ASPeCt

Antarctic Sea-Ice Processes and Climate
Science and Implementation Plan
1998-2008

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EXECUTIVE SUMMARY

With the growth of activities in Global Change research in the Antarctic, both by SCAR programmes and by other international programmes such as IGBP and WCRP, key deficiencies in our understanding and lack of data from the sea ice zone have been identified. Important problems remaining to be adequately covered by Antarctic sea ice research programmes include:

1. The broad climatology of sea ice physical characteristics;
2. Processes such as ice formation, water mass modification, the maintenance of polynyas, ice edge and coastal fronts, gas exchange, and air-ice-ocean interaction; and
3. Modelling sea-ice processes in coupled atmosphere-ice-upper ocean models and linking scales from local to regional to global scales in models.

There is a special role for the SCAR Global Change Programme in the pack ice zone from the coast of the Antarctic continent to the ice-edge. Hence, SCAR GLOCHANT has established a programme of multi-disciplinary Antarctic sea ice zone research called Antarctic Sea Ice Processes and Climate (ASPeCt).

The objectives of ASPeCt are:

1. To determine the spatial and temporal variability of the basic physical properties of sea ice that are important to air-sea interaction and to biological processes within the Antarctic sea-ice zone (ice and snow cover thickness distributions; structural, chemical and thermal properties of the snow and ice; upper ocean hydrography; floe size and lead distribution); and
2. To understand the key sea-ice zone processes necessary for improved parameterisation of these processes in coupled models.

The major focus of the ASPeCt programme is physical sea ice processes and ocean-atmosphere interaction in the sea-ice zone. As a SCAR programme, ASPeCt is focussed on the role of the unique regional environment of the Antarctic sea ice zone, but it is essential that this is closely linked to the international Global Change research agenda. Hence, the inter-disciplinary components of ASPeCt are designed to contribute to, and to extend, other international climate, ocean and biology programmes.

The ASPeCt programme will build on existing and proposed research programmes, and the shipping activities of National Antarctic operators. It will also include a component of data-rescue of valuable historical sea ice zone information. The ASPeCt programme will achieve its aims by:

1. Standardizing and using a system of quantified shipboard observations that provide statistical descriptions of ice and snow thickness distributions;
2. Providing data rescue and quantification of historical sea ice zone information (from 1980-97);
3. Conducting ship-based process experiments at coastal polynyas, ice edges and interior pack ice zones;
4. Integrating ASPeCt observations and experiments with complementary efforts in drifting buoys, upward looking sonar, satellite records and physical oceanography; and
5. Providing validation and input data on ice properties and processes for coupled numerical models.

1. OVERVIEW

1.1 Introduction

ASPeCt (Antarctic Sea Ice Processes and Climate) is a programme of multi-disciplinary Antarctic sea ice zone research within the SCAR Global Change Programme. ASPeCt specifically addresses key deficiencies in our understanding of and data from the sea ice zone. The programme is designed to complement and to also contribute to the other international programmes in this region. It builds on existing and proposed research programmes, and the shipping activities of National Antarctic operators. It also includes a component of data-rescue of valuable historical sea ice zone information.

1.2 History of the ASPeCt Programme

At a 1991 SCAR meeting, *The Role of Antarctica in Global Change*, the Antarctic sea ice zone was identified as one of the important areas where global change will be manifested. It is also a region where there were considered to be significant gaps in knowledge and understanding of processes and the response of the region to atmospheric and oceanic change, both dynamical and thermodynamical. The Group of Specialists on Global Change in Antarctica (GLOCHANT, established at the 1991 meeting) therefore had a subcommittee, headed by a GLOCHANT member (Ian Allison), examine the role of the Antarctic sea ice zone in global change. This group developed plans for studying the Antarctic sea ice zone in relation to climate processes.

The ASPeCt proposal was developed at a joint meeting of the SCAR groups GLOCHANT, EASIZ and GoSSOE in Tokyo in April 1995. These groups met on the recommendation of delegates at SCAR XXIII to review existing programmes and proposals within the Antarctic sea ice zone, and to consider in particular the overlap between the various programmes. The meeting actually identified gaps in the present research, i.e., no overlap between programmes, which warranted the expanded development of the sea ice subcommittee's plans into a specific new programme of multidisciplinary Antarctic sea ice zone research which initially included a pack ice ecosystem component.

The ASPeCt plan was developed further by correspondence and at a meeting during GLOCHANT IV in Madison, Wisconsin, U.S.A., in April 1996. SCAR XXIV then approved the ASPeCt plan, with the stipulation that the major thrust of ecosystem research (in SCAR's context) fell under EASIZ, and ASPeCt's purview was primarily on the sea ice processes and climate topical areas. S. F. Ackley was appointed Chairman of ASPeCt and joined the GLOCHANT Group of Specialists in mid-1997. The ASPeCt Science Steering Group (Appendix A) was constituted in late 1997 and held its first meeting in December 1997 at Biosphere 2, Tucson, Arizona, U.S.A. The SSG established the ASPeCt programme to be conducted for the period 1998-2008. Data recovery efforts had been initiated in early 1997 and cruises planned for 1998 that included sea ice observation programmes were designated as the first under ASPeCt. The framework for this Science and Implementation Plan was organized, building on coordination of existing data sets, and adding sea ice cruises as planned by members of the SSG.

While the major thrust of the ASPeCt programme is physical sea ice processes and ocean-atmosphere interaction in the sea-ice zone, links with programmes of ecological research in the sea ice zone will be maintained. As a SCAR programme, ASPeCt is focussed on the role of the unique regional environment of the Antarctic sea ice zone, but it is also essential that this is closely linked to the overall international Global Change research agenda. Thus, inter-disciplinary components of ASPeCt are designed to contribute to, and extend, several international ocean, climate and biology programmes.

1.3 Rationale

The Antarctic sea ice zone remains one of the least known regions of the Earth's surface. Apart from satellite-derived data on ice extent and concentration (Figure 1) there are few reasonable climatological estimates of ice conditions that can be used for validation of numerical models. What limited information we have indicates that the ice characteristics and the dominant processes in the Antarctic are substantially different from those in the central Arctic. The Antarctic sea ice zone acts as a regional boundary between the Antarctic continent and the sub-Antarctic, an interface between the upper ocean and the lower atmosphere, and, globally, as a region of important interactive physical and biogeochemical processes.

Uncertainties in, and the importance of, the role of sea ice in the climate system are highlighted in a U.S. Global Change Program Report, *Forum on Global Change Modelling*. On the basis of studies of past climates, which provide evidence for polar amplification of warming, it is predicted that under any future global warming scenario Northern Hemisphere sea ice will probably be reduced. However, the projected changes and their timing in the Southern Hemisphere sea ice extent are less certain. Current coupled model studies of increased atmospheric carbon dioxide are also essentially in conflict in their predicted Southern Hemisphere sea ice response. First simulations (GFDL) with a coupled model even suggested an expansion, but more likely a thickening, of the ice cover in particular regions. Other model studies at GISS, using different parameterizations of fluxes and sea ice processes, suggest the opposite effect, i.e., sea ice extent and thickness will be drastically reduced under increased atmospheric carbon dioxide scenarios.

Through ice-albedo feedback, the GISS simulations also suggest that the sea ice retreat itself, primarily in the Antarctic sea ice zone, accounts for a significant fraction (38%) of the consequence of global atmospheric warming that will occur under doubled atmospheric CO_2 concentrations, with larger temperature increases in the regions more local to the present day ice cover (Rind et al 1995). These projected changes are currently impossible to ascertain because without a knowledge of the present-day Antarctic sea ice thickness distribution, it is difficult to provide compelling evidence of if and when change occurs. Since the models currently give contradictory results, it suggests that the model parameterizations of sea ice physical processes are inadequate and different, and some, perhaps all, of the models are unrepresentative in some way in their depiction of the sea ice cover. Without a knowledge of the present-day ice thickness distribution, it is not possible to ascertain whether the physics of the models is correct or even verify the model results.

Several factors have limited the implementation of a coordinated Antarctic sea ice zone programme before the present, but changed circumstances now make it timely to initiate such a programme within SCAR. No other organizations have the experience or expertise for Antarctic research that is contained in the national Antarctic programmes of the SCAR countries. Many of the SCAR countries, tied also through the closely associated Council of Managers of National Antarctic Programmes (COMNAP), are already carrying out, and plan to continue, sea ice zone research in both physical and biological sciences within National programmes. Substantial new information is now available on the sea ice cover in most sectors of the Southern Ocean. A number of sophisticated, ice-capable research vessels are now working in the Antarctic. At the same time the increased number of nations working in the Antarctic has seen a growth in all types of shipping activity. New remote sensing capabilities, particularly microwave systems, and new ways of using older data, are enhancing sea ice observation from space.

Important problems that are still not being adequately covered by existing Antarctic research programmes include:

1. Broad climatology of sea ice physical characteristics. Satellite-derived data provide large scale estimates of ice extent and concentration, but not of the thickness of ice and snow, which are the primary variables affecting many physical and biological processes, as well as climate processes;
2. Processes such as ice formation, water mass modification, polyny expansion and contraction, ice edges and coastal fronts, gas exchange, and air-sea interaction; and
3. Modelling sea-ice processes and linking scales (local to regional to global) in coupled atmosphere-ice-upper ocean models.

Current models do not include all of the relevant sea ice processes and many important parameters are not available. The role of sea ice (including albedo feedback, ice thickness, flux correction and ice dynamics) is presently poorly-addressed and yet there is broad agreement that sea ice should be incorporated into both climate and ecological models. There is, therefore, a special role for the SCAR Global Change Programme in promoting studies of the pack ice zone between the coast of the Antarctic contienent and the ice edge that is not being adequately covered by other programmes, and for providing information on the sea ice system for the development of coupled models.

1.4 Overall Objectives of ASPeCt

ASPeCt is a multi-disciplinary programme of research within the Antarctic sea ice zone. Its overall aim is to understand and model the role of Antarctic sea ice in the coupled atmosphere-ice-ocean system. This requires an understanding of key processes, and the determination of physical, chemical, and biological properties of the sea ice zone. These are addressed by the following objectives:

1. To determine the spatial and temporal variability of the basic physical properties of sea ice that are important to air-sea interaction within the Antarctic sea-ice zone (ice and snow cover thickness distributions; structural, chemical and thermal properties of the snow and ice; upper ocean hydrography; surface meteorology, floe size and lead distribution). These data are required to derive forcing and validation fields for climate models; and

2. To understand and quantify the key processes at the coastal, interior and outer edges of the pack ice zone for inclusion or parameterization in coupled models.

2.0. KEY SCIENTIFIC QUESTIONS FOR ASPeCt

There are four key scientific questions that need to be answered to meet the ASPeCt objectives. They are:

1. What are the broad-scale, time-varying distributions of the ice and snow-cover thickness, ice composition and other physical characteristics in the Antarctic sea ice zone?

There are currently no systematic, spatially distributed data sets available that describe the seasonal and regional variability of the ice and snow thickness distribution for the Antarctic sea ice zone. Such data, together with those on ice extent and concentration (derivable from remote sensing and field observations) would provide a sensitive and essential baseline test of the performance of numerical atmosphere-ocean models. Similarly, climatic compilations of the main features of ice drift and, for more sophisticated models, the proportions of the ice formed by different processes (basal freezing, frazil formation, snow flooding) provide good validation of these higher resolution models. Remote sensing validation and algorithm development based on comparisons with surface-based data are also necessary to use existing and future satellite-derived data for quantitative monitoring of the ice cover and for sea ice model verification and input fields.

2. What are the dominant processes of ice formation, modification, decay and transport which influence and determine ice-thickness, composition and distribution?

Air-ice-ocean interaction effects in the Antarctic are manifested as changes in ice thickness, structure and composition. Flooding of the snow cover followed by refreezing can thicken the ice and lead to a higher than usual surface salinity, while melting at the base (thinning) due to a high oceanic heat flux can lower the salinity of the ice compared to that seen when bottom freezing (thickening) occurs.

A key early finding about the composition of Antarctic sea ice, and its fundamental difference compared to Arctic sea ice, is the high percentage of frazil ice (typically about 50% of the ice compared to 10% in the Arctic) that is observed in much of the seasonal ice cover around Antarctica (Figure 2 [Lange et al., 1989]). The dominant growth regime relating to frazil ice is the interaction of the open ocean wave field with the growing ice cover. This turbulent growth regime causes frazil ice crystals and grease ice to be transformed dynamically into pancake ice. Ice growth can take place quickly up to some tens of centimetres of ice thickness, but at these thicknesses the ice strongly attenuates the incident wave field, essentially turning off the driving force for ice growth by the pancake ice mechanism. Further modification of these initial ice covers can then proceed thermodynamically either by slow growth beneath the ice cover if the heat flux to the atmosphere is high enough, or by bottom melting in areas of relatively high oceanic heat flux.

In areas to the south of the pack ice edge, other ice modification processes observed in Antarctica include ice growth in leads created by ice divergence of as much as 10% per day under extreme conditions. Consequently, open water is frequently created within the pack ice and much of the total ice mass forms by rapid freezing in these areas. As well as thermodynamic growth, leading primarily to congelation or columnar ice structure, deformation by rafting and ridge-building processes are also important in the development and thickness distribution of sea ice. Episodic periods of divergence and ice formation in leads, followed by convergence and thickening by deformation, are related to the passage of synoptic weather systems. In addition, higher frequency ice deformation observed on daily and sub-daily scales is attributed to tidal and inertial coupling in the relatively thin Antarctic pack ice, a process that is not currently treated in numerical models (Figure 3 [Geiger, et al., 1998]).

