ICED

Integrating Climate and Ecosystem Dynamics in the Southern Ocean

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Science Plan and Implementation Strategy

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GLOBAL OCEAN ECOSYSTEM DYNAMICS

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INTEGRATED MARINE BIOGEOCHEMISTRY
AND ECOSYSTEM RESEARCH

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Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED): *A Circumpolar Ecosystem Programme*

Science Plan and Implementation Strategy

Murphy, E.J., R.D. Cavanagh, N.M. Johnston,
K. Reid and E.E. Hofmann (Eds.)

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PREFACE

The Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) Science Plan and Implementation Strategy addresses the need to increase our understanding of circumpolar ecosystem operation in the context of large-scale climate processes, local-scale ocean physics, biogeochemistry, food web dynamics and harvesting. Understanding the processes that drive ecosystem responses to climate forcing and harvesting is fundamental to policy makers in the development of management strategies for the globally important Southern Ocean. At an even greater scale, there is an increasing requirement for predictions of the impacts and feedbacks of Southern Ocean ecosystems as part of the Earth System.

The ICED programme reflects the importance placed on these issues by the International Geosphere-Biosphere Programme (IGBP), the Scientific Committee on Oceanic Research (SCOR) and the Scientific Committee on Antarctic Research (SCAR). ICED has been developed with the approval of the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) and Global Ocean Ecosystem Dynamics (GLOBEC) programmes, and is closely linked with the Southern Ocean System of the European Network of Excellence for Ocean Ecosystems Analysis (EUR-OCEANS).

This Science Plan and Implementation Strategy builds on concepts and strategies formulated and discussed at the first ICED Science Planning Workshop, held at the British Antarctic Survey in May 2005 (Murphy *et al*., 2006), involving 34 participants from 14 countries. This document will be supplemented by more detailed plans for specific aspects of the programme as it progresses. The ICED website (http://www.iced.ac.uk) will provide programme updates on a regular basis.

The ICED Science Plan and Implementation Strategy sets out an ambitious programme, to address not only the significant scientific challenges of integrating Southern Ocean ecosystem, climate and biogeochemical research at a circumpolar level, but also the challenge of bringing together a multidisciplinary group of international scientists to ensure effective cooperation and communication in addressing the objectives of ICED.

We encourage scientists from all relevant fields to collaborate and implement the ICED Science Plan to ensure major questions about Southern Ocean and Earth System science are addressed in a fully integrated manner.

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ICED Interim Steering Committee
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EXECUTIVE SUMMARY

Despite its remoteness there is a 100-year history of multidisciplinary research in the Southern Ocean, and the many past and existing national and international programmes provide the building blocks that underpin our current knowledge. Building upon this foundation, there is an increasing recognition of the need to bring these component parts together to develop integrated views of the whole ecosystem, particularly in the face of a changing climate and harvesting impacts.

In recent years some of the strongest regional expressions of global climate change have occurred in Antarctica and the Southern Ocean. Given the existence of, and potential for, dramatic responses to climate change in this region, developing the ability to predict ecosystem dynamics at a range of spatial and temporal scales is crucial. Understanding the processes that drive ecosystem responses to climate change is necessary to provide a sound basis for the sustainable management of this globally important ocean. An understanding of these processes is also necessary to predict the impacts and feedbacks of the Southern Ocean as part of the Earth System. Many of the priority scientific challenges are at the interfaces between ecosystem, climate, biogeochemistry and fisheries science. Existing studies of the impacts of climate variability on ecosystem structure and biogeochemistry, as well as the long-term effects of harvesting, need to be brought together across regions and scientific disciplines.

Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) is a decade-long, international, multidisciplinary programme. ICED has been established primarily to deliver the integrated scientific analyses required to address major ecological challenges arising as a result of climate and human driven changes.

The long-term goal of ICED is to:

Determine the major controls on the dynamics of Southern Ocean ecosystems and the potential for feedbacks as part of the Earth System.

To address this goal emphasis will be given to the analysis required to predict and evaluate the impacts of climate and harvesting driven change on Southern Ocean ecosystems. To do this the major focus for ICED will be on integrated regional and circumpolar analyses of whole ecosystem operation, particularly at the interfaces between traditional disciplines of ecosystem, climate, biogeochemistry and fisheries science. Here the emphasis will be on the interactions within ecological systems; examining how these interactions modify the impacts of climate and fishery-driven change and affect biogeochemical processes. ICED will link with other relevant groups (developing more specific climate, biogeochemical and fisheries studies) to facilitate the scientific coordination and communication required to predict Southern Ocean ecosystem dynamics in the context of climate change and harvesting impacts.

To address the long-term goal ICED has three major scientific objectives:

1. To understand the **structure and dynamics of ecosystems** in the Southern Ocean and **how they are affected by, and feed back to, climate processes**;
2. To understand how **ecosystem structure and dynamics interact with biogeochemical cycles** in the Southern Ocean;
3. To determine how **ecosystem structure and dynamics should be incorporated into management approaches for sustainable exploitation** of living resources in the Southern Ocean.

Core activity areas

ICED will consist of three major areas of science activity: model development, historical data synthesis, and fieldwork coordination and development; all of which will be guided by close collaboration and multidisciplinary integration of knowledge from research groups operating throughout the Southern Ocean.

1. Model development

A major focus of the ICED programme is to improve the reliability of predictions of future ecosystem dynamics, including ecosystem responses to climate change and harvesting. In combination with data synthesis and field activities this will be achieved through the creation of a suite of models of oceanographic circulation, biogeochemical cycles and the end-to-end operation of food webs, within a hierarchical framework of models of different spatial, temporal and trophic resolution. A strategic modelling framework will be developed; formulating a multi-scale conceptualisation of how Southern Ocean ecosystems work and how they could be modelled. To achieve this ICED will create an integrated modelling Working Group that will include expertise from the physical, biological, geochemical and climate research communities. Key aspects include:

- Trophic interactions and the end-to-end operation of food webs;
- Ecosystem structure and climate: impacts, interactions and feedbacks;
- Coupled physical-biogeochemical models and their use with ecosystem models;
- Operational ecosystem models for sustainable management;
- Multi-scale models building towards circumpolar operation of Southern Ocean ecosystems.

2. Historical data synthesis

Extensive data series have been generated during the many years of research in the Southern Ocean. These data currently exist in a variety of locations and storage media. Together these data provide an invaluable resource that has yet to be fully catalogued and utilised. The ICED programme attaches a high priority to integrating existing datasets to enable investigation of long-term, large-scale ecosystem functioning, variability and change across the Southern Ocean. Key aspects include:

- Developing access to historical data archives, e.g. key species abundance and distribution;
- Producing circumpolar maps of biogeochemical and biological distributions;
- Integration of long-term physical data;
- Data integration and syntheses for input into model development activities.

3. Fieldwork coordination and development

The ICED fieldwork component will seek to address the significant gaps in knowledge that have, and will be, identified through historical data analysis and modelling activities, and will maximise international efforts to fill them. Communication and integration of national and international field activities between groups operating in different sectors of the Southern Ocean will be improved. Key aspects include:

- Improved circumpolar coordination and integration of land-based and pelagic field studies;
- Planning and conducting new fieldwork in important and data poor regions;
- Enhanced use of satellite and remote instrumentation;
- Circumpolar genetic studies.

Integration and synthesis will be an ongoing process, linking the three main activity areas and outputs to produce a responsive and dynamic programme. To manage the three core activity areas and their relationship with the ICED objectives, a Scientific Steering Committee (SSC) will be formed consisting of scientists with expertise in relevant disciplines and who provide broad geographical representation. The SSC will form Working Groups (theme based and activity based, together with a Synthesis Working Group). These will be flexible, cross-cutting and will be formed as required to accomplish the ICED objectives.

Key linkages

ICED has been developed in conjunction with the Scientific Committee on Oceanic Research (SCOR) and the International Geosphere-Biosphere Programme (IGBP), through joint support from the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) and Global Ocean Ecosystem Dynamics (GLOBEC) programmes. ICED will lead and coordinate international research with support from the Scientific Committee on Antarctic Research (SCAR) and in international partnerships with the Southern Ocean System of the European Network of Excellence for Ocean Ecosystems Analysis (EUR-OCEANS) and the International Polar Year (IPY). ICED will link with numerous relevant Southern Ocean programmes. To develop a broader understanding of polar ocean ecosystem operation ICED will link to Arctic Ocean programmes (such the Ecosystem Studies of Sub-Arctic Seas (ESSAS) programme). The institutes currently involved in the ICED programme include those associated with the launch workshop (Appendix II) and ICED-IPY projects (Appendix I). As the programme develops it is envisaged that the number of participants, institutes and programmes involved with ICED will increase. ICED will provide the innovation, direction and coordination required to build a critical mass of multidisciplinary science and scientists to deliver this ambitious, achievable and globally important programme.

Legacy

The integration and coordination of Southern Ocean ecosystem research and analyses through ICED will provide a major contribution to the understanding of how regional and global change may impact ecosystem structure and productivity, not only in the Southern Ocean, but in the Earth System, creating a lasting legacy on which future research can build. The scientific outputs will inform scientists in the international community and provide a focus for future research on important regional, circumpolar and global issues. These outputs will also be presented in forms that provide policy makers with the sound scientific basis upon which to make decisions on ecosystem-based management in the Southern Ocean. In the global context, ICED will complement GLOBEC and IMBER in developing and inspiring a new generation of international, multidisciplinary polar marine scientists with a systems approach to their research.

INTRODUCTION

GLOBAL CONTEXT

The Southern Ocean (defined in this document as the area encompassing the Antarctic Circumpolar Current (ACC) and regions to the south) comprises around 10% of the world's oceans, plays host to one of the world's most productive and unique marine ecosystems and is an important component of the global carbon cycle, providing a large sink for anthropogenic carbon dioxide (CO_2). It has a vital role in the global thermohaline circulation, hosting major regions of mixing and upwelling, and being responsible for the production and export of water masses that regulate the planetary-scale climate. The powerful ACC, the world's largest current system, links the three Southern Hemisphere ocean basins of the Atlantic, Indian and Pacific Oceans (Fig. 1) and facilitates the transmission of signals of variability in climate related processes such as the *El Niño*-Southern Oscillation (ENSO).

The Southern Ocean is a significant sink for both heat and CO_2, acting as a buffer against human-induced climate change. In recent years, some of the strongest regional expressions of global climate change have occurred in Antarctica and the Southern Ocean (King *et al*., 2004; Meredith and King, 2005; Turner *et al*., 2005). For example, the west coast of the Antarctic Peninsula has been one of the most rapidly warming parts of the planet over the past 50 years. Annual mean atmospheric temperatures have risen here by nearly 3°C; approximately 10 times the mean rate of global warming as reported by the Intergovernmental Panel on Climate Change (IPCC, 2007). Significant changes are also influencing the Southern Ocean with the waters of the ACC warming more rapidly than the global ocean as a whole (Gille, 2002, in press).

The observed oceanographic changes reflect alterations in the coupled ocean-atmosphere-cryosphere system. In addition to reports of substantial regional increases in air and sea temperatures, there have been observations of increased precipitation as well as melting and disintegration of ice shelves and decreasing sea ice extent in some areas (Gille, 2002; IPCC, 2001; Smith *et al*., 1999; Vaughan *et al*., 2001). In other areas, however, the changes observed have been smaller or in the opposite direction,

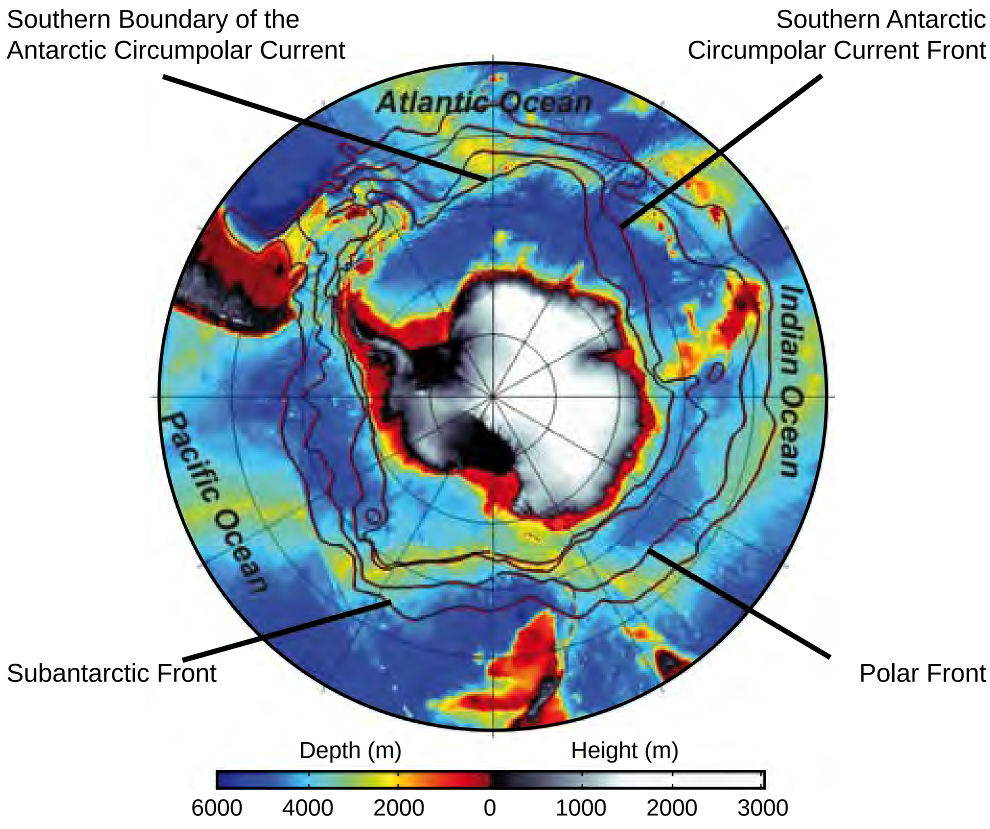


Figure 1. Map of the Southern Ocean (showing bathymetry, topography and major fronts) to illustrate links with the three ocean basins of the Southern Hemisphere. Source M. Meredith, British Antarctic Survey.

