secretary General of the International Association of Meteorology and Atmospheric Sciences. He is a member of the Steering Committee of the World Climate Research Programme's Climate and Cryosphere (CliC) project.

Prof. Paul Andrew Mayewski

Paul Andrew Mayewski is Director of the Climate Change Institute at the University of Maine. He has a PhD from the Institute of Polar Studies, Ohio State University and PhD honoraris from Stockholm University. From 1975-2000 he was Director of the Climate Change Research Center at the Unversity of New Hampshire. He has led more than 40 scientific expeditions to the Antarctic, Arctic, and Himalayas/Tibetan Plateau. From 1987-1997 he served as Chief Scientist for the Greenland Ice Sheet Project Two (GISP2) and since 1989 has been chair of the International Trans Antarctic Scientific Expedition (ITASE) SCAR and IGBP activity. He has published extensively on the causes of climate change, abrupt climate change, and change in the chemistry of the atmosphere and has served on numerous national and international scientific committees.

Dr. Mike Meredith

Mike Meredith is a physical oceanographer with many years experience studying the changing circulation and water mass characteristics around Antarctica, in particular in relation to changing climatic forcing. He is currently a Theme Leader at the Proudman Oceanographic Laboratory, UK, where he leads a project concerned with long-term monitoring of circulation in high latitude regions. He has a BSc in Physics, an MSc in Oceanography, and a PhD in the Physical Oceanography of the Southern Ocean. Upon completing his doctoral research, he worked as a Senior Research Associate at the University of East Anglia before being awarded a prestigious NERC Research Fellowship to study ocean climate variability in the Antarctica. Following this, he worked as a physical oceanographer with the British Antarctic Survey, and then joined POL to lead their high-latitude oceans project.

Dr David Bromwich

David Bromwich is a senior research scientist and director of the Polar Meteorology Group at the Byrd Polar Research Center of Ohio State University. He is also a professor with the Atmospheric Sciences Program of the Department of Geography. Dr. Bromwich's research interests include: the climatic impacts of the Greenland and Antarctic ice sheets; coupled mesoscale-global circulation model simulations; the atmospheric moisture budget of high southern latitudes, Greenland, and the Arctic basin using numerical analyses; and the influence of tropical ocean-atmosphere variability on the polar regions. Dr. Bromwich has served on the National Research Council's Committee on Geophysical and Environmental Data and was previously a U.S. Representative of the Scientific Committee on Antarctic Research. He is a member of the American Meteorological Society, the American Geophysical Union, the Royal Meteorological Society, and the American Association of Geographers. Dr. Bromwich earned his Ph.D. in meteorology from the University of Wisconsin, Madison, in 1979.

The need for SCAR support

SCAR is in an excellent position to take the lead on this work as it is a focus for Antarctic scientists in all the necessary disciplines. Over recent years it has supported a number of activities that AGCS will build upon, including ITASE, ISMASS and READER. It has recently established links with SCOR which will be essential in undertaking the oceanic element of this programme.

Anticipated degree of national and international involvement
A high degree of international cooperation will be essential to carry out this programme. If approved, we will urge national SCAR committees to support this work through national initiatives. The involvement, and close cooperation with SCOR, CliC, CLIVAR and other international programmes with interests in the Antarctic and the Southern Ocean will be critical in the implementation of this programme. The IPY will also be a vital element in undertaking this research through the additional observational data that will become available over this period.

Indicative budget for the first 4 years of the programme

Undertaking a programme of research on this scale will require considerable funding for planning, coordination, discuss of results and liaison with other organisations. However, with the uncertainty over the level of funding that will be available from SCAR, we have presented a range of options below to give an indication of the activities that we would like to carry out if additional funds become available. The items indicated by three asterisks (***) will be carried out if additional funds are found.

Funding requirements for 2005-2008:

2005

- Annual meeting of the AGCS Steering Committee (Five people at $2K each = $10K)
- Development of the ice core data base ($2K)
- Workshop on the variability of the Antarctic climate system ($3K)
- Workshop on historical oceanographic data for the Southern Ocean ($5K)***
- Support for ASPeCT ($5K)*** and ITASE ($5K) ***

2006

- Annual meeting of the AGCS Steering Committee (Five people at $2K each = $10K)
- Development of the ice core data base ($2K)
- Workshop on the representation of the Antarctic and the Southern Ocean in models ($3K)
- Workshop of the origins of signals in ice cores ($5K) ***
- Workshop on Antarctic katabatic winds and their interaction with the ocean environment ($5K) ***
- Support for ASPeCT ($5K)*** and ITASE ($5K) ***

2007

- Annual meeting of the AGCS Steering Committee (Five people at $2K each = $10K)
- Workshop on Southern Ocean water mass variability ($5K)
- Workshop on anthropogenic forcing on the Antarctic climate ($5K) ***
- Workshop on airborne aerosol campaign in the Antarctic ($5K)***
- Support for ASPeCT ($5K)*** and ITASE ($5K) ***

2008

- Annual meeting of the AGCS Steering Committee (Five people at $2K each = $10K)
- Workshop on Antarctic climate prediction ($5K)
- Workshop on tropical-Antarctic climate linkages ($5K)
- Support for ASPeCT ($5K)*** and ITASE ($5K) ***