The physical structure and the physical-chemical composition of ice cores also reveal metamorphic changes relating to thermal forcing: the creation of snow ice from surface flooding by sea water; and also formation of superimposed ice from snow melt and refreezing. In areas near ice shelves, significant amounts of bottom accretion of what is commonly referred to as platelet ice, can also occur as super-cooled water is advected to the surface. Wind and ocean current driving can also contribute to changes in the ice cover by transporting ice from source to sink regions. The consequences of such an ice dynamical effect can be contradictory: in the western Weddell Sea for example, the thickest ice is found in the north, a result of ice deformation and advection effects, rather than in the south where the lowest air temperatures are found.

3. What is the role of coastal polynyas in determining total ice production, heat, salt and biogeochemical fluxes, and water mass modification?

Coastal polynyas (area of open water and/or thin ice bounded on one side by land, ice sheet or ice shelf) are found in both polar regions but are a particularly ubiquitous feature of the coastline of Antarctica. The generally larger, deep-water polynyas, such as the Weddell Polynya, are thought to remain ice-free because of the upwelling of sensible heat from below the pycnocline. In contrast, the coastal polynyas on the continental shelf are believed to have a significant latent heat component, i.e., heat loss from the ocean surface is balanced by the latent heat of new ice formation and the polynya is maintained in part by the removal of the ice by wind or tidal currents, as well as by the addition of sensible heat by upwelling in some cases (Figure 4 [Gordon and Comiso, 1988]).

The polynyas are regions of intense heat loss from the ocean to the atmosphere, and of rapid and copious ice growth: they may be significant as ‘ice factories’ and contribute a significant proportion of the total ice formation in the sea ice zone. Brine rejected during ice growth is concentrated in the polynyas and can cause localised water mass modification as well as significantly increasing the salinity of Antarctic continental shelf water. In the southwest Weddell Sea, High Salinity Shelf Water (HSSW) formed by this process is the parent water mass for the production of Ice Shelf Water (ISW) under the Filchner-Ronne Ice Shelf. ISW leaving the continental shelf leads subsequently to the formation of Weddell Sea Bottom Water (WSBW). Adélie Bottom Water, which occurs on the shelf and shelf slope in the region from 130°E to 150°E, has a recent origin (<5 years) and appears to be intricately linked to processes in the coastal polynyas of the region. There are apparent regional differences in the activity of coastal polynyas with resultant variability in the modification of water masses.

Ice production in polynyas bordering ice shelves may be enhanced both by an off-shelf wind-field or by an oscillating tidal current. The outgoing tide opens a lead (polynya) where ice production may be very intense, whereas the incoming tide concentrates the newly-formed ice along the ice front. The accumulated production in such latent heat polynyas has been estimated to be of the order of tens of metres of sea-ice per year. The ice free polynyas play an important role in Antarctic marine biological systems and in the control of biogeochemical fluxes. Polynyas have potential importance in biogeochemical cycling in terms of air-sea gas fluxes and vertical convection as a carbon transport mechanism. Our knowledge of the local wind-fields in the ice-shelf polynya areas is poor, and the variation in the tidal currents along the edge of the floating ice-shelves is virtually unknown. Measurements of wind and tidal currents should therefore accompany any measurement programme of ice formation in polynyas.

4. What is the seasonal variability of the ice-edge and the processes that control ice-water interactions at the ice-edge?

Ice edges, or the zones where the ice cover interacts with the open ocean (Figure 5), have high seasonal and regional variability around Antarctica. Ice edges essentially can be divided into three phases: a growth phase of ice advance; a decay phase where the ice edge retreats; and an intermediate or ‘equilibrium phase‘ with small oscillations of advance and retreat.

The ice edge growth phase during the fall-winter period usually proceeds, when open ocean waves are present, by the growth of frazil ice which is transformed primarily into pancake ice fields. If shorelines are present or unusually calm conditions exist without ocean waves, the ice edge may advance instead as thin, flat sheets of nilas. In some regions, the onset of winter conditions allows ice that is advected in from other regions to remain frozen rather than melt, so the ice edge can advance by the advection of floes that have been maintained through the summer period. The seasonal cycle of increasing air temperature or warm water advection leads to ice edge retreat. Wave action at the ice edge leads to the break up of the larger floes. Combined with solar heating of the water at the increased perimeter area of the broken floes, melting is accelerated and the combined mechanical and thermal deterioration of the ice edge proceeds. In some regions, such as the northern Weddell Sea, this decay phase can be considerably delayed or halted if the ice transport from the south is great enough to keep the ocean water chilled and also shielded from solar heating until the summer is over. The equilibrium phase occurs when the ice edge occurs at a northern boundary where warm water exists, usually at an ocean frontal structure, so that the ice transported there melts as it crosses the front. Variations in the ice advection rate or alternating periods of cold air and warm air advection can then cause the ice edge to oscillate by slightly advancing or retreating once the mean equilibrium position has been reached.

The regional variability in the ice edge can be characterised by the period of time that the ice edge exists in these various phases. For example, the Weddell Sea undergoes a short advance period, a prolonged equilibrium phase, and a rapid decay phase due to the high ice transport. In other regions, the ice edge regime is primarily thermodynamically or air temperature controlled, so that the equilibrium phase is very short at the maximum ice edge extent, and the ice advance and retreat are both relatively lengthy and nearly equal in time. The result of these differences in regime can affect the amount, position and timing of fresh water flux at the ice edge, thus strongly affecting the biological regime, leading to seasonal and regional variations in ice edge blooms around Antarctica.

3. IMPLEMENTATION STRATEGY

3.1 Climatology

3.1.1. Reconstruction of 1980-1997 Sea Ice Climatology

The objective of this project is to assimilate sea ice thickness data from various national programmes into a common data set and to produce a statistical characterization or climatology of sea ice thickness for the Antarctic pack ice. The characterization will be derived from data collected in all seasons and regions of the Antarctic pack ice zone between 1980 and 1997. The final product will be solely dependent on the availability of high quality data, but will aim to produce a circumpolar distribution of sea ice and snow thickness in 30° longitude bands. There will necessarily be regional and seasonal gaps in the ice thickness climatology due to insufficient data.

The data format will be that adopted by the ASPeCt SSG and described in Appendix C. This is the observation protocol developed at the Antarctic CRC in Hobart. Many of the data sets that will be used to develop the sea ice thickness climatology are not currently in the required format. It will therefore be necessary to translate these data into the agreed format described above. This will be done within each national program and then forwarded to a central data centre (most likely the Antarctic CRC in Hobart) where all the data will be assimilated.

Table 1 includes all the voyages on which ice thickness data have been collected between 1980 and 1997. Table 2 summarises these by region and season. All data collected aboard Australian vessels (East Antarctica) and some from U.S. cruises in the Weddell, Ross, Amundsen and Bellingshausen Seas are in the required format. A program is currently underway to translate all of the Russian data to the required format; data from six Russian voyages have already been translated successfully.

Table 1.

Table 2.

3.1.2. Climatology Studies in the Implementation Period (1998-2008)

3.1.2.1 Snow and ice thickness distributions

The objective of this program is to collect sufficient data along transects through the Antarctic pack ice to produce a seasonally varying, circumpolar climatology (statistical description) of sea ice and snow cover thickness. The transects will nominally be along lines of longitude between the ice edge and the coast at approximately 15° spacing. However, all observations within the sea ice zone will be considered for inclusion in the data set.

Ship-based observations of sea ice and snow cover thickness, and other pack ice characteristics, will be conducted in the accepted ‘ASPeCt format‘ by various national programs, and forwarded to a central data archive (probably at the Antarctic CRC in Hobart). The goal will be to achieve circumpolar coverage at approximately 15° longitude spacing at least once per season during the period 1998-2007. A total of ninety six transects would therefore be computed, although this number can be reduced by about twenty through the use of satellite data to depict large-scale open water regions that exist during summer and somewhat during autumn. Investigators should use this guide to plan their own sea ice research voyages and to influence the routes travelled by vessels conducting logistic operations.

'ASPeCt format' is the ice observation protocol adopted by the ASPeCt SSG and given in Appendix C. It is the system developed at the Antarctic CRC in Hobart (Allison and Worby, 1994; Worby and Allison, in press) and involves making observations, approximately hourly, from a vessel moving through the pack ice. A PC-based software package and user manual are currently being developed for use by the sea ice community, and a CD-ROM is available for guiding sea ice observers in the observation protocols and use of the software.

The transect lines will be within defined regions within which all sea ice observations will be considered for inclusion in the climatology. The regions will each be 15° of longitude wide and will be labelled according to the longitude of their western boundary, i.e., E015 defines the region 15-30°E; W165 defines the region 165-150°W, etc. The region 0-15°E will be labelled E000 and the region 180-165°W will labelled W180. At least one north-south transect should be completed between the ice edge and the coast in each region, once per season, between 1998 and 2007. Other data, e.g., from a vessel crossing a region in the east-west direction will be considered for inclusion, providing the data meet ASPeCt standards. Voyages within each region will be identified by longitude and other parameters, e.g., E075_XXMMNNYR.log, where XX is the ship code, MM is the first month of observations, NN is the last month of observations, and YR is the year.

Key transects will be repeated more than once per season. These will be along commonly travelled routes to Antarctic bases or in regions identified as being of particular scientific interest. Regions of scientific interest, such as where ice regimes are known to change, will be identified (e.g., eastern Weddell Sea) through input from committee members, modelers and the community at large.

3.1.2.2. Snow and Ice Properties Surveys

While the importance of establishing a climatological data base of ice thickness and snow depth for different sectors of the Southern Ocean is undisputed, there is also a need for surveys of snow and ice properties. Obtaining a sufficient climatological data base of these parameters requires a greater logistic effort than and different strategies from those employed for primarily ship-based thickness surveys. Property surveys aim to:

1. Link ice-thickness climatologies to growth processes, such as the impact of snow on the mass and energy balance of sea ice;
2. Provide ground-truth data for remote-sensing studies; and
3. Establish a data base required to improve large-scale sea-ice models and process simulations.

These three goals represent an integral part of the ASPeCt initiative and will enhance understanding and prediction of the atmosphere-ice-ocean system, not least by providing validation data for remote-sensing and modelling efforts.

Ideally, such property surveys should encompass a number of different parameters, e.g., ice salinity, structure, temperature, and isotopes, discussed in depth in Appendix D. Given the logistic effort involved in carrying out these measurements, the sampling strategy and the choice of sampling locations becomes quite critical. To provide sufficient areal coverage and permit discrimination of potential regional trends, the surveys ideally encompass the entire sea-ice zone from the ice margin to the continent, with transects spaced roughly 30° longitude apart. Sampling site spacing along transects may vary from <1° to at most 5° of latitude. Sampling will concentrate on the prevailing ice types, including ship-board sampling of thin new ice, representative of a given region, as determined from ice observations along the cruise track.

Properties deviate strongly for snow and ice of different age, thickness or season. Thus, it is highly desirable to collect comparable data sets for first- and multiyear ice in late winter/early spring, at the time of maximum ice thickness, as well as during the summer. These data will be complemented by data for new ice of different age and thickness in winter. As shipboard sampling can only provide synoptic pictures of the ice situation, longer-term studies will be carried out on drift stations (e.g., Lytle and Ackley, 1996) or at fast-ice locations (e.g., Crocker, 1988) as described for ASPeCt process studies in the future (see Sections 3.2.3 and 3.4). Ice-growth/salt-flux models will then aid in separating seasonal, interannual and regional variability (Eicken, 1998).

Snow depth and properties are even more susceptible to changes with time. While parts of the depositional history can be extracted from the snow column, improved atmospheric circulation models may help in unravelling snow-property evolution. Both deposition and later metamorphic processes control vertical profiles and layering of the snow pack, which in turn affect heat and light transfer through the snow pack and its remote-sensing signature.

To minimize variability associated with morphological deformation features, specific sampling sites will in most cases be located within stretches of level or unridged ice, which are likely to account for more than 80% of the total ice surface in most areas (Wadhams et al., 1987; Lange and Eicken, 1991a; Worby et al., 1996; Worby et al., 1998). Nevertheless, at key sites, an additional effort will be made to sample ridged or rough ice and to specify the smaller-scale spatial variability of key ice and snow properties. The latter is an important, yet often neglected issue in Antarctic sea-ice research (Eicken et al., 1991; Veazy et al., 1994; Massom et al., 1997) and in particular affects interpretation of remote-sensing data (Tucker et al., 1992) and snow effective thermal conductivity (Sturm et al., 1998).

The data collected under this scheme will be integrated into snow- and ice-property data bases. Apart from providing a climatological time series, this effort will also aid in interpretation and validation of remote-sensing techniques, such as the derivation of snow-depth from passive microwave data (e.g., Markus and Cavalieri, 1998). A major aim will be to provide input and validation data required to improve modelling of sea ice and the overlying snow cover. Similar to the ice-thickness data base, an attempt will be made to compile “historical” data, which have been collected at various centers during campaigns prior to the ASPeCt implementation phase.