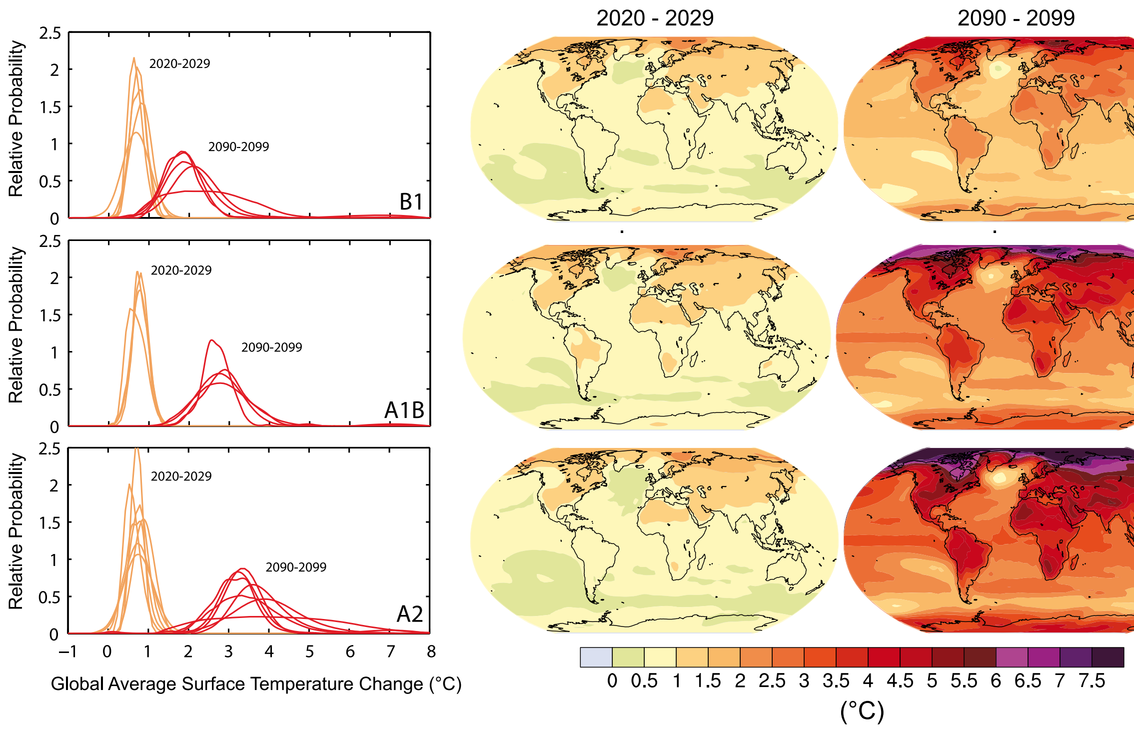


Figure 2. Projected surface temperature changes for the early (orange) and late (red) 21st century relative to the period 1980-1999. The central and right panels show Atmosphere-Ocean General Circulation multi-Model (AOGCM) average projections for three emission scenarios B1, A1B and A2 (refer to source for further details). The left panel shows corresponding uncertainties as the relative probabilities of estimated global average warming from several AOGCM and Earth Models of Intermediate Complexity. The figure highlights the warming predicted to occur in the Polar Regions. Source (IPCC, 2007). Reprinted with permission from the Intergovernmental Panel on Climate Change.

with sea ice coverage even increasing in some sectors (e.g. Stammerjohn *et al*., 2008), reflecting the complex nature of the system. The physical changes observed have also been associated with variations in Southern Ocean ecosystems, including changes in seabird and krill abundance in particular areas (e.g. Atkinson *et al*., 2004; Croxall *et al*., 2002).

Strong, large-scale changes are predicted for the coming decades (Bracegirdle *et al*., 2008). However, there is added complexity in determining climate impacts in a disturbed system where harvesting has been extensive (Croxall and Nicol, 2004; Murphy *et al*., 2007b). Understanding the underlying processes driving ecosystem responses to the physical expression of climate change on a regional and circumpolar basis is essential to provide a sound basis for the sustainable management of the living resources of this globally important ocean. At a larger scale, in order to make predictions of how the global environment may change in the future, there is an increasing requirement to understand the role of Antarctica and the Southern Ocean as part of the wider Earth System. Figure 2 shows projected global temperature changes (IPCC, 2007) including the Polar Regions.

Historical context

Despite its remoteness there is a 100-year history of multidisciplinary research in the Southern Ocean. Initially much of the biological research was carried out within a holistic framework. For example, the *Discovery Investigations* (1925–1939), initiated to provide the basis for managing Southern Ocean whales stocks, studied the ecosystem by conducting topographical, physical and biological observations. Much later, the Biological Investigation of Marine Antarctic Species and Stocks (BIOMASS) programme (1978–1988) was formed to provide a better understanding of the functioning of the Antarctic marine ecosystem. From the mid-1980s, the recognition of the need to focus research effort in specific regions of the Southern Ocean was highly influential in the development of national science programmes, and the emergence of coordinated multi-national programmes with specific geographical or scientific areas of focus (see Box 1 for examples).

Box 1. Examples of international programmes with a Southern Ocean focus or component

- International Southern Ocean Studies programme (ISOS) 1975–82;
- Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS) 1978–88;
- Joint Global Ocean Flux Study (JGOFS) 1984–2003;
- Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) 1982–ongoing, and CCAMLR's Ecosystem Monitoring Programme (CEMP) 1985–ongoing;
- European Polarstern Study (EPOS) 1988–89;
- World Ocean Circulation Experiment (WOCE) 1990–2002, now subsumed into the World Climate Research Program (WCRP)'s Climate Variability and Predictability Program (CLIVAR) 1998–2013;
- International Marine Past Global Changes Study (IMAGES) 1995–ongoing;
- Scientific Committee for Antarctic Research (SCAR) initiatives such as the Antarctic Sea Ice Processes and Climate (ASPeCt) 1996–ongoing, Coastal and Shelf Ecology of the Antarctic Sea Ice Zone (CS-EASIZ) 1993–2004 and Evolution and Biodiversity in the Antarctic (EBA) 2006–13;
- Southern Ocean Iron Release Experiment (SOIREE) 2000–02;
- International Whaling Commission's Southern Ocean Collaboration (IWC-SOC) 1999–2006, and Southern Ocean Whale and Ecosystem Research (SOWER) 1978–ongoing;
- European Network of Excellence for Ocean Ecosystems Analysis (EUR-OCEANS) 2005–2008.

These programmes have generated detailed knowledge of particular processes, such as ocean circulation and evolving physical properties, the controls on primary production, Antarctic krill (*Euphausia superba*, Dana, hereafter termed krill) and copepod life cycles, and predator foraging and behaviour. They have also provided extensive views of particular regions, such as the Ross Sea, the Antarctic Peninsula and South Georgia. For example, the Southern Ocean component of the Global Ocean Ecosystem Dynamics (SO-GLOBEC) programme (from the late 1990s onwards) examined the physical and biological factors that contribute to the survival and success of krill populations throughout the year. Field studies were focused in the southeastern Weddell Sea, Lazarev Sea, and along the western Antarctic Peninsula. The Southern Ocean component of the Joint Global Ocean Flux Study (JGOFS) was established in the late 1980s to study the ocean carbon cycle. This programme focused on biogeochemical processes with process studies in the Bellingshausen Sea (by researchers in the UK), the south Atlantic sector and Weddell Sea (Germany, Netherlands), the south Indian Ocean sector (France), the Ross Sea continental shelf (USA), East Antarctica (Australia), as well as an oceanographic transect south from Cape Town to the Antarctic (South Africa).

The role of such programmes in underpinning our current knowledge of Southern Ocean ecosystems cannot be overestimated. Building upon this knowledge there is an increasing recognition of the need to develop integrated views of the whole ecosystem. This requires that existing studies of the impacts of climate variability on ecosystem structure and biogeochemistry as well as the long-term effects of harvesting are brought together, both across regions and science disciplines. A number of comprehensive regional programmes have contributed to furthering understanding of large-scale physical and biological interactions in the Southern Ocean (e.g. BIOMASS and SO-GLOBEC). Developing integrated, large-scale analyses of Southern Ocean ecosystems to bring together elements of physics, biogeochemistry and ecology is a major challenge for the next decade. With many of the building blocks in place the Southern Ocean science community is currently well poised to undertake an ecosystem-focused programme of circumpolar research. Through ICED we will achieve the direction and coordination required to build a critical mass of science and scientists to deliver this ambitious and globally important programme.

SCIENTIFIC BACKGROUND

Some fundamental scientific issues of key relevance to ICED are outlined in this section to set the scene for the programme.

Spatial and temporal scales of operation of Southern Ocean ecosystems

The space and time scales over which different physical and biological processes operate are major determinants of marine ecosystem structure and function (Fig. 3; Denman *et al*., 1995; Hofmann and Powell, 1998; Murphy *et al*., 1988; Werner *et al*., 2003). In the Southern Ocean the circumpolar flow of the ACC and the Antarctic Coastal Current generate important physical and biological links in the ecosystem. This means that local ecosystems often have very open boundaries, and as such, regional and circumpolar processes influence their dynamics. These larger-scale process links can generate variation in local system dynamics across temporal scales from days to weeks through to years and decades. Selecting the appropriate spatial and temporal scales at which to consider ecosystem processes will inevitably depend on the specific aspect that is of interest. In order to understand the circumpolar operation of the Southern Ocean ecosystem it will be necessary to consider a hierarchy of scales of ecosystem operation that will be defined by a combination of physical (e.g. ocean circulation), biological (e.g. life history strategies of key species) and ecological (e.g. food web interactions) processes.

Ecosystems in the Southern Ocean are typically highly spatially connected through biological processes associated with movement and migration, and physical processes associated with ocean circulation. In analyses of ocean system physics the horizontal advective transport of heat and salt is a standard concept; analyses of nutrient dynamics have also adopted and extended these concepts. In recent years the crucial role of advection in generating population distributions and transporting energy in Southern Ocean food webs has been increasingly emphasised (Hofmann and Murphy, 2004; Murphy, 1995; Murphy *et al*., 2004a, 2004b). In addition to horizontal circulation, the zonation of the ACC and the vertical circulation associated with it are also fundamental to the biogeochemical system of the Southern Ocean (e.g. Pollard *et al*., 2005), with consequences for the marine ecosystem as a whole (Hempel, 1985; Longhurst, 1998; Murphy *et al*., 2007b).