3.2 Process Studies

3.2.1 Short Time Series Experiments

To better understand the processes occurring in the sea ice zone, and to improve numerical model parameterizations, short–term studies of ice properties and dynamics as well as air-ice and ice-ocean interaction are needed. Flux of momentum characterizes the dynamic interaction between the air and ice, or air and sea. Consequently, the turbulent fluxes of sensible and latent heat and the radiation fluxes define the thermal interaction and water vapor exchange. In addition to the momentum flux from air to ice, the momentum interaction between the ice and ocean defines the ice dynamics.

Local turbulent air-ice and air-sea fluxes depend on aerodynamic and scalar roughness of the surface, and on meteorological conditions. The latter include wind speed, and air and surface temperature in particular. For gases, the air-surface gas concentration difference (the partial gas pressure difference) provides the driving force to the fluxes. The Antarctic sea-ice fields tend to be broken with cracks and leads and ridges. These features yield heterogeneities in form drag and skin roughness, which produce internal ABL boundaries that affect the fluxes. In addition, due to inhomogeneities in the ice surface structure, flux variations are produced because of the sub-grid mixture of ice, cracks and leads. Typically, although an areal percentage of leads can be very small, of the order of <5 %, the high fluxes from leads may still dominate the regional fluxes.

Over the ice and snow, the determination of radiation fluxes may be affected by additional problems. Incoming short wave radiation may lead to multiple reflections between the low-level clouds and the surface. The surface-based bulk parameterization of the outgoing long-wave radiation for freezing surfaces and water also still needs improvement. For process studies and coupled short and medium range air-ice modeling, the air-ice and air-sea fluxes are to be defined as bulk fluxes. For climate and oceanographic studies, the heat flux from the ocean to the atmosphere may be calculated from budget studies or as a rough bulk estimation, e.g., observations of vertical temperature measurements in the ice may serve as a tool in this estimate.

The ice drift is physically controlled by the momentum balance between the flux of momentum from air to ice and the flux from ice to sea or, from sea to ice. In practice, the ice drift is dependent on wind speed and direction, ice floe and ice field properties, and on ocean currents. To be able to determine the spatial and temporal fluxes accurately and to parameterize the regional fluxes for large-scale modeling, field experiments, and local and mesoscale modelling are necessary.

Process studies are needed in all seasons and transitions between the seasons. They can be divided into the following three main categories that can be investigated using regional ship surveys and short-term drift experiments (nominally over a few to ten days) where the ship is moored to a floe for the experiments: ice dynamics; ice thermodynamics; and, snow and ice properties.

For ice dynamics it is necessary to determine, using drift buoys and other surface information, the response of the ice cover to atmospheric and oceanic driving (wind, barometric pressure, air temperature, ocean currents, water temperature and salinity) and to determine accurately the dynamical contribution, through ice deformation and advection, to the sea ice mass balance. It is necessary also to determine the high frequency response, if any, of the ice cover deformation field to inertial and/or tidal forcing at sub-daily scales. The role of synoptic scale weather and mesoscale features such as katabatic winds in the deformation and advection of the ice needs to be investigated. Remote sensing data obtained over experimental regions for ice drift and deformation during ground-based experimental periods can be validated.

For ice thermodynamics, it is necessary to determine the thermodynamic response of the ice cover to forcing by the sensible and latent heat flux in the atmosphere, precipitation, and oceanic heat flux. These processes can be determined by time series measurements of temperature profiles through the snow and ice cover, concurrent measurements of snow accumulation (precipitation and drifting), ice melt/freeze (thickness changes), and properties measurements. Such measurements have been made successfully during short-term drift experiments aboard ships and on ice floes (e.g., Launiainen and Vihma, 1994; Lytle and Ackley, 1996).

The study of snow and ice properties includes determination of the relative frequency of the flooding and refreezing events that contribute to snow ice formation. These can be determined by repeat profiles of snow and ice thicknesses. Ice core analysis of salinity and density can be used to determine thermal conductivities, latent heat, and heat capacity to compute the thermal balance essential for ice thermodynamics. Snow measurements and ice core parameters are described in Appendix D and are the same as for the sections of snow and ice properties described above (see Section 3.1. 2.2).

3.2.2. Coastal Polynyas

Several factors combine to provide the energy source to form coastal polynyas over wide areas around Antarctica. One is the persistent offshore wind from the Antarctic continent, driven either by the topography and cold conditions that produce a katabatic air flow of great intensity, often greater than 30 m s^{-1} or 60 kt, or sometimes by winds from synoptic systems as storms migrate in from the north. Another is the high velocity Antarctic Coastal Current that rings the continent, carrying ocean water and sea ice along and away from the coastline. The coastline irregularities, produced by, for example, floating glacier tongues or ice shelves, can also protrude into this flow of sea ice around the continent and a polynya will form in the lee of this topography while ice will pile up in front of it.

Polynyas and their effects, particularly in winter, are poorly understood, but it now appears that they are a result both of the interaction of ocean and atmosphere that takes place in the Antarctic, and a modulator of that interaction. The exchanges of energy, water and gases between the ocean and the atmosphere in the polynyas around Antarctica play a major role in determining the large scale motion, temperature and chemical composition of the ocean and atmosphere throughout the globe. Only limited field investigations, and none in winter, have been made in coastal polynyas around Antarctica. Understanding polynya processes is an inherently interdisciplinary undertaking, requiring a full complement of measurements of the turbulent processes in the interacting atmosphere, ocean and sea ice system that determine the fluxes for a given condition.

Areal surveys with water column, sea ice and atmospheric sampling are necessary to compute the three dimensional balances in the atmosphere, ocean and ice that give the input fields and boundary conditions to the formation, maintenance and resulting heat, mass and gas fluxes (water vapor and CO_2) associated with 1-dimensional and 2-dimensional processes in the polynyas. Biological processes are also linked with polynyas, as continuous removal of ice and upwelling may make them key regions for primary production, relative to the nearby, thicker–ice-covered regions, due to enhanced irradiance and nutrient fluxes into the surface layer. The CO_2 flux may, therefore, be coupled both physically and biologically with polynya processes.

Measurements of the ice production rate in polynyas are needed to determine its dependence on atmospheric and oceanic conditions. The contribution of polynyas to the mass balance of the drifting pack ice, and the flux of salt, heat and fresh water, as exported ice, need to be determined. To achieve this will require continuous mapping of polynya width, ice thickness distribution, ice velocity (advection rate), and ice production rate as manifested, for example, in the collection depth of frazil, frazil conversion into pancake ice, or the thickness and extent of deformed nilas.

Since the generation of surface gravity waves will be enhanced by high winds but suppressed by rapid ice production, wave-ice interaction is also a dynamic process of some importance. There are also suggestions that critical transitions exist in the ice growth rate that are related to the generation of pancake ice in a wave field, the thermodynamic fluxes that create the frazil ice, and the dynamics of the floes in response to wind, waves and ocean currents. Therefore, the prediction of these transitions and their dependence on atmosphere and upper ocean boundary conditions are important undertakings to specify the ice mass balance and resulting heat and salt fluxes.

Measurements should be made from the surface into the pycnocline to quantify the fluxes of heat, salt and momentum into and out of the upper ocean. One focus should be on processes that cause pycnocline heat to be entrained into the mixed layer. Combined measurements of the wind- and wave-induced Langmuir circulation and ice-induced wave suppression, which may modulate the mixing by the Langmuir circulation, with concurrent frazil and pancake ice formation rates, will be a unique geophysical measurement series and of considerable importance in understanding polynya dynamics.

The investigation of the atmosphere above a polynya should focus primarily on a surface flux, Atmospheric Boundary Layer (ABL), program. Turbulence measurements would be especially useful and help to define the sensible and latent heat, and mass exchange with the atmosphere. Radiosonde, acoustic or microwave profiling should be used to define the upper part of the ABL. Surface radiation measurements, both longwave and shortwave, over ice and water surfaces would complete the suite of surface energy balance measurements.

The investigation of the physical oceanography of a polynya should focus on larger-scale circulation, transports (on and off the shelf, and beneath and into the surface layer) and how the shelf waters and inflows interact. Adjacent ice shelves or glacier tongues may also respond to ocean interaction, either through thinning by melting (a freshwater flux) or by accumulating platelet ice, thickening and producing a brine flux into the ocean. CO_2 measurements would help define the source/sink problem in polynyas as it is likely to be quite different in a winter polynya than in the more frequently sampled, bloom-laden summer surface waters.

Appendix E identifies polynyas that would be appropriate sites for ASPeCt Winter Polynya Experiments. They have been chosen to represent different formation and maintenance processes, and regional variability around Antarctica. We expect that during the later stages of the ASPeCt programme we can extend measurements to other polynyas, possibly through remote sensing and other survey methods, as they are developed through the process experiments. Numerical modelling, developed concurrently, can then be validated and used to represent polynya processes sufficiently in future coupled models.

3.2.3 Long Time Series Experiments

Ice Station Weddell (ISW), a joint United States and Russian endeavour and the first Antarctic sea ice drifting station, was occupied in the western Weddell Sea during February-June 1992 (Gordon et al., 1993). The long time series available from Ice Station Weddell provided new information on the processes of air-ice-ocean-biology interaction in the western Weddell Sea.

The ice cover dynamics showed the important and previously undetermined role of daily and sub-daily forcing scales, from tides and inertial oscillations, in the deformation of the ice; they contributed roughly 0.5 m to the ice thickness and a significant proportion of the mass budget for the region (Geiger et al., 1998). The freezing of slush layers at the snow/ice interface in the autumn contributed significant new ice production and brine flux to the ocean (Lytle and Ackley, 1996). Convection within the sea ice, induced by the freezing of surface and near-surface slush layers, caused nutrient replenishment and triggered a previously undiscovered fall algal bloom in the ice (Fritsen et al., 1994). Convection also acted as a more efficient conduit than the conduction process for ocean heat to reach the surface (Lytle and Ackley, 1996). This is not currently simulated in numerical sea ice models.

Since Ice Station Weddell, extremes in the seasonal cycle of pack ice in the Western Weddell Sea have been observed. These include an unprecedented opening of the region in front of the Filchner-Ronne Ice Shelf in summer 1998, when 600 km of open water existed between the ice shelf and the drifting pack ice to the north. As a consequence of that event, the pack ice in the western Weddell Sea was half its normal summer area. Together with recent disappearances of summer pack ice in the Amundsen-Bellingshausen Sea (Jacobs and Comiso 1993, 1997), the variability of summer pack ice extent in Antarctica remains to be explained either in terms of the natural cycle or anthropogenic warming.

Long time series investigations of the current and future air-ice-ocean-biology interactions and how they compare with the processes first discovered to be at work in the late summer through autumn period on Ice Station Weddell are essential to determine the nature of the processes and changes described above. A drifting ice station is, therefore, a critical element of the implementation of the ASPeCt Science Plan, a prime motivation being to examine possible changes since Ice Station Weddell. A drifting ice station would provide the opportunity for research during the spring-summer through summer-autumn transitions that is vital for understanding the effects of summer on Antarctica sea ice processes and interactions. An examination of sea ice-related questions, specifically as they reflect air-ice, ocean-ice, and ice-biology interactions would provide the core of a research program. It would be valuable to compare the results of such a program with those of the SHEBA project in the Beaufort Sea, Arctic Ocean.

The magnitude of the undertaking suggests the necessity for enlisting international resources and scientific expertise, i.e., an international cooperative effort. Therefore, a series of workshops, beginning in June 2000, in Fairbanks, Alaska (in conjunction with the International Glaciological Society Symposium on Sea Ice and its Interactions with Ocean, Atmosphere and Biosphere), and culminating in a drifting ice station experiment in 2005-2006, are planned. The workshops will use recent theoretical and observational results and predictions of numerical models to define the key scientific questions and develop the Science and Implementation Plan for the ASPeCt drifting ice station.

3.2.4. Ice Edge Experiments

The sector of pack ice close to the Antarctic sea ice margin is distinguished by the intensity of the interactions that occur there. Predominant is the action of waves, which affect the way that sea ice forms through, for example, the pancake ice cycle (Wadhams et al., 1987), and contributes to its evolution in time by the destruction and pummelling of the floes. While such processes occur in the Arctic, they are particularly fierce in the Antarctic marginal ice zone because of a tendency to high seas and long swells. Storms rapidly obliterate a particular configuration of ice floes leading to a constantly changing floe size distribution. Secondary effects of waves are: the modification of ice concentration under both compact and divergent winds, leading to a concomitant change in average heat flux in the region; adjustment of the atmospheric boundary layer (ABL) brought about by spatial and temporal variations in surface roughness due to collision-induced ridging and rafting and the altered input of oceanic heat; stirring of the upper oceanic boundary layer by wave-induced turbulence; and modification of local sea ice physical properties.

The marked changes in surface topography that arise near the ice edge present a roughness change to the ABL, as the drag coefficient there is usually much greater than in the open sea. Increased roughness leads to greater turbulence, which in turn thickens the ABL, while reducing the wind speed. Further downstream, as the ABL encounters either ice or open water, it will thin and the wind speed will decrease. In winter, particularly, when off-ice winds move from cold air and ice to comparatively warm water, the ABL is further modified by heat input from the open sea. The change in surface roughness from the open sea to the very rough outer marginal ice zone also produces regions of divergence (high-to-low drag) and convergence (low-to-high drag). Divergence will lead to an upward flux of water, i.e., upwelling. Moreover, strong currents are often observed to flow along the ice margin, their presence being due to the internal density structure induced in the upper ocean by melt water.