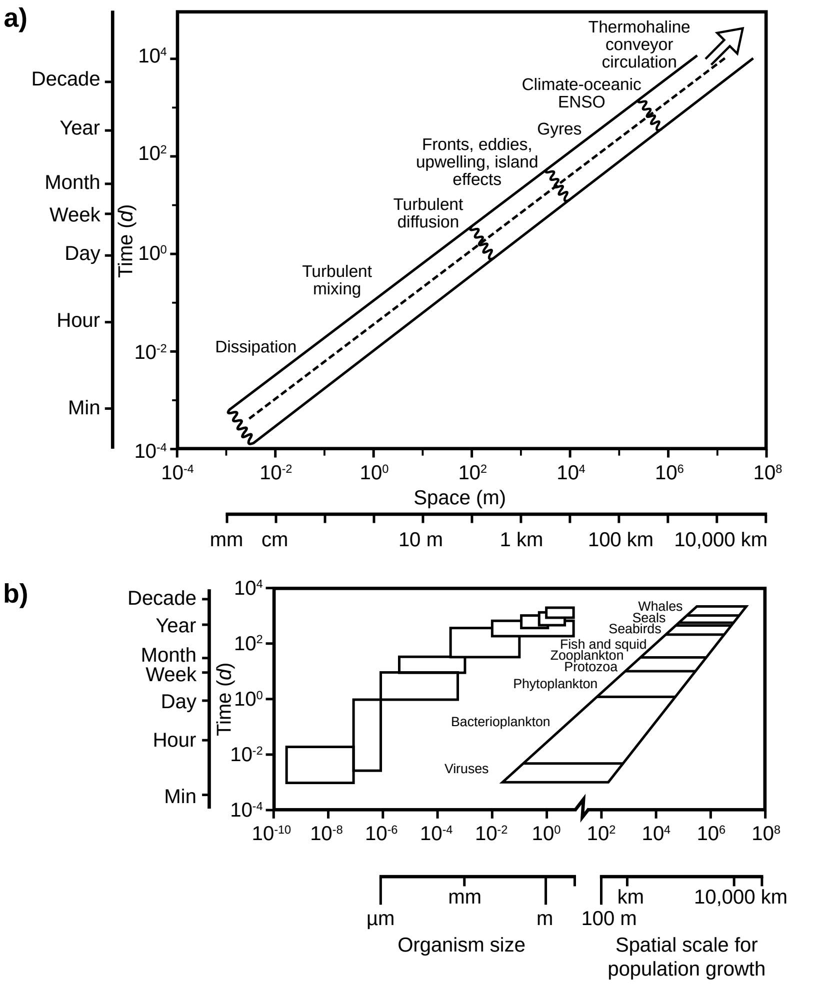


Figure 3. Dominant space and time-scales in the ocean for a) physical motions and b) biological scales. In b) the left-hand overlapping boxes represent typical size ranges (on the x-axis) and typical times for population doubling (on the y-axis) for each type of organism; the right-hand boxes represent typical spatial ranges of each organism during their lifetime. Adapted from (Murphy *et al*., 1988). Source (Denman *et al*., 1995). Reprinted with permission from Cambridge University Press, Cambridge, UK.

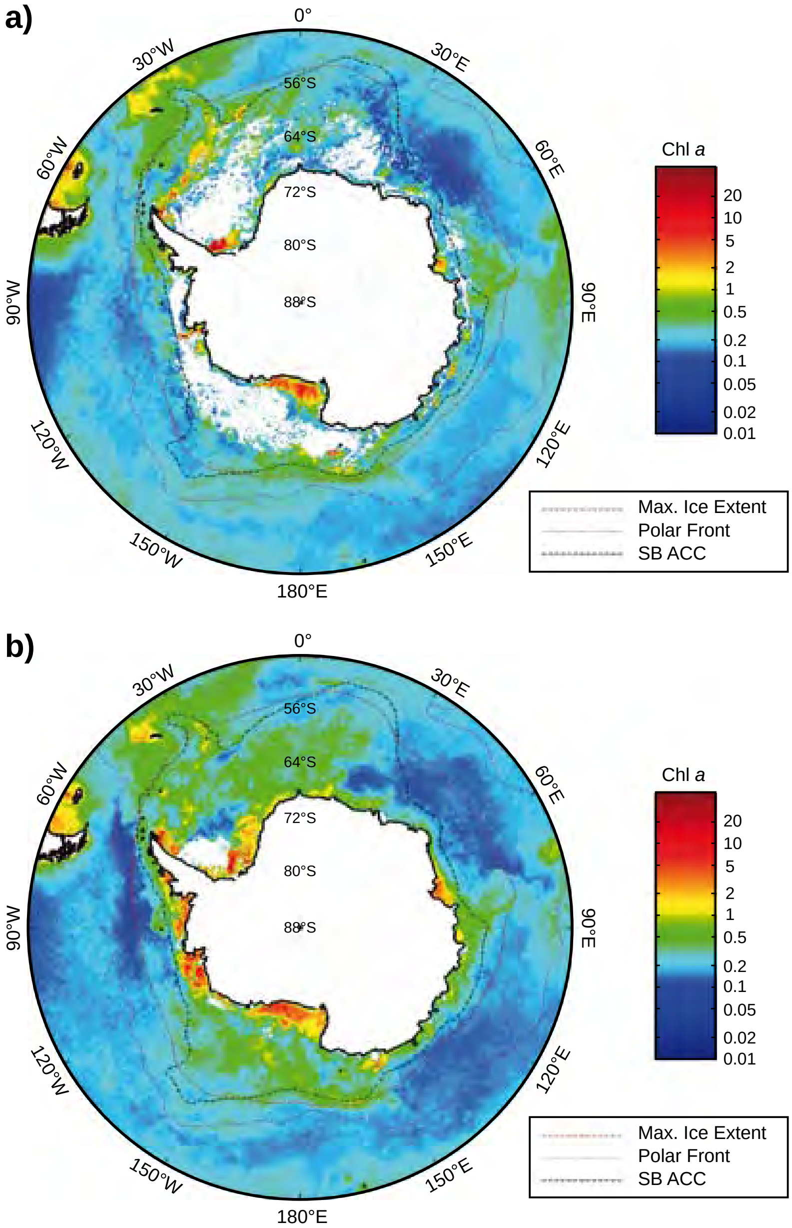


Figure 4. Large-scale surface chlorophyll *a* (Chl *a*) concentrations (mg m^{-3}) around the Antarctic derived from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project. Average concentrations are shown during a) spring (1997-2004) and b) summer (1998-2005). This type of data can be used to examine primary productivity and biogeochemistry in the Southern Ocean. SB ACC = southern boundary of the Antarctic Circumpolar Current. Source Australian Antarctic Division.

Analyses of circumpolar and regional plankton systems are possible using ocean colour data from satellites series that now span several years (Holm-Hansen *et al*., 2004b; Le Quere *et al*., 2002). This has highlighted the importance of large-scale oceanographic conditions, connections and flow regimes in determining the level and distribution of primary production (Fig. 4). The spatial and temporal variation of Southern Ocean food webs has been further highlighted by studies on the dynamics of foraging and migration strategies of higher predators (Croxall, 2006; Staniland *et al*., 2006). Many higher predators forage over large distances and/or undertake seasonal or life cycle related migrations that may extend over the Southern Hemisphere (Fig. 5; e.g. Boyd *et al*., 2002; Bradshaw *et al*., 2004a, 2004b; Croxall *et al*., 2005).

Analyses of temporal variability in ecosystem dynamics provide insight into the response to natural variability, which can help determine the mechanisms involved in linking climate related fluctuations to ecological changes. Analyses of physical-biological interactions undertaken during the last decade have furthered our understanding of how climate variability is propagated through Southern Ocean ecosystems. Of particular interest are the physical factors generating inter-annual changes, which have become tractable issues with the development of time series of ecological monitoring data of sufficient duration. Several sources of such physical variability have been identified through modelling and observational studies (Carleton, 2003; Liu *et al*., 2004; Meredith *et al*., 2003; Park *et al*., 2004).

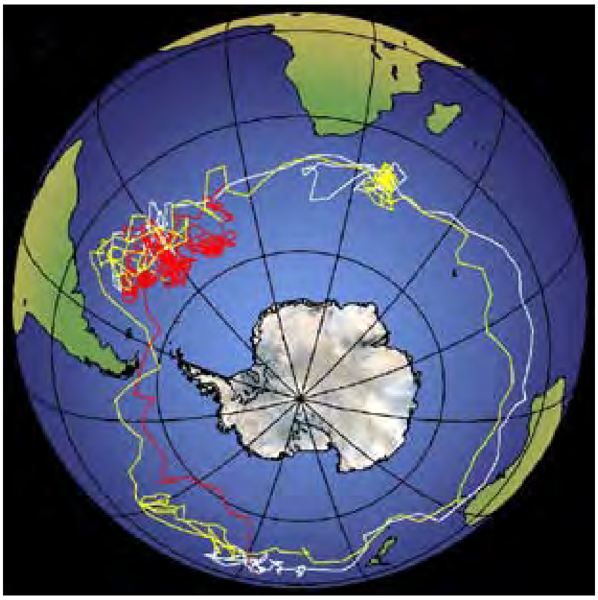


Figure 5. Circumpolar navigations of female grey-headed albatross (*Thalassarche chrysostoma*). This is a biennially breeding species, and the lines indicate the migration route of a single female in the 18 months between breeding attempts (winter 1999 = white; summer 2000 = red; winter 2000 = yellow). Source (Croxall *et al*., 2005). Reprinted with permission from AAAS.

In terms of inter-annual variability, ENSO has been shown to have a strong impact over the Southern Ocean, especially in the south Pacific sector (see Turner, 2004 for a review). Anomalies in surface atmospheric pressure, winds and air-sea fluxes are generated, together with coupled anomalies in sea surface temperature (SST) and sea ice concentration/extent. These anomalies are then advected eastwards in the ACC and can influence ecosystem functions at South Georgia in the south Atlantic sector (Meredith *et al*., 2005; Trathan and Murphy, 2002). Direct atmospheric teleconnections from the equatorial Pacific also affect ocean temperatures here (Meredith *et al*., 2005; Meredith *et al*., in press). The expression of ENSO is strongest in the South Pacific whereas the Southern Annular Mode (SAM; Thompson and Wallace, 2000) is a truly circumpolar mode of climate variability. The SAM is known to have a broad range of impacts on the Southern Ocean, including influences on SST, sea ice extent, rates of formation of water masses, the ACC transport and even the level of oceanic mesoscale eddy variability (Hall and Visbeck, 2002; Kwok and Comiso, 2002; Meredith *et al*., 2004; Meredith and Hogg, 2006). The Antarctic Circumpolar Wave (ACW; White and Peterson, 1996) is another circumpolar mode of climate variability. It is characterised by paired anomalies in SST, sea ice extent and surface atmospheric pressure that propagate within the ACC, generating quasi-periodic signals with 4–5 year periods. However, recent analyses have shown that the ACW was only readily apparent during 1985–1994. At other times a precessional signal was not apparent, indicating significant long period behaviour in the system (Connolley, 2002).

The effects of environment variability are not only evident in atmospheric and oceanographic signals, but are also known to propagate throughout the entire marine food web with significant impacts at a range of trophic levels including in top predators (Croxall, 1992; Forcada *et al*., 2005, 2006; Leaper *et al*., 2006; Murphy *et al*., 2007a; Trathan *et al*., 2006, 2007b; Waluda *et al*., 1999). In some situations, such impacts are known to be profound and long lasting (Costa *et al*., 1989). Recent works have highlighted the importance of ENSO in this context, though modes such as the SAM are increasingly seen as being highly relevant and requiring further study.

Studies of variability have shown that regional ecosystems (e.g. Ross Sea, Scotia Sea, etc.) in the Southern Ocean are affected by Southern Hemisphere scale climate related fluctuations. In addition, analyses of the spatial operation of ecosystems have demonstrated a high degree of circumpolar connectivity through both physical and biological process interactions.

Together these studies have highlighted the crucial need to determine spatial and temporal operation of Southern Ocean ecosystems across a range of scales.

This emphasizes the importance of determining:

- **How ecosystems operate at regional and circumpolar scales and the physical and biological links across these scales.**
- **The controls on the dynamics of Southern Ocean ecosystems and how variability affects structure and function.**

Variability and change in Southern Ocean ecosystems

Physical change

The importance of climate-related influences in generating inter-annual and decadal changes in Southern Ocean ecosystems has been highlighted during the last decade. Change is evident over much of the Southern Ocean (Summerhayes *et al*., 2007) and determining how physical processes impact regional Southern Ocean ecosystems has been a focus of recent research effort (see below and also the Fieldwork section, p.30). Large-scale changes include the strong surface intensified warming of the ACC (Gille, 2002, in press), which is increasingly seen as being at least partially anthropogenic in origin. Potentially the strongest recent regional change has been at the west Antarctic Peninsula where strong decreases in sea ice extent and concentration have been observed (Parkinson, 2002; Fig. 6). These changes have been associated with local atmospheric warming (King *et al*., 2004; Turner *et al*., 2005), and strong increases in upper ocean summer temperatures and salinity (Meredith and King, 2005). The magnitude of the ocean changes is profound, with SSTs increasing by over 1°C during the second half of the twentieth century (Meredith and King, 2005). In other areas, such as the Ross Sea, winter sea ice extent and concentration have increased (Gloersen *et al*., 1992; Stammerjohn *et al*., 2008), and very strong freshening of the upper layers of the ocean has been observed (Jacobs *et al*., 2002).

The ability to reliably predict the future physical evolution of the Southern Ocean is key to predicting and managing its ecosystem. For this, increasingly accurate climate models are required together with observational data to assess and improve their predictive competence. Few continuous observations of Antarctic climate are available prior to the International Geophysical Year of 1957–58, but increased effort in recent decades and planned enhancements and coordination of Southern Ocean observing systems promise to provide the observations required (see Fieldwork section, p.30). Based on recent IPCC models (IPCC, 2007), a new assessment of Antarctic climate change has been conducted by weighting model output depending on ability to reproduce the climate of the 20th century. Predictions include a strengthening of westerly winds over the Southern Ocean, a large warming in the sea ice zone, decreasing sea ice extent and an increase in precipitation over Antarctica (Bracegirdle *et al*., 2008).