Several of the mechanisms described above occur over sufficiently large scales to be felt by a significant portion of the Antarctic sea ice zone, but are noticeable by their absence in large scale models. Accordingly, an effective parameterization of such processes is a necessary development of ice-ocean coupled models.

The objectives listed here have two goals: (1) to collect data to allow the ice edge zone to be correctly parameterized in modelling studies, i.e., to provide the required data for the next generation of ice-ocean coupled models; and (2) to use those data to improve and refine remote sensing algorithms that aspire to describe the ice morphology in the region.

Because of the strength of the processes occurring near the Antarctic ice margin and the relationship of interactions to sea ice morphology and physical properties, there is a pressing need for a series of experiments to take place near the ice edge. Work should focus on upper ocean processes, including ocean waves, meteorology, and the physical structure of the sea ice in the zone nearest the edge. While some experiments have been done serendipitously at the ice margin itself, they are limited in seasonal and geographic extent, as such data are invariably obtained from ships on route to other Antarctic areas.

Measurements of wave activity on either side of the ice edge should be made, under different wind regimes, at a growing ice edge and at one that is being systematically abraded and destroyed. In these experiments, sea state at different locations should be recorded routinely, along with position acquired by differential GPS, which will also give the accelerations and bearing for single ice floes brought into motion by the incoming sea and local winds. The relative motions between floes lead to zones of compression and divergence in the ice, and to pumping, rafting and ridging events that cause changes in surface roughness. While the focus is the vicinity of the ice edge, measurements will need to be done as far south into the ice pack to the point at which the influence of waves ceases to be perceptible.

Simultaneous with the wave experiments, measurements to quantify the fluxes of heat, salt and momentum into and out of the upper ocean should be made, together with an ABL programme that centres primarily on surface fluxes. The latter would involve turbulence and radiation measurements, the deployment of radiosondes, and the use of profiling equipment.

The quantification of the physical nature of the sea ice in the vicinity of the ice edge is problematical, especially where fields of frazil and pancake ice exist in large amounts. However, in relation to the overall objectives of ASPeCt, it is imperative that this is done, despite its difficulty, as models and remote sensing algorithms will fall well short of reality if correct parameterization is not achieved. Methods of sampling the sea ice near the edge under conditions of growth and decay may need to be developed, but the experience of scientists who measure sea ice physical properties is such that this is not insurmountable.

Of the greatest importance to ice edge observation programmes is that the strong linkages that exist in the science, namely the interdependence between waves, surface oceanography, the ABL and the ice physics, are embodied in the design of the experimental campaigns. A sequence of unrelated investigations will not work because the process that is creating the ice edge zone is predominantly ocean waves interacting with ice, the ABL and the surface oceanography. This must be recognized from the outset.

3.3 Long Term Observations: Landfast Ice

Although landfast ice occupies only a small proportion (1%) of the total area of sea ice which forms around Antarctica, it acts as an important interface between the Antarctic ice sheet and the pack ice, and may record floating ice-ocean interaction processes. It is important for the local ecology, as it may provide a habitat for seals or penguins and frequently supports an abundant algal community. The landfast ice extends out from the continent and remains fixed, i.e., landfast, to the coast for much of the winter. It exists primarily in sheltered bays and inlets or behind coastal protuberances such as iceberg tongues.

Landfast ice thickens by a variety of accretion processes. It may be of uniform thickness and result from simple thermodynamic growth at the ice-ocean interface and/or from the accumulation of different types of frazil/platelet ice generated in the water column in the vicinity of ice shelves and ice tongues. It may also be highly deformed due to ice accumulation near coastal protuberances such as iceberg tongues or ice shelves. The northern limit of the landfast ice is often defined by a row of grounded icebergs which helps to protect it from the more dynamic outer pack ice. Although stationary for much of the winter, landfast ice may periodically break out during intense storms. In spring and early autumn, some of the landfast ice melts in place, but much of it breaks out when it is no longer protected from the spring storms by the outer pack. Some of the ice in more sheltered bays and inlets may remain for many years, only breaking out during extreme storm events.

Oceanic heat fluxes have been derived from historical data of fast ice formed from thermodynamic processes (Heil et al., 1996). The variability of landfast sea ice facies can be interpreted in terms of the various processes occurring at the ice-ocean interface below or in front of floating ice bodies. For recent developments in this area see, for example, Tison et al. (1991), Jeffries and Weeks (1991), Jeffries et al. (1993), Kawamura et al. (1997), Gow et al. (1998) and Tison et al. 1998). In some cases, the processes of landfast ice accretion may be linked to bottom melting and the mass balance of ice shelves and ice tongues, and thus control their stability. The landfast ice may also provide indications of climate change. For example, the Japanese Antarctic Station, Syowa, located in Lützow-Holm Bay, is usually surrounded by landfast ice and until recently the ice has broken out only occasionally. However, satellite observations indicate that since July 1997 an extraordinarily large and potentially long term breakup has been underway.

Until recently, polar orbiting satellites have provided coarse resolution data and/or poor areal coverage of the landfast ice regions and no baseline map exists. In addition to the time series data, a snapshot of the landfast ice extent, using high resolution satellite imagery in conjunction with field observations will be developed. Synthetic aperture radar (SAR) data collected during the RADARSAT Antarctic Mapping Mission in October 1997 could provide the foundation for this exercise.

Where available, historical data on fast ice thickness, snow cover and extent will be compiled. It is expected that the data will be primarily from locations near Antarctic bases, where the fast ice thickness has been monitored for logistical purposes. For Antarctic programme operators interested in monitoring the fast ice thickness, a standardised measurement protocol will be provided. The data will be archived for easy access at a data centre, possibly the Antarctic CRC in Hobart. The landfast ice also lends itself to long-term process studies of physical-chemical properties as they relate, for example, to atmosphere-ice-ocean interactions and relationships with biological processes.

4. RELATED DATA SETS AND PROGRAMME COORDINATION

4.1 Satellite Data Records

Passive microwave radiometers provide year-round, all-weather daily maps of sea-ice concentration and extent for the entire Antarctic region. The current operational sensor is the Special Sensor Microwave/Imager (SSM/I, 1987-present) aboard Defense Meteorological Satellite Program (DMSP) spacecraft. Previous sensors were the Nimbus-5 Electrically Scanning Microwave Radiometer (ESMR, 1973-76), and the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR, 1978-87).

Monthly climatologies of Antarctic sea-ice concentration and extent, derived from ESMR and SMMR data, are presented in two NASA atlases (Zwally et al., 1983; Gloersen et al., 1992). The time series, dating back to 1973, will continue with the launch of the Advanced Microwave Scanning Radiometer/E (AMSR/E) on ADEOS-2 and the EOS PM-1 satellites in the year 2000. Gridded data (mapped to a polar stereographic projection) are available from the U.S. National Snow and Ice Data Center (NSIDC), University of Colorado, on the World Wide Web at:

http://www-nsidc.colorado.edu/NSIDC/CATALOG/ENTRIES/nsi-0051.html

Issues remain regarding the accuracy of ice concentration retrievals using current algorithms (the NASA Team and the Comiso 'Bootstrap') and ASPECT could make an important contribution to the validation of these key climate-research products. Data from both algorithms, and mapped brightness temperature data, are available from the NSIDC.

Visible and near-infrared radiometers, e.g., DMSP Operational Linescan Sensor (OLS) and NOAA Advanced Very High Resolution Radiometer (AVHRR), provide information on surface albedo, while thermal infrared radiometers on the same instruments provide important information on snow/ice surface physical temperature. Visible and near-infrared sensors cannot penetrate cloud and darkness, while thermal infrared radiometers cannot penetrate cloud. However, ice motion products have been derived from these data when cloud-free (Emery et al., 1991).

Ice motion products are now being derived also from passive microwave data (Agnew et al., 1997; Emery et al., 1997) and scatterometer data (Drinkwater, 1998). Through buoy deployments, ASPECT could make an important contribution to the validation of the satellite-derived ice motion products.

Initiated by NOAA and NASA, the recent Pathfinder effort has reprocessed SMMR-SSM/I, AVHRR and TOVS datasets onto a common projection, the NSIDC Equal-Area Scalable Earth Grid (EASE-Grid), using standard validation methods to develop consistently processed data sets that are easy to combine and compare. Also available from NSIDC are a high-resolution AVHRR Polar Subset and digitised ice charts. Data sources for the latter include AVHRR local-area coverage (LAC), global-area coverage (GAC) and high-resolution picture transmission (HRPT), DMSP OLS and SSM/I. The AVHRR Polar Pathfinder World Wide Web site at the University of Colorado can be found at:

http://polarbear.colorado.edu/toc.html

So far, only TOVS Pathfinder products for the Arctic region north of 60°N have been produced. A similar data set for the sea-level region south of 50°S, but not over the Antarctic continent, will become available in approximately 2001.

A complete list of NSIDC sea ice and related data sets can be found on the World Wide Web at:

http://www-nsidc.colorado.edu/NSIDC/CATALOG/data_list_by_subject.html

Finally, it is important to note the availability of synthetic aperture radar (SAR) data studies of Antarctic sea ice. The principal advantages of SAR are its ability to obtain data regardless of light and atmospheric conditions, and its high spatial resolution compared to the sensors mentioned above. Some applications of SAR in Antarctic sea ice studies are described in Drinkwater (1998), Morris et al. (1998) and Lytle et al. (1998)

SAR data have been available since August 1991, when ERS-1 was launched by the European Space Agency (ESA). Since then, ESA has launched ERS-2, NASDA (the Japanese National Space Development Agency) has operated JERS-1, and CSA (Canadian Space Agency) has operated RADARSAT. Typically, the raw SAR signal data are downlinked directly to ground stations in Antarctica and then transferred to facilities elsewhere for processing into image format. The main Antarctic SAR ground receiving stations are located at Syowa Station, McMurdo Station and Base Bernardo O'Higgins. Antarctic SAR data can be received also in Hobart, Tasmania.

Information on SAR data acquisition and processing can be obtained from the Alaska SAR Facility, ESA, NASDA and RADARSAT International on the World Wide Web at:

http://www.asf.alaska.edu
http://earthnet.esrin.esa.it
http://www.nasda.go.jp/index_e.html
http://www.rsi.ca

4.2 World Climate Research Programme (WCRP)

ASPeCt will complement and contribute to the other international programmes concerned with global change, and with an interest in the Antarctic sea ice zone. Currently active components of other programmes relevant to ASPeCt are WCRP activities and IanZone.

The WCRP emphasises the physical climate system, while the companion IGBP focusses on biological and chemical processes involved in global change. The Antarctic climate research issues of interest to the WCRP can be considered broadly to include the global climate roles of Antarctic sea ice, ocean circulation, ice sheets, and atmosphere, and, of course, the interactions among these components. The time scales of interest span a great range because of the very long intrinsic time scales of the ice sheets (centuries), while ocean-ice sheet interactions might be much more rapid. Other parts of the system likely have important seasonal to decadal variability, as well as trends.

WCRP is sponsored by WMO, ICSU, and the IOC of UNESCO. Its research activities include the Arctic Climate System Study (ACSYS), focussing on Artic Ocean ice-ocean-atmosphere interactions, and the Climate Variability and Predictability (CLIVAR) programme which is considering global climate variability on decadal-centennial (DEC-CEN) and seasonal-interannual time scales. In particular, CLIVAR is addressing the role of the Southern Ocean in the thermohaline circulation and coherent climatic patterns such as the Antarctic Circumpolar Wave, the Antarctic Oscillation and the Pacific-South America teleconnection. CLIVAR requires input from other communities on Antarctic sea ice and the mass balance of the Antarctic ice sheet and ice shelves.

A new WCRP Task Group has been established to address the organization of internationally coordinated research into Climate and the Cryosphere (CLIC: Barry and Cattle, 1998). A summary report on the First Session of the WCRP (JSC/ACSYS) CLIC Task Group (WCRP, 1999) has been prepared. The scientific strategy for CLIC is to consider:

Cryosphere-atmosphere interactions on a global scale;
Cryosphere-ocean interactions on a global scale;
Atmosphere-sea ice-ocean interactions;
Atmosphere-snow-land interactions;
Atmosphere-land ice-sea level interactions; and
Modelling, as well as cryospheric indicators of climate.

Strategies through which CLIC can coordinate with existing programmes of WCRP, SCAR, SCOR, IASC and ICSU bodies, without disrupting any existing activities, will be developed by the Second Session of the CLIC Task Group, which will meet in Grenoble, France, in August 1999. The final draft Science and Implementation Plan for CLIC will be submitted to the WCRP Joint Scientific Committee in March 2000, following review by the ACSYS SSG in autumn 1999.

The WCRP has established two programmes which use automatic observing systems to increase the amount of meteorological and sea ice-related data from the Antarctic region. These are the International Programme for Antarctic Buoys (IPAB) and the Antarctic Ice Thickness Measurement Programme (AnITMP). Both programmes are essentially routine observing exercises, providing data for initialisation and validation of climate models and for monitoring. The major contributions to IPAB and AnITMP come from the national programmes of SCAR members. Data from ASPeCt will contribute to and build on these programmes.