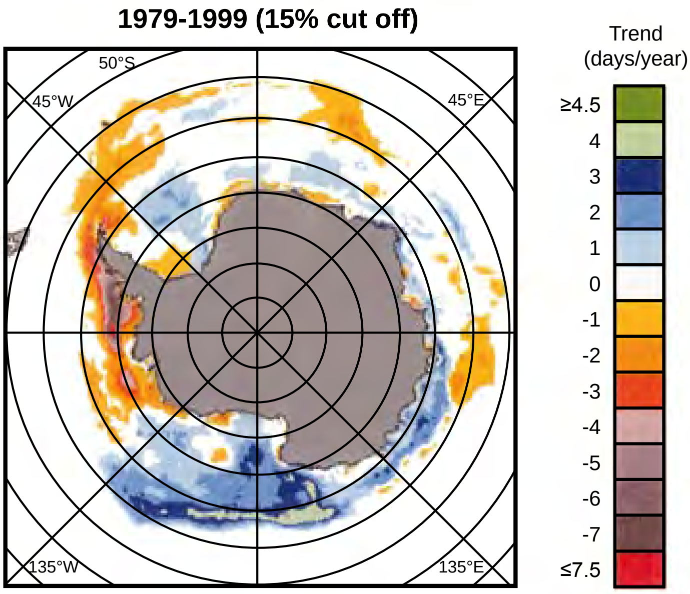


Figure 6. Trends, identified by Parkinson (2002), in the length of the Southern Ocean sea ice season between 1979-99 using a 15% ice concentration cut-off (i.e. considering a location to have sea ice if ice concentration calculations, derived from satellite passive-microwave data, show at least 15% ice coverage). Over this period most of the Ross Sea ice cover has, on average, undergone a lengthening of the sea ice season, whereas most of the Amundsen Sea ice cover and almost the entire Bellingshausen Sea ice cover have undergone a shortening of the sea ice season. Results for the Weddell Sea are mixed, with the north-western portion of the sea having experienced a shortening of the sea ice season but a substantial area in the south-central portion of the sea having experienced a lengthening of the ice season. Overall, the area of the Southern Ocean experiencing a lengthening of the sea ice season by at least 1 day per year over the period 1979-99 is 5.6 x 10^6 km^2, whereas the area experiencing a shortening of the sea ice season by at least 1 day per year is 46% less than that, at 3.0 x 10^6 km^2. Source: Parkinson (2002). Reprinted from the Annals of Glaciology with permission of the International Glaciological Society.

Attributing observed changes in climate to particular changes in anthropogenic forcing or to natural variability is a difficult process. Fyfe (2006) suggests significant human influence on Southern Ocean temperatures, with climate models producing a warming similar to that observed if they include time-varying changes in anthropogenic greenhouse gases, sulphate aerosols and volcanic aerosols in the Earth's atmosphere. Most of the recent IPCC models (IPCC, 2007) simulate the observed strengthening of the circumpolar westerly winds. The increase in winds results from a shift of the SAM, which in turn is attributed to changes in temperature patterns caused by stratospheric ozone depletion and increases in greenhouse gases, both due to human influence (Fyfe *et al*., 2007; Gillett and Thompson, 2003; Marshall *et al*., 2004).

Rapid change is occurring in oceanic and sea ice conditions in regions of the Southern Ocean.

These changes are linked to Southern Hemisphere and global climate changes and significant further changes are expected during the next few decades.

Ecosystem responses to variability and change

Evidence for marked inter-annual, decadal and longer-term changes in Southern Ocean ecosystems due to physical factors exists in a range of ongoing long-term studies and are strongly supported by an increasing number of paleoecological studies (e.g. Domack *et al*., 1993; Emslie *et al*., 1998; Emslie and McDaniel, 2002; Smith *et al*., 1999). Regional physical fluctuations, such as changes in SST and sea ice extent, are associated with major inter-annual changes in the development and operation of ecosystems (Croxall *et al*., 1988; Fraser and Hofmann, 2003; Murphy *et al*., 1998; Priddle *et al*., 1988; Quetin and Ross, 2003; Trathan *et al*., 2003). The effects of such variations have been identified in analyses of biogeochemistry, phyto- and zooplankton dynamics, fish population dynamics and in the foraging and breeding performance of air-breathing predators (Boyd and Roberts, 1993; Costa *et al*., 1989; Croxall, 1992; Croxall *et al*., 2002; Forcada *et al*., 2005, 2006; Fraser and Hofmann, 2003; Hense *et al*., 2003a; Jenouvrier *et al*., 2003; Leaper *et al*., 2006; Loeb *et al*., 1997; Trathan *et al*., 2003, 2006, 2007b).

However, integrating these manifestations of variability at such a range of spatial and temporal scales and trophic levels has proved elusive and is an important focus for the next phases of Southern Ocean research.

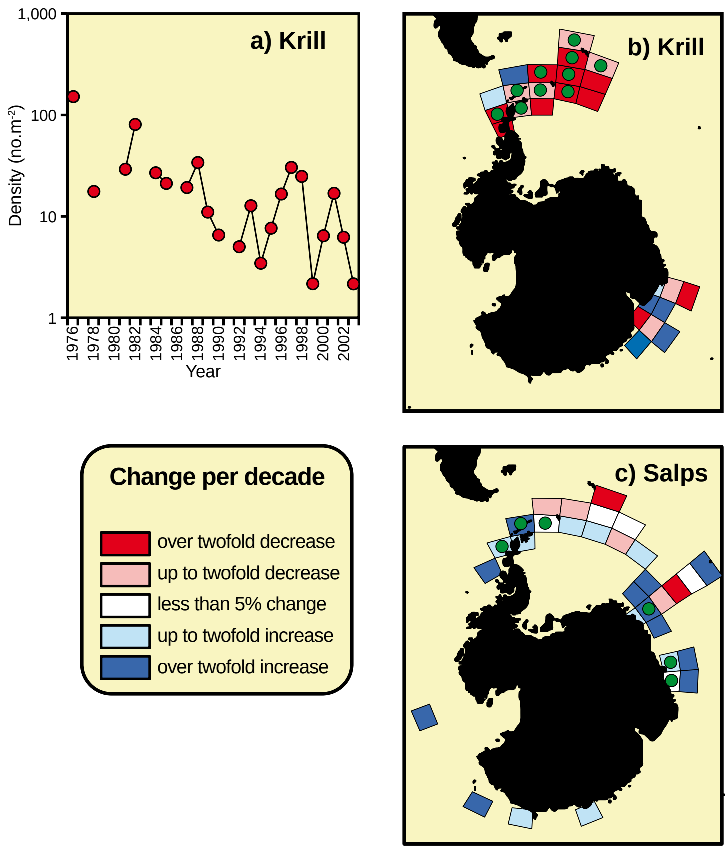


Figure 7. Spatial and temporal changes of Antarctic krill and salps. a) Krill density in the southwest Atlantic sector of the Southern Ocean (4,948 stations in years with >50 stations). Temporal trends include b) post-1976 krill data from scientific trawls; c) 1926-2003 circumpolar salp data south of the Southern Boundary (SB) of the Antarctic Circumpolar Current. Regressions of log10 (mean no. m^2) on year were calculated for cells with ≥ 3 yr of data, weighted by number of stations in that year. One-sample t-tests supported a post-1976 decrease in krill density in the southwest Atlantic (scientific trawls: $t = -3.4$, $P = 0.004$, 16 cells, smaller nets: $t = -2.5$, $P = 0.04$, 8 cells). Salp densities increased south of the SB after 1926 ($t = 3.1$, $P = 0.004$, 32 cells). Green spots denote cells usable in a spatio-temporal model of these time-trends. Reprinted by permission from Macmillan Publishers Ltd: Nature (Atkinson *et al*., 2004), copyright 2004 http://www.nature.com/index.html

Alterations in winter sea ice dynamics are likely to have a direct impact on the marine fauna of the Southern Ocean through shifts in the spatial extent and duration of habitat for ice-associated biota. Adélie penguins, a species well adapted to sea ice conditions, have declined in the Antarctic Peninsula region whilst open water species, such as chinstrap penguins, have increased (Fraser *et al*., 1992). Recent analyses of historical data from net samples have revealed changes in the circumpolar distribution of krill (Fig. 7) and shown a major decline in their abundance across the south Atlantic sector that has been associated with the changing sea ice conditions. These analyses have also suggested that as krill densities have decreased salps (which tolerate warmer, less productive water than krill) have increased. These changes have profound implications for the Southern Ocean food web (Atkinson *et al*., 2004).

The relative intra-annual thermal stability of the Southern Ocean and the stenothermic physiology of many Antarctic marine species means that some species suffer impaired physiological performance with minor temperature increases; however, little is known about the ability of many species to acclimate to longer-term temperature changes (Clarke *et al*., 2007a). Further studies are essential to provide early insights into the fundamental effects of climate change on biological communities at a range of spatial and temporal scales and trophic levels. The knowledge gained through such studies should also be applicable to other marine ecosystems (Clarke *et al*., 2007b).

Detection of the effects of sub-decadal climate variability on ecosystems will reveal potential consequences for long-term changes associated with climate change. However, over longer time-scales the effects of climate change, particularly on upper trophic level species, are difficult to disentangle from those of historical harvesting. The effects of these perturbations, particularly the near removal of baleen whales from the system (Fig. 8), will have generated major shifts in the food web, the impacts of which may still be occurring (Everson, 1977; Laws, 1984). The recovery of previously exploited populations will depend on intra- and inter-species interactions that in turn depend on species-specific vital rates (such as growth and reproduction), as well as long-term changes in the ecosystem.

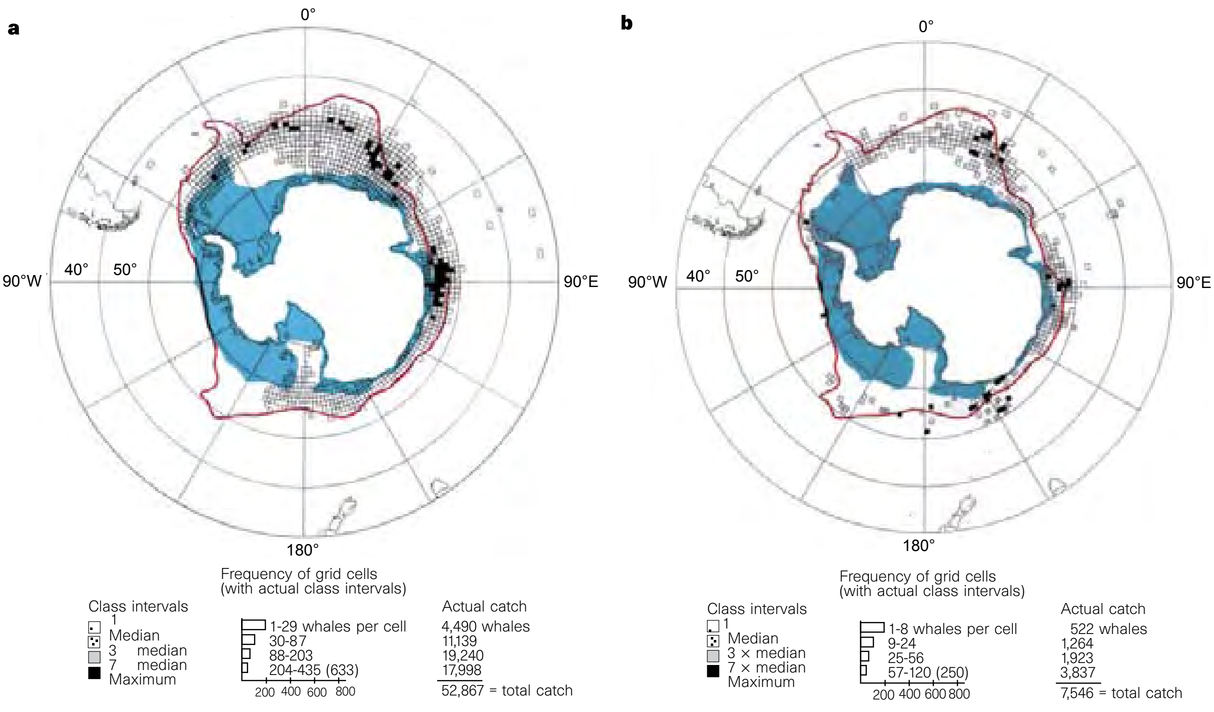


Figure 8. Several species of baleen whales were hunted to near extinction during the first half of the 20th Century. Catch distributions in the Southern Ocean were related to distinct oceanographic regions. Here, catch distributions are shown of a) blue whales during January of 1931-67 and b) humpback whales during January of 1931-63 around Antarctica. The red line delimits the Southern Boundary of the Antarctic Circumpolar Current and the blue area represents the mean monthly extent of sea ice coverage in January between 1979-87. Grid size for catch data is 18 degrees latitude by 3 degrees longitude. Reprinted by permission from Macmillan Publishers Ltd: Nature (Tynan, 1998), copyright 1998 http://www.nature.com/index.html

Similar impacts have been documented in other marine systems (Springer *et al*., 2003). Climate processes can affect oceanic physical systems thus impacting primary production and zooplankton survival, and in turn, the higher trophic levels in the food web; these are known as bottom-up effects. Conversely, top-down effects occur due to competitive and predatory release, and resulting system response (Frank *et al*., 2007; Hunt and McKinnell, 2006; Murphy *et al*., 2007b; Trites *et al*., 2007). These effects could be generated through changes in the abundance of higher trophic level species due to harvesting or direct climate change impacts. In addition, climate impacts on species central to the food web, such as krill, can produce effects that propagate in both directions. Such complex interactions can produce unexpected outcomes that cascade between trophic levels and affect the overall ecosystem structure (Frank *et al*., 2007). For example, in the North Pacific, sea otters are important in determining littoral and sublittoral community structure (Estes and Palmisano, 1974). Removal of sea otters or predation by orcas causes increased herbivory and ultimately results in the destruction of macrophyte associations (Estes and Palmisano, 1974; Estes *et al*., 1998). However, sea otter predation by orcas is only thought to have increased after their main prey, the great whales, were removed through industrial whaling (Springer *et al*., 2003). The non-linearity of the interactions can have a major impact on the response of ecological systems to secular physical change. Indeed gradual physical changes may produce rapid changes in ecological regime as a result of the complexity of the interactions involved (Frank *et al*., 2007).