4.2.1 International Programme on Antarctic Buoys (IPAB)

The objective of IPAB is to establish and maintain a network of drifting buoys in the Antarctic sea ice zone in order to support research in the region related to global climate processes, to meet real-time operational meteorological data requirements, and to establish a base for ongoing monitoring. For a number of years, a relatively large number of buoys have been deployed in the East Antarctic pack ice (e.g., Allison, 1989a, 1989b; Worby et al, 1998), in the Weddell Sea (e.g., Ackley, 1979, 1981; Limbert et al., 1989; Kottmeier and Hartig, 1990; Massom, 1992; Launiainen and Vihma, 1994) and in the Ross Sea (Moritz, 1988; Jeffries, unpublished data). The number of buoys deployed is far fewer than have been deployed in the Arctic Ocean, but the data have, nevertheless, provided valuable information on the large–scale drift and forcing mechanisms, and small–scale motion and deformation.

4.2.2 Antartic Ice Thickness Measurement Programme (AnITMP)

This programme aims principally to obtain ice thickness data using upward looking sonar (ULS) instruments. These instruments, moored to the ocean bottom, record the keel depth of sea ice drifting over their location from sonar ranging measurements made every few minutes. A network of ULS instruments deployed in the Weddell Sea from 1990 to 1994 has provided valuable information on the regional variability of sea ice thickness and mass balance (Strass and Fahrbach, 1998).

4.3 IAnZone

AnZone (Antarctic Zone) has been an affiliation of scientists concerned with the physical marine sciences (primarily physical oceanography, with contributions from sea ice physics and boundary layer atmospheric sciences) in that region of the Southern Ocean poleward of the Antarctic Circumpolar Current (the Antarctic Zone). Three major experiments in the Southern Ocean have been completed under AnZone auspices: the Ice Station Weddell (ISW) drift in 1992; the Antarctic Zone Flux Experiment (ANZFLUX) conducted in the eastern Weddell Sea in 1994; and oceanographic work on deep ocean ventilation in the confluence of the Weddell and Scotia Seas near the Antarctic Peninsula (DOVETAIL, 1997-99).

Significant sea ice work relating to the design of ASPeCt has been conducted on the AnZone experiments. These efforts have provided some historical climatology of the ice thickness distribution for the Weddell Sea region, and contributed process experiments on the dynamics and thermodynamics of pack ice in the first and second-year ice of the eastern and western Weddell Sea (see Section 3.2.3.). They form a firm foundation for future ASPeCt studies in this and other regions. The climatology of the ice thickness distribution in the Weddell Sea can build on the existing base, and ASPeCt transects will be designed to fill gaps rather than provide the full seasonal and regional sets that are necessary for other regions.

The international group of IAnZone (International Antarctic Zone) has recently been affiliated as a standing committee of SCOR. The goal of IAnZone is to advance the knowledge of climate processes within the Antarctic Zone through the development and coordination of observational and modelling programmes. It will have a primary role in overviewing many of the physical aspects of Antarctic oceanography. It will also conduct process experiments primarily relating to water mass formation processes and the longer-term climatic variability of the ocean, contributing to the CLIVAR program at the decadal to century time scales.

IAnZone and ASPeCt have intersecting interests in terms of the role of sea ice in the oceanic and climate systems, and close coordination has been established. Joint IAnZone and ASPeCt interaction with CLIVAR has been initiated to ensure that a unified Antarctic contribution to the physical side of climate studies will be both adequately considered and presented in that forum. From the operational side, close coordination will also be undertaken to conduct, for example, joint cruises to those regions that satisfy the aims of both projects. Coordination of the science, e.g., the role of coastal polynyas in water mass modification as well as sea ice formation and air-sea interaction, on the optimal use of limited numbers and schedules of suitable icebreakers, as well as the presentation of the unified air-ice-ocean science to the climate community, will be satisfied by this cooperative approach. To ensure such co-ordination, ASPeCt scientists and IAnZone scientists have participated in each other’s meetings and in the formulation of their respective science programmes.

5. REFERENCES

Ackley, S. F. 1979. Mass balance aspects of Weddell pack ice. *J. Glaciol.*, 24, 391-406.

Ackley, S. F. 1981. Sea ice-atmosphere interactions in the Weddell Sea using drifting buoys. In *Sea Level, Ice and Climatic Change*, edited by I. Allison, *IAHS Publ.*, 131, 177-191.

Agnew, T. A., H. L and T. Hirose. 1997. Estimation of large-scale sea ice motion from SSM/I 85 GHz imagery. *Ann. Glaciol.*, 25, 305-311.

Allison, I. 1989a. The East Antarctic sea ice zone: Ice characteristics and drift. *GeoJournal*, 18, 103-115.

Allison, I. 1989b. Pack ice drift off East Antarctic and some implications. *Ann. Glaciol.*, 12, 1-8.

Allison, I., R. E. Brandt and S. G. Warren. 1993. East Antarctic sea ice: Albedo, thickness distribution and snow cover. *J. Geophys. Res.*, 98, 12417-12429.

Allison, I., and A. P. Worby. 1994. Seasonal changes of sea-ice characteristics off East Antarctica. *Ann. Glaciol.*, 20, 195–201.

Adolphs, U. and G. Wendler. 1995. A pilot study on the interaction between katakatic winds and polynyas at the Adélie Coast, eastern Antarctica. *Antarct. Sci.*, 7, 307-314.

Arrigo, K. R. and C. R. McClain. 1994. Spring phytoplankton production in the western Ross Sea. *Science*, 266, 261-63.

Barry, R. G. and Cattle, H. 1998 Cryosphere and Climate: The ACSYS Statement. WCRP Newsletter No. 3.

Bromwich, D. H. and D. D. Kurtz. 1984. Katabatic wind forcing of the Terra Nova Bay polynya. *J. Geophys. Res.*, 89, 3561-3572.

Bromwich, D., Z. Liu, A. N. Rogers and M. L. Van Woert. 1998. Winter atmospheric forcing of the Ross Sea Polynya. In *Ocean, Ice and Atmosphere: Interactions at the Antarctic Continental Margin*, *Antarct. Res. Ser.*, Vol. 75, edited by S. S. Jacobs and R. F. Weiss, pp. 101-133, AGU, Washington, D.C.

Colbeck S., E. Akitaya, R. Armstrong, H. Gubler, J. Lafeuille, K. Lied, D. McClung and E. Morris. 1990. *The International Classification for Seasonal Snow on the Ground*, ICSI/IAHS/IGS, World Data Center A, University of Colorado, Boulder, CO, U.S.A.

Comiso J. C., T. C. Grenfell, M. Lange, A. W. Lohanick, R. K. Moore and P. Wadhams. 1992. Microwave remote sensing of the Southern Ocean sea ice cover. In *Microwave Remote Sensing of Sea Ice*, edited by F. D. Carsey, Geophysical Monograph 68, pp. 243-259, AGU, Washington, D.C.

Cox G. F. N. and W. F. Weeks. 1983. Equations for determining the gas and brine volumes in sea-ice samples. *J. Glaciol.*, 29, 306-316.

Crocker G. B. 1988. Physical processes in Antarctic landfast sea ice. Ph.D. Dissertation, University of Cambridge, U.K., 211pp.

Drinkwater, M. R. 1998. Active microwave remote sensing observations of Weddell sea ice. In *Antarctic Sea Ice: Physical Processes, Interactions and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 187-212, AGU, Washington, D.C.

Eicken, H. 1998. Factors determining microstructure, salinity and stable-isotope composition of Antarctic sea ice: Deriving modes and rates of ice growth in the Weddell Sea. In *Antarctic Sea Ice: Physical Processes, Interactions and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 89-122, AGU, Washington, D.C.

Eicken H. and M. A. Lange. 1991. Image analysis of sea-ice thin sections: a step towards automated texture classification. *Ann. Glaciol.*, 15, 204-209.

Eicken H., M. A. Lange and G. S. Dieckmann. 1991. Spatial variability of sea-ice properties in the northwestern Weddell Sea. *J. Geophys. Res.*, 96, 10,603-10,615.

Eicken H., M. A. Lange, H.-W. Hubberten and P. Wadhams. 1994. Characteristics and distribution patterns of snow and meteoric in the Weddell Sea and their contribution to the mass balance of sea ice. *Ann. Geophys.*, 12, 80-93.

Eicken H., H. Fischer and P. Lemke. 1995. Effects of the snow cover on Antarctic sea ice and potential modulation of its response to climate change. *Ann. Glaciol.*, 21, 369-376.

Emery, W. J, C. Fowler, J. Hawkins and R. H. Preller. 1991. Fram Strait satellite image derived ice motions. *J. Geophys. Res.*, 96, 4751-4768.

Emery, W. J, C. Fowler and J. Maslanik. 1997. Satellite-derived maps of Arctic and Antarctic sea ice motion. *Geophys. Res. Lett.*, 24, 897-900.

Fritsen, C. H., V. I. Lytle, S. F. Ackley, and C. W. Sullivan. 1994. Autumn bloom of Antarctic pack-ice algae. *Science*, 266, 782–784.

Gallée, H. 1997. Air-sea interactions over Terra Nova Bay during winter: simulation with a coupled atmosphere-polynya model. *J. Geophys. Res.*, 102, 13,835-13849.

Garrity, K. 1992. Characterization of snow on floating ice and case studies of brightness temperature changes during the onset of melt. In *Microwave Remote Sensing of Sea Ice*, edited by F. D. Carsey, Geophysical Monograph 68, pp. 313-328, AGU, Washington, D.C.

Geiger, C. A., S. F. Ackley and W. D. Hibler III. Sea ice drift and deformation processes in the western Weddell Sea. In *Antarctic Sea Ice: Physical Processes, Interactions and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 141-160, AGU, Washington, D.C.

Gloersen, P., W. J. Campbell, D. J. Cavalieri, J. C. Comiso, C. L. Parkinson, and H. J. Zwally. 1992. Arctic and Antarctic Sea Ice 1978-87: Satellite Passive Microwave Bbservations and Analysis. *NASA Spec. Publ.*, *SP-511*, 290 pp., National Aeronautics and Space Administration, Washington, D.C.

Gordon, A. L. and J. C. Comiso. 1988. Polynyas in the Southern Ocean. *Scientific American*, 258, 90–97.

Gordon, A. L. and Ice Station Weddell Group of Principal Investigators and Chief Scientists. 1993. Weddell Sea exploration from ice station. *Eos Trans. AGU*, 74, 121, 124-126.

Gow A. J., S. F. Ackley, K. R. Buck and K. M. Golden. 1987. Physical and structural characteristics of Weddell Sea pack ice. *CRREL Rep.*, 87-14

Gow, A. J., S. F. Ackley, J. W. Govoni and W. F. Weeks. 1998. Physical and structural properties of land-fast sea ice in McMurdo Sound, Antarctica. In *Antarctic Sea Ice: Physical Processes, Interactions and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 355-374, AGU, Washington, D.C.

Heil, P., I. Allison and V. I. Lytle. 1996. Seasonal and interannual variations of the oceanic heat flux under a fast ice cover. *J. Geophys. Res.*, 101, 25,741-25,752.

Jacobs, S. S., R. G., Fairbanks and Y. Horibe. 1985. Origin and evolution of the water masses near the Antarctic continental margin: Evidence from $H_2{}^{18}O/H_2{}^{16}O$ ratios in seawater. In *Oceanology of the Antarctic Continental Shelf*, *Antarct. Res. Ser.*, vol. 43, edited by S. S. Jacobs, pp. 59-85, AGU, Washington, D.C.

Jacobs, S. S. and J. C. Comiso. 1989. Sea ice and oceanic processes on the Ross Sea continental shelf. *J. Geophys. Res.*, 94, 18,195-18,211.

Jacobs, S. S. and J. C. Comiso. 1993. A recent sea-ice retreat west of the Antarctic peninsula. *Geophys. Res. Lett.*, 20, 1171-1174

Jacobs, S. S. and J. C. Comiso. 1997. Climate variability in the Amundsen and Bellingshausen seas. *J. Climate*, 10, 697-709.

Jeffries, M. O. and W. F. Weeks. 1991. Fast-ice properties and structure in McMurdo Sound. *Ant. J. of the U.S.*, 26, 94-95.

Jeffries, M. O., W. F. Weeks, R. A. Shaw and K. Morris. 1993. Structural characteristics of congelation and platelet ice and their role in the development of antarctic landfast sea ice. *J. Glaciol.*, 39, 223–238.

Jeffries, M. O., R. A. Shaw, K. Morris, A. L. Veazey and H. R. Krouse. 1994a. Crystal structure, stable isotopes ($\delta^{18}O$) and development of sea ice in the Ross, Amundsen and Bellingshausen Seas, Antarctica. *J. Geophys. Res.*, 99, 985–995.

Jeffries, M. O., K. Morris, A. L. Veazey and H. R. Krouse. 1994b. Depositional environment of the snowcover on West Antarctic pack ice floes. *Ann. Glaciol.*, 20, 33–38.

Jeffries, M. O. and U. Adolphs. 1997. Early winter snow and ice thickness distribution, ice struture and development of the western Ross Sea pack ice between the ice edge and the Ross Ice Shelf. *Antarct. Sci.*, 9, 188-200.

Jeffries, M. O., A. P. Worby, K. Morris and W. F. Weeks. 1997. Seasonal variations in the properties and structural composition of sea ice and snow cover in the Bellingshausen and Amundsen seas, Antarctica. *J. Glaciol.*, 43, 138–151.