The biodiversity, ecosystem structure and network of interactions can also be a major determinant of the overall stability of the ecosystem and its resilience to climate and direct human driven change (Neutel *et al*., 2007). Ecosystem structure and biodiversity can therefore be crucial in determining the impacts of physical change on particular species. To fully understand the impacts of variability and change requires integrated end-to-end analyses of Southern Ocean food webs, from primary production systems through to top predators. Determining how ecological complexity affects the structure and function of oceanic ecosystems, and modifies the impacts of climate and harvesting change, is a fundamental scientific challenge for ocean science in the next decade.

Understanding the importance of ecological complexity and biodiversity in determining ecosystem structure and function will be crucial in analyses of change in Southern Ocean ecosystems. Major climate, oceanic and sea ice changes are already occurring in Southern Ocean systems and these are generating significant effects on ecosystems. In addition the system has been subject to over two centuries of harvesting impacts encompassing marine mammals, fish and krill. Bottom-up and top-down effects will be occurring simultaneously, but there is insufficient understanding of how such large scale ecosystems operate in order to predict the impacts of future change. Developing integrated analyses and models to examine the relative contribution of climate variability and harvesting on populations is vital to improve predictions of the status and dynamics of the Southern Ocean ecosystem, but also for wider application. Changes in the structure and function of Southern Ocean ecosystems have the potential to impact biogeochemical cycles and provide major challenges to developing sustainable management procedures for fisheries.

> **Harvesting impacts over more than two centuries and physically driven regional changes are having a profound effect on Southern Ocean ecosystems.**
>
> **Determining how physical and harvesting driven changes impact the structure and function of Southern Ocean ecosystems is crucial to predict the effects of future change.**

Biogeochemical processes–carbon and nutrient cycling

The Southern Ocean is a key region in the global carbon cycle. During glaciations the Southern Ocean played a dominant role in the control of atmospheric CO_2 (Sigman and Boyle, 2000) and is now a large sink for anthropogenic CO_2. Oceanic measurements and inversion methods estimate that about one third of the global oceanic CO_2 sink is located in the Southern Ocean, mainly in the sub-polar region. (Mikaloff Fletcher *et al*., 2006). This uptake of anthropogenic CO_2 occurs on top of an active natural cycle that outgases CO_2 to the atmosphere (Mikaloff Fletcher *et al*., 2007). The combined natural and anthropogenic CO_2 fluxes in the Southern Ocean are thought to result in a small net sink for CO_2 (Takahashi *et al*., in press).

Also of great significance, the Southern Ocean is by far the largest region of the global ocean with unused macronutrients in its surface waters. The distribution and extent of the uptake of these nutrients affects Antarctic marine ecosystems, the exchange of CO_2 between the atmosphere and ocean, and the biogeochemistry of the global ocean (Sarmiento *et al*., 2007). Indeed, there is increased recognition of the need to include ecosystem structure in analyses of biogeochemical cycles in the Southern Ocean and the global ocean (Buitenhuis *et al*., 2006; Froneman *et al*., 2004). This is a major science theme in the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) programme (IMBER, 2005).

There is considerable spatial and temporal variation in the distribution of nutrients and interaction of planktonic systems around the Antarctic. Much of the open ocean around the Antarctic has high concentrations of major nutrients but low levels of phytoplankton growth, known as high-nutrient low-chlorophyll (HNLC) regions. It is thought that phytoplankton growth in these regions is limited by low levels of micronutrients, particularly iron (e.g. de Baar *et al*., 1995). Intense phytoplankton blooms, however, develop in coastal waters and along the various fronts in the ACC, in the vicinity of the sub-Antarctic islands, around the Scotia Arc and in areas where seasonal sea ice melt occurs (Holm-Hansen *et al*., 2004a, 2004b; Korb and Whitehouse, 2004; Korb *et al*., 2004, 2005). In these areas iron is thought to be available in higher concentrations, perhaps as a result of continental or aerosol inputs, local upwelling and/or suspension of sediments. Elevated iron concentration of an order of magnitude higher than the adjacent water has been recently measured in east Antarctic sea ice (Lannuzel *et al*., 2007). Sea ice melt may then provide a significant input of iron to surface Antarctic waters during spring with the potential to significantly enhance primary production (Holm-Hansen *et al*., 2004b; Lannuzel *et al*., 2007). The role of food web processes in determining iron residence time in the upper water column is also of potential importance in the Southern Ocean region (Smetacek and Nicol, 2005; Tovar-Sanchez *et al*., 2007).

The intense phytoplankton blooms are generally dominated by the growth of large diatoms (Holm-Hansen *et al*., 2004b). The fate of the production generated in these regions depends on the trophic structure of the food webs (Atkinson *et al*., 2001). Grazing by smaller zooplankton may lead to smaller particles in the water column that are recycled through microbial interactions or rapidly re-mineralised as they sink below the mixed layer. Larger particles that are not consumed, or generated by grazing by larger zooplankton, may sink more rapidly to depth and are transferred into the deeper ocean (Dubischar and Bathmann, 2002; Ducklow *et al*., 2006).

Food web interactions can, therefore, be crucial in influencing Southern Ocean biogeochemical cycles (Dubischar and Bathmann, 2002). However, although we have detailed knowledge of some processes in particular areas, information on these aspects is generally limited. How variation in food web structure influences or indeed controls, biogeochemical cycles is far from clear. There is obvious potential for feedback processes, involving complex food web interactions, to affect biogeochemical cycling over a range of time scales (e.g. Buitenhuis *et al*., 2006). A major challenge ahead is to further identify, resolve and quantify Southern Ocean food web processes and their effects and feedbacks on key biogeochemical processes, particularly over decadal time scales.

Evidence for a weakening of the Southern Ocean sink for anthropogenic CO_2 has also been identified in response to an increase in winds in the region (Le Quere *et al*., 2007). The winds are thought to increase upwelling of the natural carbon stored in the deep ocean, thus reducing further absorption of anthropogenic CO_2 emissions. This is an ongoing subject of research, for recent discussions see Le Quéré *et al*. (2007, 2008), Law *et al*. (2008) and Zickfeld *et al*. (2008). Changes in the winds and associated circulation will also have effects on the marine ecosystems, though the nature of these effects is not yet fully determined.

Another important aspect of the interaction of biogeochemical processes and ecosystems is the change in water chemistry associated with increased concentrations of CO_2. Projected CO_2 emissions over the next century will double surface seawater CO_2 concentrations, with a resulting drop in pH of 0.35 (IMBER, 2005). The impacts of such changes on biogeochemical cycles and ecosystems could be substantial. Acidification will act to decrease calcium carbonate ($CaCO_3$) saturation levels and affect the ability of calciferous organisms to build and maintain their skeletons. Due to its high drawdown of atmospheric carbon combined with its already low concentration of carbonate ions, the Southern Ocean ecosystem is at particular risk because the levels of carbonate ions (especially in the form of aragonite) are already close to saturation due to the combination of cold water and carbonate chemistry of the region;

current models predict that Antarctic surface waters may begin to become under-saturated by 2050 (Orr *et al*., 2005). The need for an internationally coordinated effort to study and predict the impacts of ocean acidification, and how these might interact with the effects of temperature change has been highlighted by the Royal Society (2005), and the IMBER and Surface Ocean-Lower Atmosphere Study (SOLAS) Science Plans (IMBER, 2005; SOLAS, 2004). Ocean acidification is a further driver of change that will occur simultaneously with direct physically driven changes in ocean circulation and sea ice conditions, and interactive ecological change. Determining how multiple drivers of change affect Southern Ocean biogeochemical cycles poses a major challenge.

Southern Ocean ecosystems play an important role in global biogeochemical cycles, and changes in ocean and sea ice physics will affect circumpolar and potentially global biogeochemistry.

Ecological interactions in Southern Ocean ecosystems may modify the impacts of physical and chemical change and produce unexpected feedback effects on biogeochemical processes.

The biogeochemical and ecological impacts of ocean acidification need to be examined in the context of rapid physical and ecological change.

Exploitation and management of the Southern Ocean

Southern Ocean ecosystems are currently in a highly dynamic phase resulting from the combined effects of major changes in the physical environment, recovery of some species from past exploitation (e.g. Antarctic fur seals) and the impact of current harvesting (e.g. krill: a major global resource; Croxall and Nicol, 2004). Fishing continues to develop, while the historical effects of harvesting are likely continue to affect the dynamics of Southern Ocean ecosystems for many decades (Smetacek and Nicol, 2005). The ability to predict the future status and dynamics of the Southern Ocean ecosystem, taking account of the combined impacts of historical harvesting and climate change, is crucial in developing management procedures for the sustainable exploitation of Southern Ocean ecosystems.

In the Southern Ocean, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR)–the international body responsible for the management of exploitation of Southern Ocean resources under the Antarctic Treaty, has pioneered an ecosystem approach to management: recognising the need to manage the target species within the context of the ecosystem, in contrast to the traditional, more simplistic single-species approach (Constable, 2004; Grumbine, 1994; Mangel, 2000). This means that, in addition to the dynamics of the exploited population, management must also consider the impacts of harvesting on dependent, associated and related species. This approach requires a much wider understanding of the complexity of trophic interactions in the ocean ecosystem. This pioneering application of precautionary and ecosystem approaches to management has had some success; notably in applying conservative yield models for finfish and krill stocks, and in establishing strict rules for undertaking new and exploratory fisheries. However, like any fisheries management system, the CCAMLR process has been recently compromised by Illegal, Unreported and Unregulated (IUU) fishing activities driven primarily by forces outside the Southern Ocean (Croxall and Nicol, 2004).

As part of its management approach, CCAMLR instigated the CCAMLR Ecosystem Monitoring Programme (CEMP), with a network of monitoring sites around the Antarctic. Given their position at the top of the food web, upper trophic level predators have an implicit role as indicator species for the impacts of fishing in ocean ecosystems. The aims of CEMP are to use land-based krill predators to detect changes in key parts of the ecosystem and to distinguish between those changes arising as a result of fishing and those of natural variability. CEMP has generated data that are extremely useful for examining the impacts of climate related changes in Southern Ocean ecosystems.

It is necessary to evaluate uncertainties in our understanding of ecosystem operation and dynamics, and to accompany predictions of the impacts of harvesting with an indication of this uncertainty.

Developing the ecosystem approach to management requires inter-disciplinary analyses of physical and biological interactions in ocean systems.

Accounting for the interacting effects of harvesting and climate change is crucial in developing management procedures for fisheries.

Summary

As this background section has outlined, the Southern Ocean ecosystem is changing rapidly as a result of both climate and harvesting driven effects. These changes will have profound consequences for individual species, overall biodiversity and ecosystem structure and function. They will affect the role of the system in regional biogeochemical cycles and have the potential to generate important feedback effects on global biogeochemistry and earth system dynamics. In addition, with rising global demand for protein driving expansion in fisheries, managing the impacts of harvesting will become increasingly important over the coming decades. As we have noted there are a wide range of distinct challenges in analyses of whole ecosystem operation, climate impacts, biogeochemistry and fisheries. However, it is also clear that major overlaps exist between these areas in the questions being addressed and the analyses required. Indeed, many of the major issues lie at the interfaces between these sub-disciplines, centring on the need to understand the factors determining the structure and function of ocean ecosystems.

The rapid decadal change occurring in these systems means that addressing these challenges is both important and urgent. This requires a strong focus by the scientific community on the large-scale operation of whole Southern Ocean ecosystems. Whilst a vast amount of focused data collection (field and experimental) and model development studies have already been undertaken, what we currently lack is a dedicated, multidisciplinary effort to bring these together more coherently.

INTRODUCTION TO ICED

It is upon the scientific foundation described above that the Southern Ocean science community is now well poised to undertake a multidisciplinary programme of research to develop an integrated understanding of this important oceanic ecosystem. There are 29 countries currently engaged in Antarctic research, and whilst a high level of coordination exists between some of the programmes, many are independent and are often spatially and temporally limited. A more holistic approach to understanding the Southern Ocean is essential given its vast size and remoteness, its direct connection with the global oceans, its role in the Earth System, the harvesting by international fisheries, the impending climate change scenarios envisaged for the region, and the potential implications for the marine ecosystem as a whole.

The ICED programme was initiated in response to the clear need to develop coordination and communication between all nations engaged in Southern Ocean research and between international programmes that have different scientific priorities. To achieve this requires an interdisciplinary approach at local, regional and circumpolar scales and will maximise the efficiency and scientific value of individual programmes.

A major focus for ICED is to improve the reliability of predictions of Southern Ocean ecosystem dynamics at the circumpolar scale, including ecosystem responses to climate change and harvesting. In combination with data synthesis and field activities this will be achieved through the creation of a suite of models of oceanographic circulation, biogeochemical cycles and the end-to-end operation of food webs, within a hierarchical framework of models of different spatial, temporal and trophic resolution.

ICED will:

- develop a coordinated, circumpolar approach to determine the major controls on the dynamics of Southern Ocean ecosystems and the potential for feedbacks as part of the Earth System;
- focus on developing models to improve the reliability of predictions of future ecosystem dynamics in the Southern Ocean, including responses to climate change and harvesting;
- work towards integrating and analysing existing datasets to facilitate investigation of long-term, large-scale marine ecosystem functioning and change;
- help to bring together the scientific outcomes of existing studies, identify priority areas for research, and develop and coordinate future field studies to fulfil spatial and temporal gaps in Southern Ocean data;
- coordinate and link existing national and international programmes with a Southern Ocean focus, maximising their effectiveness and providing added value.

To plan the first phases of the ICED programme, a Science Planning Workshop (Murphy *et al*., 2006) was held at the British Antarctic Survey, UK in May 2005. The workshop involved 34 participants from 14 countries (Appendix II) and the outcomes form the basis for this Science Plan and Implementation Strategy.

SCIENCE PLAN AND IMPLEMENTATION STRATEGY

This section provides the basis for the planning, development and implementation of ICED science. This will be supplemented by more detailed plans for specific aspects of the programme as it progresses. The ICED website (http://www.iced.ac.uk) will provide updates on a regular basis. Implementation of the ICED programme will be structured around three major scientific objectives each highlighting thematic areas of particular importance in Southern Ocean ecosystem research (outlined below):

GOALS AND OBJECTIVES

The long-term goal of ICED is to determine the major controls on the dynamics of Southern Ocean ecosystems and the potential for feedbacks as part of the Earth System.

Achieving this goal requires an understanding of the interactions and feedbacks of the physical environment, biogeochemistry and food webs in the Southern Ocean. Identifying and mapping patterns of variability and change across a range of spatial (from local to circumpolar) and temporal (seasonal, interannual, decadal and longer-term) scales and trophic levels will be the precursor to determining the processes driving these changes. Through this, the ability to predict the outcomes of future change scenarios will improve. In order to structure the work plan the ICED programme has the following three major scientific objectives:

1. *To understand the structure and dynamics of ecosystems in the Southern Ocean and how they are affected by, and feed back to, climate processes.*

   This will focus on the role of physical and biological processes in determining the structure of Southern Ocean food webs and will address the following major issues:

   » dynamics of interannual, decadal and longer-term temporal changes in the distribution and abundance of key species in relation to climatic variability, including the effects of changes in temperature, sea ice extent and ocean circulation patterns;

   » the structure and dynamics of Southern Ocean food webs, including pathways other than krill;

   » life histories and interactions of linked food web components, especially mid and upper tropic level species;

   » spatio-temporal variations in food webs, including the vertical migrations of mesozooplankton and their changing availability to predators, and the role of ocean circulation in the transport and retention of organisms;

   » the impacts of physical climate change due to anthropogenic processes on Southern Ocean food web structures, and distinguishing these from natural variability;

   » physical and biological links between benthic and pelagic systems, particularly in coastal regions.

2. *To understand how ecosystem structure and dynamics interact with biogeochemical cycles in the Southern Ocean.*

   This will focus on the influence of both physical and biological processes on biogeochemical and nutrient cycles (and vice versa) and will address the following major issues:

   » patterns and variation in nutrient dynamics and biogeochemical processes at different temporal and spatial scales and their relationships with physical and biological processes;

   » the role of physical processes such as upwelling, mixing and lateral oceanic advection on nutrient and CO_2 distributions and fluxes;

   » links between biogeochemical processes and food web structure, including the identification of key functional groups and interactions, and the role of depth-related links in food webs in influencing biogeochemical cycles (e.g. through the mesopelagic layer);

   » the role of life histories (including vertical movement, interaction with ice biota and over-wintering strategies) of lower trophic level species of zooplankton on microzooplankton and phytoplankton dynamics, and the potential consequences on nutrient dynamics;

   » impacts of the combined changes in ocean physics and marine ecosystems on the Southern Ocean sink for CO_2;

- » impacts of ocean acidification on upper ocean biogeochemical processes and food web dynamics;
- » the role of iron on phytoplankton growth and the importance of iron recycling in food webs in high-nutrient low-chlorophyll regions.

3. *To determine how ecosystem structure and dynamics should be incorporated into management approaches for sustainable exploitation for living resources in the Southern Ocean*.

   This will focus on creating strong links with CCAMLR in developing its ecosystem-based approach to managing fisheries, and the International Whaling Commission (IWC) in managing whale stocks, and will address the following major issues:

   - » how should the structure and dynamics of Southern Ocean ecosystems be represented in ecosystem models used in resource management?
   - » how should the complexity and uncertainty in our understanding of the functioning of these ecosystems be reflected in the preparation and delivery of management advice?
   - » what are the principles required to utilise data from ecosystem monitoring programmes as part of management?

For all three of the ICED objectives there will also be an emphasis on producing models to provide the ability to predict and evaluate ecosystem responses to climate and harvesting at scales relevant to management of resources at the circumpolar scale.

Implementation Activities

In order to deliver its goals and objectives ICED will consist of three major areas of science activity: modelling, historical data synthesis and analysis, and fieldwork, all of which will require close collaboration and multidisciplinary integration of knowledge from groups operating throughout the Southern Ocean. To link these three areas there will be a continual process of integration and synthesis, drawing together the outputs of the activities (Fig. 9). This will be an ongoing process that will gather pace over the course of the programme.

The three major areas of science activity are detailed below; the modelling section is presented first as it lays the logical foundation for the ICED science programme and sets the agenda for the subsequent sections on data syntheses and field activities. There are currently varying levels of detail in the different sections; the balance will be appropriately redressed as ICED Working Groups become established and further develop the plans and strategies in each of the activity areas. The content below reflects the current assessment of priorities and as the programme develops these will be re-assessed and revised appropriately.

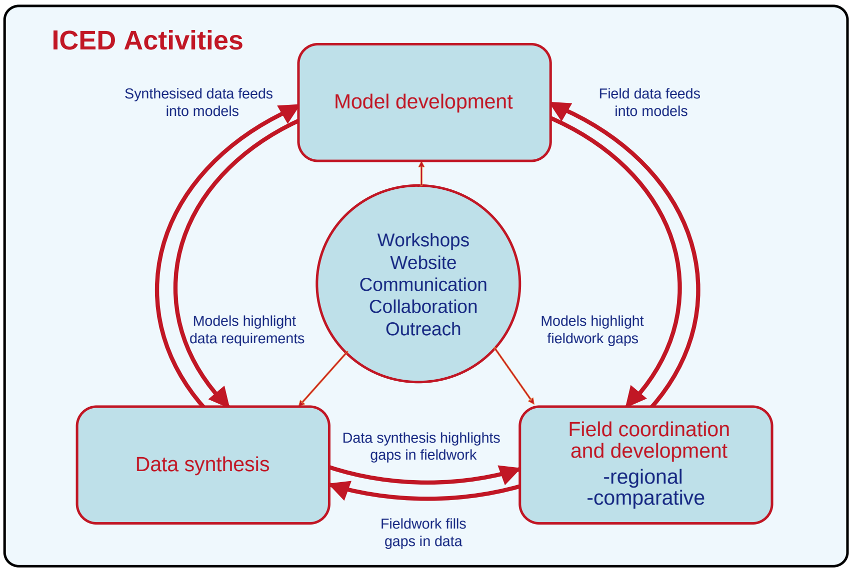


Figure 9. Simplified representation of ICED activities illustrating links between the three main areas: modelling, data synthesis, and fieldwork, all of which will be guided by close collaboration and multidisciplinary integration of knowledge from research groups operating throughout the Southern Ocean. The three main activity areas and their outputs will be linked together through workshops and other communication strategies, resulting in a responsive and dynamic programme.

Model development

Background to model development

Analyses of the dynamics of Southern Ocean ecosystems over the last decade have highlighted the importance of understanding circumpolar physical and biological connections (e.g. Ainley *et al*., 2003; Atkinson *et al*., 2004; Croxall *et al*., 2002, 2005; Loeb *et al*., 1997; Meredith and Hogg, 2006; Murphy *et al*., 2007a, 2007b; Smetacek and Nicol, 2005; Summerhayes *et al*., 2007; Thorpe *et al*., 2007; Trathan *et al*., 2007b; Tynan 1998). These connections are fundamental to predicting the impacts of climate and harvesting in the Southern Ocean and in improving sustainable management strategies. Development of a circumpolar view of ecosystem operation and understanding of ecosystem responses to variability and change is, however, a major challenge for Southern Ocean ecosystem modellers. Ecosystem modelling for the Southern Ocean is in its early stages with much of the work restricted in geographic and/or trophic scope (Hill *et al*., 2006; Murphy *et al*., 2006). These models are useful in addressing specific, focused questions, but as outlined in the science background section, there is a pressing need for models that consider whole ecosystem operation and account for complex interactions in their predictions.

In a global context, there is a requirement to begin to make predictions of the impacts and feedbacks of changes in Southern Ocean ecosystems as part of the Earth System (IMBER, 2005). The science background section (p.6) highlights that developing such predictions is a crucial requirement in Southern Ocean science over the next decade. The current generation of models are of limited resolution as noted above. Global models are being developed and used to make predictions that have little basis in the Southern Ocean. Models are also being used to set management procedures for fisheries. However, there are considerable questions regarding appropriate model structures that allow for integration of different scales and processes, and identify areas of overlap and distinction. Decisions are required about the level of detail required (or available) at different scales and at different trophic levels (Fig. 10). A wide range of spatial (approximately 10 m to 10,000 km) and temporal (minutes to centuries) scales need to be considered, as do different trophic levels (primary producers to top predators).

Physical ocean circulation models are required for detailed simulations of Southern Ocean ecosystem dynamics. Progress has been made with coupled circulation-sea ice models that accurately simulate conditions in specific regions of the Southern Ocean, such as the Ross Sea (Dinniman *et al*., 2003, 2007), western Antarctic Peninsula (Dinniman and Klinck, 2004) and the Weddell Sea (Beckmann *et al*., 1999). These coupled models include the space and time resolution and circulation dynamics (upper water column processes) needed to accurately simulate biogeochemical and food web processes (e.g. Smith *et al*., 2003). Current efforts are focused on extending the regional circulation-sea ice models to include explicit coupling to mesoscale atmospheric models and models of circulation underneath ice shelves. The latter are important in correct simulation of coastal circulation and hence of potential importance in coupled circulation-ecosystem models.