Jeffries, M. O., S. Li, R. Jaña, H. R. Krouse and B. Hurst–Cushing. 1998a. Late winter first–year ice floe thickness variability, seawater flooding and snow ice formation in the Amundsen and Ross seas. In *Antarctic Sea Ice: Physical Processes, Interactions and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 69–88, AGU, Washington, D.C.

Jeffries, M. O., B. Hurst–Cushing, H. R. Krouse and T. Maksym. 1998b. The role of snow in the thickening and mass budget of first–year floes in the eastern Pacific sector of the Antarctic pack ice. University of Alaska Fairbanks, Geophysical Institute, *Rep. UAG R–327*, 34pp.

Kawamura, T., K. I. Ohshima, T. Takizawa and S. Ushio. 1997. Physical, structural and isotopic characteristics and growth processes of fast sea ice in Lützow-Holm Bay, Antarctica. *J. Geophys. Res.*, 102, 3345–3355.

Kottmeier, C. and R. Hartig. 1990. Winter observations of the atmosphere over Antarctic sea ice. *J. Geophys. Res.*, 95, 15,551-16,560.

Kurtz D. D. and D. H. Browich. 1983. Satellite observed behavior of the Terra Nova Bay Polynya. *J. Geophys. Res.*, 88, 9717-9722.

Kurtz, D. D. and D. H. Bromwich. 1985. A recurring atmospherically forced polynya in Terra Nova Bay. In *Oceanology of the Antarctic Continental Shelf*, *Antarct. Res. Ser.*, vol. 43, edited by S. S. Jacobs, pp. 177-201, AGU, Washington, D.C.

Lange, M. A. 1988. Basic properties of Antarctic sea ice as revealed by textural analysis of ice cores. *Ann. Glaciol.*, 10, 95-101.

Lange, M. A., S. F. Ackley, P. Wadhams, G. S. Dieckmann, and H. Eicken. 1989. Development of sea ice in the Weddell Sea. *Ann. Glaciol.*, 12, 92–96.

Lange M. A., P. Schlosser, S. F. Ackley, P. Wadhams and G. S. Dieckmann. 1990. ^{18}O concentrations in sea ice of the Weddell Sea, Antarctica. *J. Glaciol.*, 36, 315-323.

Lange, M. A. and H. Eicken. 1991a. The sea ice thickness distribution in the northwestern Weddell Sea. *J. Geophys. Res.*, 96, 4821-4837.

Lange, M. A. and H. Eicken. 1991b. Textural characteristics of sea ice and the major mechanisms of ice growth in the Weddell Sea. *Ann. Glaciol.*, 15, 210-215.

Launiainen, J. and T. Vihma. 1994. On the surface heat fluxes in the Weddell Sea. In *Polar Oceans and their Role in Shaping the Global Environment*, edited by O. M. Johannessen, R. D. Muench, and J. E. Overland, Geophysical Monograph 85, pp. 399-419, AGU, Washington, D.C.

Limbert, D. W. S., S. J. Morison, C. B. Sear, P. Wadhams and M. A. Rowe. 1989. Pack-ice motion in the Weddell Sea in relation to weather systems and determination of a Weddell Sea sea-ice budget. *Ann. Glaciol.*, 12, 104-112.

Loth B., H.-F. Graf, and J. M. Oberhuber. 1993. Snow cover model for global climate simulations. *J. Geophys. Res.*, 98, 10,451-10,464.

Lytle V. I., and S. F. Ackley. 1996. Heat flux through sea ice in the western Weddell Sea: Convective and conductive transfer processes. *J. Geophys. Res.*, 101, 8853-8868.

Lytle V. I., A. P. Worby and R. A. Massom. 1998. Sea ice pressure ridges in East Antarctica. *Ann. Glaciol.*, 27, 149-154.

Markus T. and D. J. Cavalieri. 1998. Snow depth distribution over sea ice in the Southern Ocean from satellite passive microwave data. In, *Antarctic Sea Ice: Physical Processes, Interactions and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 19-40, AGU, Washington, D.C.

Markus, T., C. Kottmeier and E. Fahrbach. 1998. Ice formation in coastal polynyas in the Weddell Sea and their impact on oceanic salinity. In, *Antarctic Sea Ice: Physical Processes, Interactions and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 273-292, AGU, Washington, D.C.

Massom, R. A. 1992. Observing the advection of sea ice in the Weddell Sea using buoy and satellite passive microwave data. *J. Geophys. Res.*, 97, 15,559-15,572.

Massom, R. A., M. R. Drinkwater and C. Haas. 1997. Winter snow cover on sea ice in the Weddell Sea. *J. Geophys. Res.*, *102*, 1101–1117.

Massom, R. A., V. I. Lytle, A. P. Worby and I. Allison. 1998a. Winter snow cover variability on East Antarctic sea ice. *J. Geophys. Res.*, *103*, 24,837–24,855.

Massom, R. A., P. T. Harris, K. J. Michael and M. J. Potter. 1998b. The distribution and formative processes of latent-heat polynyas in East Antarctica. *Ann. Glaciol.*, 27, 420-426.

Maykut G. A. 1986. The surface heat and mass balance. In *The Geophysics of Sea Ice*, edited by N. Untersteiner, pp. 395-463, NATO ASI Ser., Ser. B, Physics vol. 146, Plenum Press, New York.

Moritz, R. 1988. The Ross Sea data buoy project, 1986–1988. *Antarct. J. of the U. S.*, 23, 78–80.

Morris, K., M. O. Jeffries and S. Li. 1998. Sea ice characteristics and seasonal variability of ERS–1 SAR backscatter in the Bellingshausen Sea. In, *Antarctic Sea Ice: Physical Processes, Interactions and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 213–242, AGU, Washington, D.C.

Nicholls, K. W. and K. Makinson. 1998. Ocean circulation beneath the western Ronne Ice Shelf, as derived from in situ measurements of water currents and properties. In *Ocean, Ice and Atmosphere: Interactions at the Antarctic Continental Margin*, *Antarct. Res. Ser.*, vol. 75, edited by S. S. Jacobs and R. F. Weiss, pp. 301-318, AGU, Washington, D.C.

Pillsbury, R. D. and S. S. Jacobs. 1985. Preliminary observations from long-term current meter moorings near the Ross Ice Shelf, Antarctica. In *Oceanology of the Antarctic Continental Shelf*, *Antarct. Res. Ser.*, vol 43, edited by S. S. Jacobs, pp. 87-107, AGU, Washington, D.C.

Pease, C. H. 1987. The size of wind-driven coastal polynyas. *J. Geophys. Res.*, 92, 7049-7059.

Rind, D., R. Healy, C. Parkinson and D. Martinson. 1995. The role of sea ice in 2 x CO_2 climate model sensitivity. Part I: The total influence of sea ice thickness and extent. *J. Climate*, 8, 449-463.

Schlosser, E. 1988. Optical studies of Antarctic sea ice. *Cold Reg. Sci. Technol.*, 15, 289-293.

Schwarz J., R. M. W. Frederking, V. P. Gavrilo, I. G. Petrov, K.-I. Hirayama, M. Mellor, P. Tryde and K. D. Vaudrey. 1981. Standardized testing methods for measuring mechanical properties of sea ice. *Cold Reg. Sci. Technol.*, 4, 245-253.

Strass, V. H. and E. Fahrbach. 1998. Temporal and regional variation of sea ice draft and coverage in the Weddell Sea obtained from upward looking sonars. In, *Antarctic Sea Ice: Physical Processes, Interactions and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 123-139, AGU, Washington, D.C.

Sturm M., K. Morris and R. A. Massom. 1998. The winter snow cover of the West Antarctic pack ice: Its spatial and temporal variability. In, *Antarctic Sea Ice: Physical Processes, Interactions and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 1-18, AGU, Washington, D.C.

Takizawa, T., K. I. Ohshima, S. Ushio, T. Kawamura and H. Enomoto. 1994. Temperature structure and characteristics appearing on SSM/I images of the Cosmonaut Sea, Antarctica. *Ann. Glaciol.*, 20, 298-306.

Tison, J.-L., E. M. Morris, R. A. Souchez and J. Jouzel. 1991. Stratigraphy, stable isotopes and salinity in multi-year sea ice from the rift area, south George VI Ice Shelf, Antarctic Peninsula. *J. Glaciol.*, 37, 357-367.

Tison, J.-L., R. D. Lorrain, A. Bouzette, M. Dini, A. Bondesan and M. Stiévenard. 1998. Linking landfast sea ice variability to marine ice accretion at Hells Gate Ice Shelf, Ross Sea. In, *Antarctic Sea Ice: Physical Processes, Interactions and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 375-407, AGU, Washington, D.C.

Tucker W. B. III, D. K. Perovich, A. J. Gow, W. F. Weeks and M. R. Drinkwater. 1992. Physical properties of sea ice relevant to remote sensing. In *Microwave Remote Sensing of Sea Ice*, edited by F. D. Carsey, Geophysical Monograph 68, pp. 9-28., AGU, Washington, D.C.

Van Woert, M. L. 1999a. The winterime expansion and contraction of the Terra Nova Bay polynya. In *Oceanography of the Ross Sea, Antarctica*, edited by G. Spezie and G. M. R. Manzella, pp. 145-64, Springer-Verlag, Heidelberg.

Van Woert, M. L. 1999b. Wintertime dynamics of the Terra Nova Bay polynya. *J. Geophys. Res.*, 101, 7753-7769.

Veazey A. L., M. O. Jeffries and K. Morris. 1994. Small-scale variability of physical properties and structural characteristics of Antarctic fast ice. *Ann. Glaciol.*, 20, 61-66.

Wadhams P., M. A. Lange and S. F. Ackley. 1987. The ice thickness distribution across the Atlantic sector of the Antarctic ocean in midwinter. *J. Geophys. Res.*, 92, 14535-14552.

WCRP. 1999. Summary report of the First Session of the WCRP (JSC/ACSYS) Climate and Cryosphere (CLIC) Task Group, Utrecht, Nethlerlands, 8-11 July 1998, edited by R. G. Barry, *WCRP Informal Report.*

Weeks W. F. and S. F. Ackley (1986) The growth, structure and properties of sea ice. In *The Geophysics of Sea Ice*, edited by N. Untersteiner, pp. 9-164, NATO ASI Ser., Ser. B, Physics vol. 146, Plenum Press, New York.

Worby A. P., M. O. Jeffries, W. F. Weeks, K. Morris and R. Jaña. 1996. The thickness distribution of sea ice and snow cover during late winter in the Bellingshausen and Amundsen Seas, Antarctica. *J. Geophys. Res.*, 101, 28,441-28,455.

Worby A. P., R. A. Massom, I. Allison, V. I. Lytle and P. Heil. 1998. East Antarctic sea ice: A review of its structure, properties and drift. In, *Antarctic Sea Ice: Physical Processes, Interactions and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 41-67, AGU, Washington, D.C.

Worby, A. P. and I. Allison. 1999. A ship-based technique for observing Antarctic sea ice. Part I: Observational techniques and results. University of Tasmania, Antarctic CRC, *Rep. ??*, ?? pp.

Zwally, H. J., J. C. Comiso, C. L. Parkinson, W. J. Campbell, F. D. Carsey and P. Gloersen. 1983. Antarctic Sea Ice, 1973-76: Satellite Passive Microwave Observations. *NASA Spec. Publ., SP-459*, 206 pp., National Aeronautics and Space Administration, Washington, D.C.

Zwally, H. J., J. C. Comiso and A. L. Gordon. 1985. Antarctic offshore leads and polynyas and oceanographic effects. In *Oceanology of the Antarctic Continental Shelf*, *Antarct. Res. Ser.*, vol. 43, edited by S. S. Jacobs, pp. 203-206, AGU, Washington, D.C.

Appendix A

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Appendix B

ASPeCt Activities and Schedule

Cruises
January-February 1998: Weddell Sea (S. F. Ackley)
May-June 1998: Ross Sea (M. O. Jeffries)
December 1998-February 1999: Ross Sea (M. O. Jeffries)
June 1999: Bellingshausen Sea (R. Smith)
July–August 99: Mertz Glacier Polynya and East Antarctic pack ice (A. P. Worby and V. I. Lytle)
January-February 2000: Ross Sea (S. F. Ackley)

Process Experiments
Antarctic Coastal Polynya Study (Australia): Mertz Glacier Polynya, July-August 1999
Coastal Polynya Experiment (USA and Italy): Terra Nova Bay and Ross Ice Shelf, Winter 2001
Ice-T Ice Edge Experiment (Australia): East Antarctic pack ice

Drifting Ice Station (International): western Weddell Sea, 2005-2006

Appendix C

Shipboard ice observation protocols

Using simple, but quantified observations from vessels traversing the sea ice zone, it is possible to derive information on the ice and snow thickness distributions, and their regional and seasonal variability. Underway shipboard observations are able to provide useful information, particularly of the relatively undeformed ice between ridges, because much of the pack area in the Antarctic is composed of floes 0.7 m or less in thickness. Such observations obviously do not compare with instrumentally derived records for precision, but data can be collected over large areas and, provided the data base is large enough, have been shown to provide statistically meaningful thickness distributions. The observations are less reliable in ridged or heavily deformed ice, and proper account must be made for the bias that arises from the vessel's route, particularly for non-ice-breaking ships.

The method used for several years by a number of nations, and forming the basis of the ASPeCt ice thickness climatology, makes use of three different types of observations. Each type of observation has different strengths and weaknesses, but they can be combined to provide a best-estimate distribution.