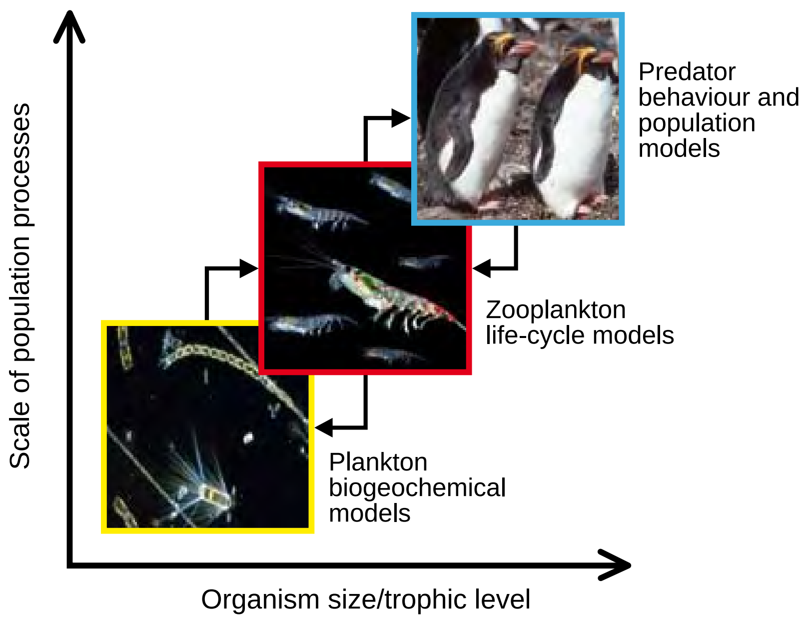


Figure 10. Producing coupled models of ecosystem operation requires the development of models encompassing different temporal and spatial scales. At different scales the biological processes and trophic resolution included will vary and depend on the main scientific issues being addressed. A major challenge is to develop the appropriate links between different types of models that resolve different biological processes, and apply these at different scales. Source E.J. Murphy, British Antarctic Survey.

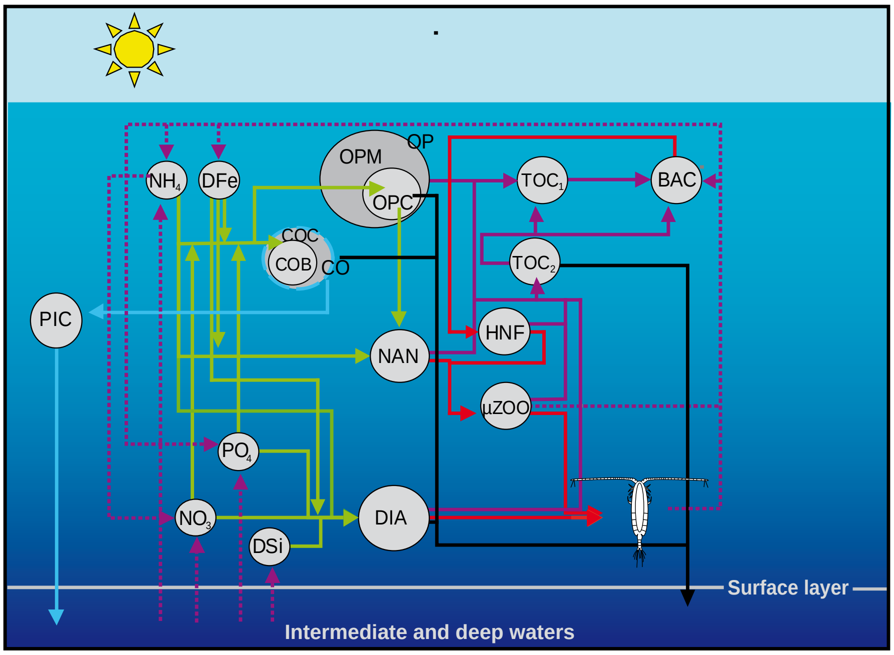


Figure 11. Structure of the ecosystem model SWAMCO-4, including processes (arrows) and state variables (including major nutrients NH_4: ammonium; NO_3: nitrate; PO_4: phosphate; DSi: dissolved silica; and DFe: dissolved iron). The model explicitly details the dynamics of 4 relevant phytoplankton groups: i) DIA: diatoms; ii) NAN: pico/nano phytoflagellate; iii) OP, OPC, OPM: *Phaeocystis* colony, cell, colony polysaccharide matrix; iv) CO, COB, COC: coccolithophorid cell, biomass, attached coccoliths and PIC: COC+detached coccoliths. TOCi: fast (i = 1) and slowly (i = 2) biodegradable organic matter; BAC: bacteria; HNF: heterotrophic nanoflagellate; µZOO: microzooplankton. The model integrates knowledge on mechanisms controlling biological productivity and the structure of the planktonic ecosystem. Source (Pasquer *et al*., 2005). Copyright Elsevier 2005.

Biogeochemically-based models have been developed for selected regions of, and across, the Southern Ocean, for example: Weddell Sea (Lancelot *et al*., 1991), Atlantic sector (Fennel *et al*., 2003; Lancelot *et al*., 2000), Indian sector (Pondaven *et al*., 1998), Ross Sea (Arrigo *et al*., 2003a; Hecq *et al*., 2000; Tagliabue and Arrigo, 2005) and the Antarctic Peninsula region (Walsh *et al*., 2001). Hense *et al*., (2003a, 2003b) used a coupled physical-biochemical model for oceanic regions of the Southern Ocean (south of 50°S). These models provide useful insights as a basis for the next generation of modelling studies. Studies of Southern Ocean biogeochemistry have recently begun to consider the importance of these lower trophic level interactions in determining nutrient dynamics. One example is SWAMCO-4, a complex model of the marine plankton system (developed using data from the Southern Ocean and the North Atlantic) calculating carbon, nitrogen, phosphorus, silicon and iron cycling within the upper ocean, the export production and the exchange of CO_2 between the ocean and atmosphere (Fig. 11). Models integrating biogeochemical models with higher trophic level ecosystem models are currently under development but not specifically for the Southern Ocean. Models that yield circumpolar distributions of biogeochemical properties are beginning to be available (Fig. 12) and acquisition of datasets that can provide evaluation of such models is a necessary focus for the next generation of Southern Ocean research programmes. These are some examples of progress towards improving the links between biogeochemical cycles and ecosystem structure and function in ocean models.

The development of detailed life cycle models for species in the Antarctic food web to facilitate analyses of the physical and biological controls on their abundance and distribution is a major focus of current research. Ocean circulation models, such as the Ocean Circulation and Climate Advanced Modelling (OCCAM) project, provide flow fields that can be used to investigate transport pathways (Fig. 13) and can be incorporated into life cycle models of plankton and fish. The results of such Lagrangian particle tracking simulations, based on the biology of key plankton species and simple food web models, have been used to consider the physical-biological interactions affecting mid- and higher-trophic level species (see Hill *et al*., 2006 for a review). Demographic model studies of a range of plankton, fish and marine mammal and seabirds have also been developed, particularly in relation to the progression of sustainable management procedures with CCAMLR (Hill *et al*., 2006). Such species specific, simple interactive models provide a valuable basis for addressing questions focused on key species or interactions.

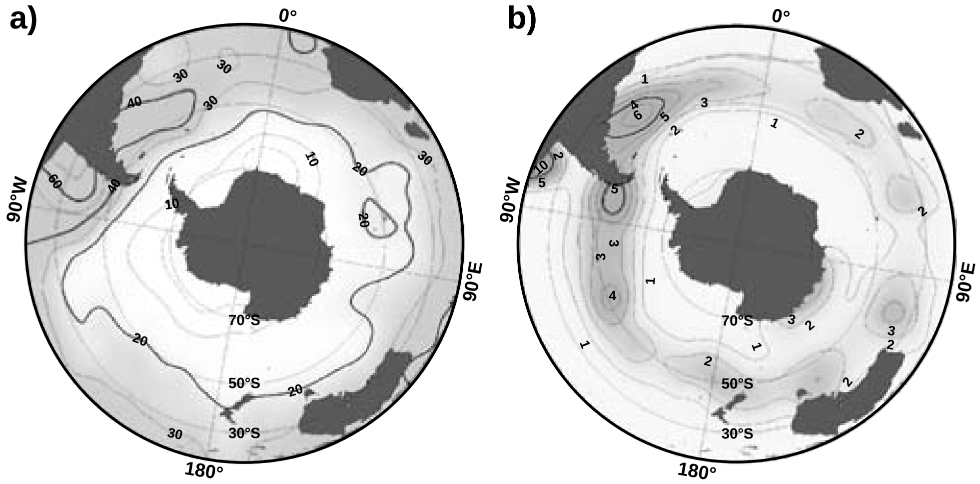


Figure 12. An ocean circulation, biogeochemical model was developed to determine rates of export production and vertical carbon fluxes in the Southern Ocean. The model exploited large sets of hydrographic, oxygen, nutrient and carbon data with information on underlying biogeochemical processes. Here, the simulated distribution of semi-labile dissolved organic carbon (μmol kg^{-1}) is shown (represented by the numbers and shading) for the Southern Hemisphere in a) surface layer (30 m depth) and b) 500 m depth. This shows the results from only 1 of 7 experiments that differed with respect to element ratios of particulate and dissolved organic matter, nitrification/de-nitrification processes and other factors (refer to source for details). Comparing carbon export fluxes with export production from satellite data, the model was in good agreement for low- and mid-latitudes, but for the Southern Ocean discrepancies were apparent. More direct observations are needed for a clearer understanding of the Southern Ocean's role in the carbon cycle and to fully utilise available satellite data. Source (Schlitzer, 2002). Copyright Elsevier 2002.

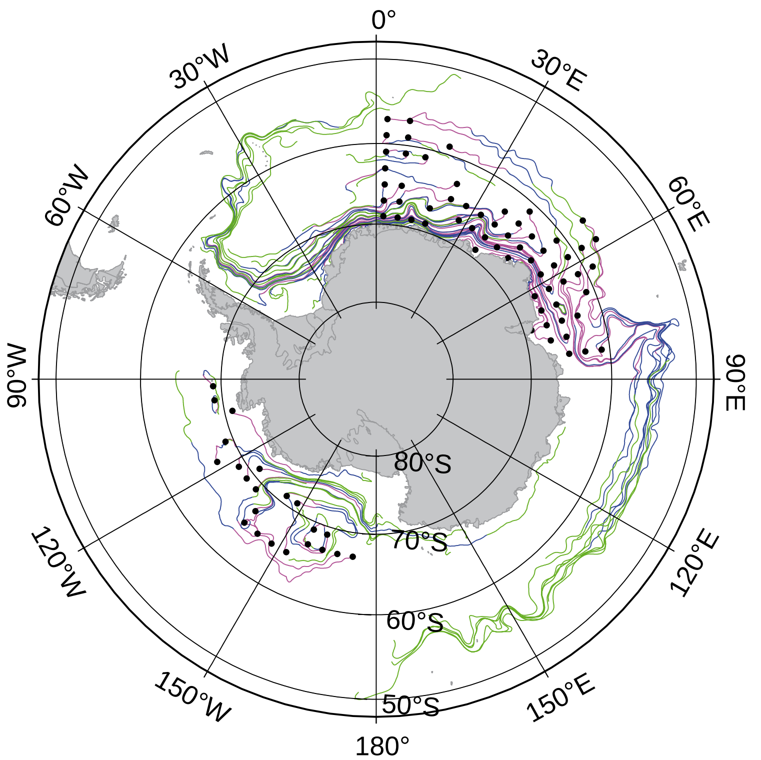


Figure 13. Lagrangian particle tracking analysis around Antarctica examining the circumpolar connection of Antarctic krill populations using OCCAM circulation model output. Particles were released into OCCAM velocity fields (marked by black dots) and tracked for 3 years in the upper 180 m of the water column. Trajectories are coloured according to time (0-1 yr: pink, 1-2 yrs: blue, 2-3 yrs: green). Source (Thorpe *et al*., 2007). Copyright Elsevier 2007.

Models of broader oceanic food web operation are less well developed than those with biogeochemically based or species-specific approaches. However, Southern Ocean ecosystems have a number of characteristics (such as relatively restricted trophic structure and a circumpolar nature) that make the region an ideal focus for modelling studies of large-scale marine ecosystems (Hill *et al*., 2006). The central role of krill in some areas makes the Southern Ocean an ideal system for examining trophic interactions and the end-to-end operation of food webs. In many areas of the Southern Ocean much of the energy flows to higher trophic levels through the dominant summer food chain of diatoms-krill-predators. However, at other times of year, and in many other regions, other species dominate (Reid *et al*., 2005; Smith *et al*., 2007; Trathan *et al*., 2007a) and the food webs are re-organised accordingly. Microbial systems recycle production generating complex pathways of energy flow through food webs (Clarke *et al*., 2007b; Smetacek *et al*., 2004), and the potential importance of alternative pathways of energy flow in maintaining ecosystem structure and biodiversity for the Southern Ocean is becoming an increasing focus of attention (see for example Donnelly and Torres, 2008; Murphy *et al*., 2007b; Shreeve *et al*., 2007). Similarly the potential importance of overall ecosystem structure and hence higher trophic level species in regulating lower trophic level species abundance and composition as well as local biogeochemical cycles is only now beginning to be assessed. Increasing significance is being placed on the development of end to end food web models (see IMBER, 2005). Such interactions may produce potentially important feedback in Southern Ocean food webs and as such certainly warrant further study.