A. From some vessels, direct thickness measurements can be made *in situ* by drilling, preferably along transects across floes. Such observations are necessarily limited in number, and do not represent very thin or unconsolidated ice, which is dangerous to access. Nor do they represent very thick, heavily ridged floes which the ship is unable to penetrate (e.g., multi-year ice or very heavy first year ice) and which would be extremely time consuming to sample. The advantages of direct ice and snow thickness measurements include their accuracy, the information they provide on the freeboard and extent of flooding at the snow/ice interface, and the potential for the determination of top and bottom roughness.

B. This method involves estimating the ice and snow cover thicknesses of individual floes tipped on their side by the passage of the ship. These estimates are made once per hour for 25 randomly selected floes. A 0.4 m diameter buoy, hung on a rope over the side of the ship and approximately 1 m above the ice, provides a scale for the thickness estimates. To avoid biassing caused by slow progress in heavy ice conditions, the data are edited to exclude any observations within 6 nautical miles of the previous observations.

Individual ship-based estimates of overturned floes are accurate to about 0.1 m in thickness, but depend on floes turning sufficiently for their keels to become clearly visible. However, the sample may be biassed because: (1) a high percentage of ridged floes, which represent the thickest ice in the pack, tend to break into their component parts when hit by the ship and are not measured; and (2) in low concentration pack near the ice edge, floes tend to be pushed aside rather than turning over, making such observations impossible.

C. For the third observation, an observer, usually on the bridge of the vessel, visually estimates the thickness, concentration, and snow cover of the three dominant ice thickness categories (based on the WMO classification) in the vicinity (~0.5 nautical mile) of the vessel. Thickness estimates are supported by the observations on over-turned floes, as above. The data are entered on log sheets using a code for different classifications. The categories recorded include:

Ice concentration: the fractional ice concentration of each of the 3 dominant ice categories.
Ice type: for each category based on the WMO classifications, but also including three different new ice types and brash.
Ice and snow thickness: for most thin ice categories ice thickness is a redundant check of ice type estimates.
Floe size: classified into approximately logarithmic spaced bins.
Topography: generally only the thickness of level ice is estimated, but the extent (area and sail height) of ridging is also estimated to derive an approximation of total ice mass using a simple model which assumes that the overall pack is in hydrostatic balance, and that ridge sails have a triangular section. The inadequacies of this model are acknowledged, but there is clearly a need for such a correction if realistic average ice thicknesses over large areas of the pack are to be determined from the ship-based observations. The topography code also includes a descriptor for the state of consolidation and weathering of ridges.
Snow Type: a descriptor, used primarily for estimating area-averaged surface albedo.
Open Water: a descriptor.

These data are also edited to exclude any observations within 6 nautical miles of the previous observations. Individually these visual estimates provide the least accurate ice and snow thickness, but they do provide a reasonable estimate of the areal coverage of different ice thickness categories and of their topography. They give a good estimate of the thin ice end of the distribution, since the thickness of new snow-free ice is distinguishable by its albedo, and of the open water fraction within the pack. They also provide, albeit crudely, an estimate of ridged ice.

Observational bias is a concern when making sea ice observations from a ship because of the inherent tendency to avoid heavy ice and follow easily navigable routes. On cruises entirely dedicated to sea ice research, the ship's course can be chosen to minimise this bias, but some areas of extreme ridging or multi-year ice may remain unsampled. In practice, however, the three different methods have been shown to give surprisingly similar thickness distributions over a range of thicknesses from about 0.3 m to 1.2 m, with method C providing reasonable information on the thinner ice.

These methods, and the results derived from them, are detailed further in Allison and Worby (1994) and Worby et al. (1998). The ASPeCt SSG will produce and distribute an observational manual, logging sheets, and software for checking and analysing the data.

Sea ice observations have been made successfully also using a ship-based VCR system by scientists of the Japanese Antarctic Research Expeditions (JARE). Images of sea ice fields were taken and analyzed for ice concentration, floe size, ice thickness and snow thickness. The original system, consisting of video cameras and a time-lapse recorder, was mounted aboard the icebreaker SHIRASE. One camera was located at the upper steering house with an angle of 10 degrees downward from the horizon. The other camera was installed on the side deck to record the total thickness of ice floes broken by the icebreaker and rotated at an angle of about 90 degrees along the side of the hull (see description of Set B method above). These total thicknesses include the snow cover on the sea ice.

These ice measurements were made in the austral summer from 1988 to 1991 by JARE. The observation area is on the usual cruise course of the icebreaker in the Indian Ocean sector of the Southern Ocean, particularly the area between 30°E and 50°E. The video observations were discontinued in 1991, then recommenced in austral summer 1997. These observations will be continued as much as possible during the ASPeCt experimental period to detect inter-annual variation of sea ice extent, decay, and ice thicknesses in this sector.

Appendix D

Snow and Ice Properties: Survey Protocols

Snow property surveys

Snow has been shown to play a major role in the energy and mass balance of Antarctic sea ice, mainly by raising the albedo, insulating the ice cover from the atmosphere, and inducing widespread flooding through ice-surface depression (Lange et al., 1990; Jeffries et al., 1994a, 1998a, 1998b; Eicken et al., 1995; Massom et al., 1997, 1998a). The snow cover also affects the remote-sensing signature of sea ice, in particular during the warm summer months (Comiso et al., 1992). Finally, the snow blanket is of considerable ecological importance as it greatly reduces light levels (including UV) in the ice and the underlying water column.

As outlined in the Table D1, characterization of the state of the snow cover requires the measurement of a number of parameters. Of these, snow density and microstructure are the most relevant, as they provide information about the depositional and metamorphic history and control a number of important physical properties. Large-scale sea-ice models and dedicated snow cover models each parameterize the thermal conductivity as a function of density and sometimes even microstructure (Loth et al., 1993, Massom et al., 1997, 1998a; Sturm et al., 1998). Density measurements are also required to derive the snow-water equivalent for mass-balance and modelling studies. Ideally, snow measurements should be made at the same spatial and temporal sampling frequency as ice cores are obtained during dedicated ASPeCt cruises.

Density will be measured gravimetrically on undisturbed constant-volume samples extracted with a "LaChapelle" cutter or a sampling tube (sample volumes of few tens to several hundreds of cubic centimeters). While an average density over the entire depth of the snow column may suffice in some cases, vertical spacings of 5 cm or less are optimal, allowing distinction of depth-hoar layers, wind crusts etc. For the microstructural characterization, preferrably carried out with a magnifying lens and a grain-size grid or sieve, adherance to the standard nomenclature is recommended (Colbeck et al., 1990). While snow microstructure encompasses a number of parameters, grain size is of particular importance with respect to snow optical properties and passive-microwave remote sensing signatures.

Compactness of the snow cover should also be tested to augment information on layering. Temperature profiles through the snow cover (vertical spacing of 5 to 10 cm depending on snow depth and temperature variability) will aid in assessing vapour and heat fluxes as well as snow metamorphism. Temperature may also serve as ground-truth for passive-microwave remote-sensing data, and to a lesser extent thermal IR data, which ideally require radiometric determination of the snow skin temperature. Snow salinity, which may exceed 1 psu, provides information on atmospheric salt deposition or flooding and strongly affects the amount of liquid phase present within the snow pack. Details of sampling procedures and characteristics of the Antarctic snow pack on sea ice are described by, for example, Jeffries et al. (1994b), Eicken et al. (1994), Massom et al. (1997, 1998a) and Sturm et al. (1998).

Accurate determination of snow albedo and water content, which are of importance for the sea-ice energy balance and remote-sensing applications (Garrity, 1992), is associated with a larger effort and will thus be restricted to dedicated programs (e.g., Schlosser, 1988, Allison et al., 1993). While the albedo of Antarctic sea ice is mostly controlled by the overlying snow cover, measurements of albedo over bare, young ice are nevertheless relevant, in particular for shortwave-fluxes in leads or polynyas and for regional energy-balance estimates (Allison et al., 1993).

The stable-isotope composition of the snow cover (typically $\delta^{18}O$) is of importance for the identification of snow ice formed by flooding of the snow/ice interface, and for the derivation of meteoric-ice fractions in the snow ice layers and the total ice thickness (Lange et al., 1990; Jeffries et al., 1994a, 1997, 1998a, 1998b). Stable isotope data may also provide valuable information about atmospheric vapour transport and the snow depositional environment (Eicken et al., 1994; Jeffries et al. 1994b). Obtaining samples for stable isotope measurements is straightforward, as it requires only that one retain the snow samples taken originally for density measurements. These samples should be stored in solid form in sealed bags or as liquid water in gas-tight bottles until the isotope analysis has been completed.

Table D1: Major snow properties, technique employed for measurements and relevance, priority and required logistic effort within ASPeCt

Ice property surveys

Owing to the importance of sea-ice properties in the study of atmosphere-ice-ocean interaction, numerous field programs have included components dedicated to the determination of key ice properties. For an overview of different Antarctic regions see Weeks and Ackley (1986), Lange (1988), Lange and Eicken (1991b), Jeffries et al. (1994a, 1997; 1998a, 1998b), Worby et al. (1998) and Eicken (1998). Within the framework of ASPeCt, which aims at establishing a "climatological" data set or statistical description of the spatial and temporal variability of sea-ice properties during the implementation period, as well as drawing on existing data bases, two major groups of parameters will be determined. All of these require ice core drilling and sample processing in a cold laboratory at temperatures below -20°C, employing standard techniques described in Schwarz (1981), Weeks and Ackley (1986) and Lange (1988).

The most important parameters, ice temperature, salinity and density (the latter only if the ice contains substantial volumes of gas), can be considered sea-ice state variables. The volume fraction of liquid brine contained within the pore space is controlled by the thermodynamic phase relations, i.e., bulk ice salinity and *in situ* temperature, and typically varies between less than 1% at temperatures below -25°C and more than 10% as the freezing point of seawater is approached (Cox and Weeks, 1983; Weeks and Ackley, 1986). Key ice properties, such as thermal conductivity, specific heat capacity, optical properties and others are generally parameterized as a function of temperature and salinity in numerical models of ice growth (Maykut, 1986). Hence, the minimum effort for ice property surveys would consist of drilling ice cores, measuring ice temperature (thermometer inserted into boreholes at roughly 5 to 10 cm intervals depending on ice thickness) and cutting the core into 5 to 10 cm sections. Salinity will be determined from the melted samples with a conductivity/salinity meter. For multiyear or summer sea ice, where gas inclusions may account for 5% or more of the total volume, thereby reducing thermal conductivity and increasing albedo, for example, ice density also has to be measured in order to arrive at reliable estimates of the relevant phase fractions. More detailed assessments of heat transport through the ice cover also require an analysis of the pore structure of sea ice to account for differences in diffusive and convective transport, the latter commonly associated with surface flooding events (Lytle and Ackley, 1996). Due to technical and logistic difficulties, such studies are likely to be limited to a very small number of sites.

Determination of the grain microstructure as the basis for a textural classification provides valuable information on sea-ice growth processes. Thickening of Antarctic sea ice is mostly dominated by dynamic growth processes (frazil and pancake ice growth, rafting and deformation) rather than congelation growth under quiescent conditions (Gow et al., 1987; Lange and Eicken, 1991b; Jeffries et al., 1997, 1998a; Worby et al., 1998). Snow-ice, formed through flooding of the snow cover and subsequent congelation of the seawater-snow mixture, constitutes the third major ice-accretion process in the Southern Ocean (Lange et al., 1990; Jeffries et al., 1994a, 1997; 1998a, 1998b; Eicken et al., 1995). Since the proportion of frazil, congelation or snow-ice growth has important consequences for the mass and energy balance of the ice cover, and has to be taken into account in sea-ice models, the ASPeCt ice-property surveys will determine the relative contribution of these processes to the ice-mass balance and their temporal and regional variability. Previous work has indicated that, depending on the timing of ice advance in autumn and the synoptic regime governing ice formation in leads and polynyas, such regional and interannual variability may be considerable (Eicken et al., 1994; Eicken, 1998).

Determination of ice texture is generally carried out on vertical thick sections cut along an entire core, augmented by vertical and horizontal thin sections. While the key distinction to be made is between ice originating from frazil or congelation growth, a number of textural classes are recognized. For an overview and discussion see Weeks and Ackley (1986); Gow et al. (1987), Eicken and Lange (1991) and Tison et al. (1998). Distinction of snow ice from frazil can be quite problematic due to textural ambiguities; hence, determination of the snow-ice fraction should be based on stable-isotope measurements, as described above.

Biological and chemical parameters which are of great importance for sea-ice ecological studies will not be among the basic parameters routinely determined on ASPeCt cruises. Nevertheless, they constitute an important component of the ASPeCt framework which also addresses the role of sea ice in biogeochemical processes. Hence, an effort will be made to integrate biological and chemical data into the physical property database and assure cross-referencing between physical and biological measurement campaigns.

Table D2: Major sea-ice properties, technique employed for measurements and relevance, priority and required logistic effort within ASPeCt

Appendix E

Antarctic Coastal Polynas: Candidates for ASPeCt Study

This section describes what is currently known about a circum-Antarctic distribution of polynyas, which have been identified as candidates for study under ASPeCt auspices.

Weddell Coastal Polynyas (65-77°S, 60°W-10°E)

These polynyas typically form in the lee of headlands and ice shelves. They open and close in response primarily to synoptic weather systems and, in the eastern and southeastern region, to the high velocity coastal current. Using satellite images, Markus et al. (1998) reported mean polynya widths of 1.2 to 2.5 km, and using calculated ice growth rates they estimated the annual ice production to be 12 m yr^{-1}, with resultant large net salt fluxes to the ocean. The Weddell Sea pack ice is more extensive than that in other regions, so the polynya contribution to total sea ice volume in the Weddell region is considered small (<5%). However, the concentration of high salt fluxes in narrow coastal regions with relatively long water mass residence times has a significant effect on water mass formation in the Weddell Sea.

The Ronne Ice Shelf Polynya (76°S, 50°W) is one of the Weddell Coastal polynyas. It forms in front of the Ronne Ice Shelf and appears to have been controlled in recent years by the interaction between synoptic weather systems and the blocking influence of large, grounded icebergs. Investigations of Ice Shelf Water flow (Nicholls and Makinson, 1998) have suggested there is a seasonal fluctuation of waters from beneath the ice shelf, associated with the annual cycle of High Salinity Shelf Water formation, which is attributed to winter activity of the Ronne Ice Shelf Polynya. These observations suggest that the opening and closing of the polynya play an active role in controlling production and distribution of water masses, and consequently the sea ice production and associated salt fluxes that drive the water mass transformation.

Cosmonaut Sea Polynya (66°S, 45°E)

The Cosmonaut Sea Polynya, which forms both in the nearshore and offshore regions of the Cosmonaut Sea, has the characteristics of both a coastal and deep water polynya. Water temperature data obtained during regular austral summer investigations from the Japanese icebreaker *Shirase* and SSM/I image analysis from 1987 to 1991 have helped to characterize the ocean and polynya in the region of 60-68°S, 35-65°E (Takizawa et al., 1994). Circumpolar Deep Water (CDW), with a temperature higher than 1.0°C, is found at 150-1000m depth, except in the region of 45-50°E. Cold water with a temperature below -1.5°C (Winter Water, WW) spreads over the continental shelf region and extends offshore along the seafloor, where the bottom topography contributes to a strong meandering eastward current. The CDW intrudes southward and a slightly warm area forms as a precondition for polynya formation.

A coastal, primarily latent heat, polynya forms frequently every year around 50-60°E, 66°S. The polynya is influenced by strong offshore winds, and its area, size, shape and duration are subject to wide variations. It has also been found from sequences of satellite images that the coastal polynya occasionally becomes connected to the deep ocean, sensible heat Cosmonaut Sea Polynya, to form a much larger area of open water/reduced sea ice cover.

Almost every year, a train of polynyas appears between 40°E and 90°E. The Cosmonaut Polynya is situated at the west end of the train, which is considered to be due to significant ice divergence around the Atmospheric Convergence Line (ACL) and/or due to an enhanced oceanic heat flux at the Antarctic Divergence (AD). The enhanced oceanic heat flux associated with upwelling of CDW around the AD triggers and contributes to the maintainenance of the train of polynyas. The ACL and AD are closely related to each other, so both atmospheric and oceanic forcing effects can be substantial in polynya processes in the Cosmonaut Sea.

Prydz Bay Polynya (67°S, 78°E)

The Prydz Bay Polynya forms in front of the Amery Ice Shelf in East Antarctica and is one of the most persistent in East Antarctica. Based on the <75% ice concentration threshold in satellite passive microwave ice concentration data, the mean annual winter extent of the polynya from 1987 to 1994 varied from 6,000 to 22,000 km^2 (Massom et al., 1998b). The polynya is thought to form due to the combined effects of grounded icebergs and ice shelf blocking the advection of ice into the region and possible upwelling of warm Circumpolar Deep Water. The polynya is believed to exert a strong influence on regional water mass modification and formation, including Antarctic Bottom Water, air-sea exchange, ice production and biological productivity. It may also play an important role in the breeding success of nearby Emperor penguin colonies.

Mertz Glacier Polynya (67°S, 140°E)

Two of the characteristics that contribute to persistent polynya formation adjacent to the Mertz Glacier are: 1) the intrusion of the floating ice tongue into the mean flow of sea ice in the coastal current; and 2) ice sheet topography that channels katabatic winds leading to high and persistent offshore winds near the Glacier (Adolphs and Wendler, 1995). A relatively deep basin (>1000m) just north of the polynya region also underlies the Mertz Glacier and creates an unusual bottom topography for the generally shallower shelf region. With the bottom relief collecting cold dense waters, warm deep water may follow an intermediate depth pathway, then upwell and contribute to sensible heat exchanges in the polynya region.

The polynya is shown in Figure 6, a photograph of the coastal polynya taken from the Space Shuttle. Open water is evident along one side of the glacier tongue. Further out, open water undergoes a transition into frazil ice streamers, and further still piles up into an area of thicker, gray white ice. The frazil, or possibly frazil-pancake, streamers in the area adjacent to the open water have some regularity to their spacing, suggestive of the Langmuir rolls seen in other polynyas, e.g., St. Lawrence Island Polynya in the Bering Sea (Pease, 1987). A lead system in the consolidated ice in the lee of the glacier tongue may be formed by the westward flow of pack ice past the tongue (left to right in the photograph). There is a bank of low level cloud or fog downstream of the polynya, probably due to the moisture flux from the open water region of the polynya.

Terra Nova Bay Polynya (75°S 165°W)

The Terra Nova Bay Polynya, located in the western Ross Sea, has been the subject of a number of detailed remote sensing and analytical studies. The polynya is maintained by strong westerly katabatic winds that blow sea ice offshore, combined with the blocking effect of the Drygalski Ice Tongue that prevents sea ice drifting in from the south (Bromwich and Kurtz, 1984; Kurtz and Bromwich, 1983, 1985). It has been shown also that the sensible and longwave heat fluxes play a key role in determining the open water fraction, and that the contribution from the wind is primarily through its amplification of the longwave flux (Van Woert 1999a).

The cumulative annual ice production in the polynya has been estimated to be of the order of 50-80 km^3, and this amounts to 10% of the total ice production over the Ross Sea continental shelf

(Kurtz and Bromwich 1985; Van Woert, 1999b). Numerical simulations by Gallée (1997) suggest that the ocean to atmosphere heat fluxes might be greater than previously thought, although this result could be due to the representation of frazil ice production and dynamics in the model. Brine rejection during ice production in the polynya leads to the formation of High Salinity Shelf Water (HSSW), which may amount to 20% of all shelf water in the Ross Sea (Jacobs et al., 1985; Kurtz and Bromwich, 1985). The export of HSSW from the polynya has been estimated to be 1 Sv (Van Woert, 1999b).

Ross Ice Shelf Polynya (77°S, 175°E)

The polynya forms in front of the Ross Ice Shelf. The opening and closing of the polynya was once thought to be controlled primarily by the passage of strong migratory cyclones, i.e., synoptic weather systems (Zwally et al 1985; Jacobs and Comiso 1989) but it has since been shown that 60% of the polynya events are linked to katabatic wind surge events (Bromwich et al., 1998). Polynya fomration might be influenced also by oceanic sensible heat, as oceanographic investigations have shown a strong upwelling of Warm Deep Water onto the continental shelf in front of the ice shelf (Pillsbury and Jacobs, 1985).

Opening and closing of the polynya occurs on a roughly 30-day cycle and the open water area during winter can reach a peak of almost 50,000 km^2 with a mean of 27,000 km^2 (Zwally et al., 1985). However, there is significant interannual variability, with the greatest extents occurring during warm winters with the strongest winds (Bromwich et al., 1998). Beginning in spring, the polynya increases in size and and eventually becomes contiguous with the Ross Sea to the north, i.e., the ice cover in the Ross embayment appears to decay from south to north (Zwally et al., 1983; Gloersen et al., 1992; Arrigo and McClain, 1994).

With the exception of late May 1995 and 1998, when the R.V. *Nathaniel B. Palmer* entered the Ross Polynya from the north, there have been few shipboard observations of winter ice conditions in the polynya. In late May 1995, there was very little open water present, despite the southerly winds with speeds of 8-10 ms^{-1}; instead there was significant nilas formation and rafting (M. O. Jeffries, unpublished data). The mean level ice thickness (0.2m) in the polynya in May 1995 was 2-3 times lower than the ice 100-200 km further north (Jeffries and Adolphs, 1997). Similar ice characteristics were observed in May 1998.

In addtion to the Terra Nova Bay Polynya, which is described in the previous section, there are two other significant polynya-like features in the Ross Sea: the Ross Passage polynya and the Pennell Polynya, which occur near the continental shelf break in the northwestern Ross Sea in the vicinity of 70°-71°S (Jacobs and Comiso, 1989). These polynyas appear to be maintained in part by divergence above a submarine bank and by upwelling of warmer water near the slope front (Jacobs and Comiso, 1989).

Pine Island Glacier Polynya (74°S, 100°W)

The Pine Island Glacier Polynya apparently varies on synoptic scales, and is presumably driven by offshore winds as migratory cyclones enter the area. Recent glaciological evidence from satellite data analysis has indicated a recession of the grounding line of Pine Island Glacier, suggesting circulation of warm ocean waters at intermediate depths. The polynya may, therefore, be in freshened stable surface waters fed by glacier melt. A stronger pycnocline may be characteristic of the region, and the polynya's effects on heat and salt fluxes may be confined mainly to the upper layers of the ocean. Consequently, some isolation from bottom water formation processes may be more characteristic of this region compared to other polynyas.

Western Antarctic Peninsula Polynya (65°S, 65°W)

This polynya has apparent synoptic scale variability associated with wind changes. Its location in the lower latitudes in the Antarctic Peninsula subjects it to the storm systems at the edge of the circumpolar midlatitude storm belt at a much higher, synoptic scale frequency than seen elsewhere in Antarctica. Higher overall air temperatures, and a shorter seasonal cycle of pack ice variability lead to significantly greater overall effects on the pack ice mass budget than observed elsewhere. The area is also characterized by light levels sufficient to support photosynthesis, extensive coastal areas and shelf, and upwelling induced by bottom topographic features, all leading to high overall biological productivity and extensive habitat for marine life throughout the region.

Appendix F

List of Acronyms and abbreviations.

ACSYS	Arctic Climate System Study (WCRP)
AnITMP	Antarctic Ice Thickness Measurement Programme (WCRP)
ASPeCt	Antarctic Sea-Ice Processes and Climate (SCAR-GLOCHANT)
CLIC	Climate and the Cryosphere (WCRP)
CLIVAR	Climate Variability and Prediction Research (WCRP)
COMNAP	Council of Managers of National Antarctic Programmes
EASIZ	Ecology of the Antarctic Sea-Ice Zone (SCAR-GoSSOE)
GFDL	Geophysical Fluid Dynamics Laboratory (Princeton, NJ, USA)
GLOCHANT	Group of Specialists on Global Change in Antarctica (SCAR)
GISS	Goddard Institute of Space Studies (New York, NY, USA)
GoSSOE	Group of Specialists on Southern Ocean Ecology (SCAR)
IAnZone	International Coordination of Oceanographic Research within the Antarctic Zone
IAHS	International Association of Hydrological Sciences
IASC	International Arctic Science Committee
ICSU	International Council of Scientific Unions
IGBP	International Geosphere-Biosphere Programme
IGS	International Glaciological Society
IOC	International Oceanographic Commission
IPAB	International Programme for Antarctic Buoys (WCRP)
IPCC	Intergovernmental Panel on Climate Change
ISW	Ice Station Weddell
JARE	Japanese Antarctic Research Expedition
SCAR	Scientific Committee on Antarctic Research
SCOR	Scientific Committee on Oceanic Research
SHEBA	Surface Heat Budget of the Arctic Ocean
SO-JGOFS	Southern Ocean-Joint Global Ocean Flux Study
SSG	Science Steering Group
SSM/I	Special Sensor Microwave Imager, DMSP Satellite Program.
WCRP	World Climate Research Programme
WMO	World Meteorological Organization

Figures

Figure 1. Winter sea ice coverage in the Antarctic sea ice zone derived from SSM/I passive microwave imagery.

Figure 2. Distribution of ice types in ice cores from the eastern Weddell Sea in winter. >80% frazil (PF, Predominantly Frazil), >60% frazil (MF, Mainly Frazil), 50% frazil, 50% congelation (M, Mixed), >60% congelation (MC, Mainly Congelation), >80% congelation (PC< Predominantly Congelation). Similar distributions have been found in most other sea ice regions around Antarctica.

Figure 3. Power spectra of ice velocities and derivatives obtained at Ice Station Weddell in the western Weddell Sea. Spectral peaks at one and two per day are caused by tidal and inertial forcing of the ice motion and deformation.

Figure 4. Diagram of the air-ice-ocean interactions in coastal polynyas, leading to enhanced ice production and intense air and water mass conversion through heat and moisture, and salt exchanges.

Figure 5. Space Shuttle photograph of an Antarctic ice edge. Large floes from the pack ice interior are broken by waves that penetrate into the pack ice. Winds and local currents disperse the ice at the edge into bands of high concentration ice separated by open water areas with little ice.

Figure 6. Space Shuttle photograph of the Mertz Glacier and the polynya in its lee. Grounded icebergs anchor fast ice in the region offshore of the glacier, extending the polynya region to approximately twice the distance (140km) that would result from the blocking action of the glacier tongue alone.