In developing Southern Ocean ecosystem models it is, therefore, particularly important to understand the structure of the food webs and the food requirements of different trophic levels in order to represent the flow of energy or mass between them. There are complex issues regarding the criteria required to develop realistic Southern Ocean food web models at the circumpolar scale. The regionally different systems (e.g. Ross Sea, west Antarctic Peninsula and Scotia Sea) need to be taken into consideration. The level of species aggregation or functional group definition needed to resolve the dynamics of these systems is the subject of active research (Hood *et al*., 2006; Pinnegar *et al*., 2005). The development of regional models will provide guidance on processes and parameterizations that need to be transferred to circumpolar-scale circulation-sea ice models. The challenge is to provide a means to integrate the results of regional studies into larger scale models; and do this in a manner that will advance coupled physical-biological modelling at larger scales, including circumpolar.

Recent changes in Southern Ocean ecosystems, such as the reduction of krill abundance across the south Atlantic sector (Atkinson *et al*., 2004) may be interpreted as either climate or harvesting driven effects (see above). Understanding the interactive effects of bottom-up or top-down effects in ecosystems requires an explicit focus on the role of complexity in determining the dynamics of ecological systems. To assess these complex interactions more thoroughly a new generation of ecosystem models, that include realistic physical and biological processes, is required.

No one particular model structure will address such a range of issues. However, it is clear that models of broader ecosystem operation are necessary. Creating a suite of models that operate in an integrated framework will provide the basis for addressing the issues raised. Some of these models will be of simplified, generic food webs, while others may be more detailed views of local or regional systems. The challenge is to develop the theoretical and strategic framework to integrate models of ocean physics, biogeochemistry and end-to-end food webs that allow prediction and validation at different space and time scales. These are complex and technically challenging objectives and can only be addressed through a coordinated international, multidisciplinary approach.

As such, ICED has highlighted the need for an integrated modelling community for the Southern Ocean that includes expertise from the physical, biological, geochemical and climate communities (Murphy *et al*., 2006). With the major legacy of field studies together with regional circulation and biological models from SO GLOBEC and a number of national programmes (e.g. Dinniman and Klinck, 2004; Smith *et al*., 2003), ICED is now in a position to bring together relevant scientists and groups to work towards the next generation of integrated Southern Ocean ecosystem models.

Priority areas for model development

The modelling work will be organised around the three ICED objectives with the following structure (leading eventually to integrated circumpolar models that link Southern Ocean models to Earth System models):

- models examining how ecosystem structure (including physical processes) influences responses to perturbation and change;
- models examining the influence of ecosystem structure on biogeochemistry;
- models to complement the development of management models by CCAMLR.

A range of issues was highlighted and discussed at the first ICED workshop (Murphy *et al*., 2006) for consideration during model development; these are all detailed in Appendix III. Some of the key areas are briefly outlined below.

Key concepts: multi-scale ecosystem operation

As previously mentioned, the Southern Ocean has some particular characteristics that make it an ideal focus for modelling studies of large-scale marine ecosystems. Nevertheless, there remains a major challenge to develop models that explicitly and effectively integrate the multi-scale operation of the ecosystem. The relationship between the scale of operation of temporal and spatial processes in marine ecosystems has been recognised in analyses of the Southern Ocean (see Fig. 3) and will be a fundamental consideration in the development of integrated models linking local and circumpolar processes. The challenge for ICED is to develop the theoretical and strategic basis for bringing together models of different regions and/or trophic complexity to develop a hierarchy of models that operate at the scales appropriate for the process (or processes) under investigation (see deYoung *et al*., 2004; Speirs *et al*., 2004) for discussions of some of the major issues. The strategic modelling framework (see below) will require several approaches to address the many issues involved; formulating a multi-scale conceptualisation of how Southern Ocean ecosystems work and how they might be modelled. This will be a major goal during the initial stages of ICED.

Physical processes

Sub-decadal physical fluctuations are crucial in determining inter-annual to decadal dynamics of ecological systems and provide an important and tractable scale for examining ecosystem responses to physical variation (Bakun, 2004; McGowan, 1995). Understanding climate effects on Southern Ocean food webs will therefore require models that include large-scale physical interactions (atmosphere-sea and ice-ocean) and their connections with Southern Hemisphere climate related processes (e.g. the Antarctic Oscillation, the Antarctic Dipole, SAM and the ENSO). Clarification of the interactive nature of these physical processes is also required to allow the drivers of ecological change to be determined. Large-scale models do not generally capture the regional variation which will be crucial in determining the ecosystem responses. For example, dynamic sea ice models that provide realistic simulations at regional scales are needed to better understand biological responses to changing sea ice conditions. Similarly, accurate simulation of upper water column processes (e.g. stratification) and mixed layer dynamics are important for resolving circulation effects on biological distributions and potential changes to these that may occur due to climate variability.

Other Southern Ocean groups are currently undertaking detailed physical modelling. Links are already being made to these groups (see Linkages sub-section, p.25) and will be strengthened and expanded as the programme grows. ICED workshops will include representatives from the physical modelling community and in turn, ICED scientists will contribute to specific physical modelling workshops. These links will facilitate development, through ICED, of specifically targeted and tailored models relevant to the objectives. As a basis for ICED modelling efforts physical models are required that provide outputs relevant to the scales of operation of the biological processes under consideration, for example such models may include:

- Circumpolar scale atmospheric-sea and ice-ocean models;
- Coupled models for key regions of the Southern Ocean;
- High-resolution models of shelf and cross-shelf processes, island and frontal regions and sea-ice/ ocean processes in ice zones.

A number of other issues and points for consideration regarding physical models are outlined in Appendix III.

Biogeochemical processes

As with the physical processes, much of the biogeochemical model development in ICED will come through linkages and collaborations with relevant individuals and groups, particularly through IMBER (see Linkages sub-section, p.25). Issues of importance include (for more information see Appendix III):

- Coupling of circulation-biogeochemical models; sea ice-biogeochemical models and their use in conjunction with ecosystem models;
- Biogeochemical models including specific food web dynamics;
- Generic models to determine how ecosystem structure influences biogeochemistry.

Food webs

As noted above, in developing Southern Ocean ecosystem models it is important to understand the structure of the food webs and the food requirements of different trophic levels. Regionally different systems need to be accounted for in building a circumpolar approach. Identification of major and alternative food web energy pathways is a high priority of ICED. Attention must be given to the level of species aggregation or functional groups needed to resolve the dynamics of the systems. A range of approaches to food web representation will be required involving models with different spatial, temporal and trophic complexity (e.g. Steele *et al*., 2007).

Life cycles of key species

Models will also need to include the explicit operation of the life cycles of key species of plankton, fish, seabirds and marine mammals. This will require a focus on determining the critical life history stages and vital rates as well as the important physical-biological processes links that control population dynamics. The development of such models would allow, for example, studies of the effects of processes and strategies for over-wintering, as well as behaviour on distribution, abundance and production of different components of the food web. Particular attention is also required in the case of organisms with discrete life cycle stages that interact with the environment at different space and time scales, such as krill and copepods (Speirs *et al*., 2004). The development of detailed life history and behavioural models must be done in cooperation with experimental and field studies that will provide the basis for model parameterisations.

Ecosystem approach

There will be considerable emphasis within ICED to ensure that the integrated Southern Ocean models developed complement the work being undertaken by CCAMLR, and the IWC. Important aspects of these linkages will be to address the appropriate scales at which biological populations/meta-populations need to be managed, and to understand climate impacts. It is envisaged that this will work most efficiently as an ongoing and iterative process involving explicit consideration of the implications of model uncertainty on the delivery of management advice.

Strategic framework

The strategic framework for ICED modelling activities is focused around specific research areas that have been identified as key to furthering development of Southern Ocean models. These are summarised here and developing approaches for addressing these research areas is a major goal for the initial stages of ICED:

- The impact of climate processes on Southern Ocean ecosystems and the importance of ecosystem structure in determining responses and feedbacks;
- Coupled physical-biological simulations to examine the importance of ecosystem structure in biogeochemical cycles;
- Assessment of the extent to which generic models can be developed for regional sub-systems and the whole Southern Ocean ecosystem;
- Development of multi-scale model analyses of complete ecosystems;
- Development of basic models of the operation of Southern Ocean ecosystems to help characterise and quantify the uncertainty of parameter values, variables and assumptions required for development of management models;
- Development of models of the impacts, interactive effects and feedbacks of climate fluctuations and harvesting on Southern Ocean ecosystems and as part of the Earth System.

Methods–a strategic approach to modelling

Potential modelling approaches

Multiple approaches are required to address the many issues raised in previous sections; formulating a multi-scale conceptualisation of how Southern Ocean ecosystems work and how they might be modelled is a high priority for the initial phase of ICED. Approaches and methods for doing this will be fully explored through ICED model development workshops. To facilitate ICED model development, a cross disciplinary Southern Ocean ecosystem modelling community/expert Working Group will be formed by the ICED Scientific Steering Committee (SSC). Specific strategies, within the overall strategic framework, will be developed to address the programme objectives. This will occur primarily through workshops, expert consultation and links with relevant groups (see below).

Workshops

A series of ICED modelling workshops will be convened in collaboration with IMBER, the Global Ocean Ecosystem Dynamics programme (GLOBEC), the European Network of Excellence for Ocean Ecosystems Analysis (EUR-OCEANS), ICED during the International Polar Year (ICED-IPY), the Scientific Committee for Antarctic Research (SCAR), CCAMLR and the Scientific Committee on Oceanic Research (SCOR) and other relevant groups. In the early phases of ICED, the strategic modelling framework will be developed, through expert consultation based on the Science Plan and outcomes of the first modelling workshop.

The initial priority, to take place during ICED-IPY, is to convene a modelling workshop focusing on food web structure and operation. A multidisciplinary group of experts will convene to bring together end-to-end and regional understanding of Southern Ocean food webs as a first step towards building circumpolar ecosystem models. Assessing the appropriate spatial, temporal and trophic resolution required for Southern Ocean models will be a particular focus.

The workshops will provide a forum to discuss, develop, standardise and evaluate approaches to modelling and take new ideas forward. They will involve early career scientists as well as experts from a broad range of relevant disciplines. Potential themes for workshops are most likely to include (this list is by no means definitive or exhaustive and serves as a guide at this stage):

- Models of Southern Ocean food webs: advantages and limitations of generic views;
- Linking lower- and upper-trophic levels in models of marine ecosystems: ecosystem structure and biogeochemistry;
- Modelling ecosystems-linking processes at different scales of space and time;
- Coupled sea-ice-pelagic biota/biogeochemistry models;
- Ecosystem structure and climate: impacts, interactions and feedbacks, including genetic variability;
- Ecosystem models and operational ecosystem models for management: linking reality and pragmatism;
- Ecosystem modelling for field studies;
- Statistical modelling of distribution and abundance of key species in relation to environment and ecosystem structure;
- Circumpolar operation of Southern Ocean ecosystems;
- Application of data assimilation to improve parameterizations, parameter values, and model structure.

Papers and reports

Model development will be initiated through the first in a series of model workshops as outlined above. Key outcomes from the workshops will include peer-review papers and reports to highlight priority research issues and guide the international scientific community in taking Southern Ocean ecosystem modelling forward. A series of ecosystem and model review and synthesis papers are envisaged throughout the programme; including consideration of the current status of Southern Ocean modelling and the appropriate ways forward.

Evaluation and integration

Throughout the development of the ICED modelling there will be continual linkages to the fieldwork and data analysis activities in order to direct those activities towards the main questions raised by the modelling. This emphasis on continual testing, standardisation and evaluation of models will ensure that ICED delivers an integrated product that benefits from the breadth of knowledge available within the entire Southern Ocean science community.

Linkages–an ICED modelling community

Establishing a cross disciplinary Southern Ocean ecosystem modelling Working Group is a priority for ICED. This group will include relevant expertise from the physical, biological, geochemical and climate disciplines. ICED will bring together scientists with different expertise to special topic workshops (see above). The involvement of students and postdoctoral researchers in these workshops will also be encouraged.

ICED models will build on results from past and ongoing programmes, such as the JGOFS regional test bed study (Friedrichs *et al*., 2007), which will help in the development of structures and clarify the degree of complexity needed in biogeochemical and food web models for the Southern Ocean. ICED envisages contributing to and complementing CCAMLR's role in the ecosystem approach to sustainable resource management. The interaction between CCAMLR, IWC and ICED has the potential to facilitate and accelerate the development of these models to provide a stronger basis for sustainable management of Southern Ocean resources.

Forging links with the physical modelling community is another important requirement for ICED. ICED has already established links with groups such as Climate Variability and Predictability (CLIVAR), Climate and Cryosphere (CliC), Southern Ocean Observing System (SOOS), Southern Ocean Physical Oceanography and Cryospheric Linkages (SOPHOCLES) and the National Oceanic and Atmospheric Administration (NOAA) Climate Process Team. Indeed, development of all modelling approaches relevant to the ICED programme will be encouraged and are a priority for the IPY phase of ICED. Links with Climate of Antarctica and the Southern Ocean (CASO), the IPY project Bipolar Atlantic Thermohaline Circulation (BIAC-IPY) and the SCAR-Oceanography Expert Group will be particularly important in this regard. A wider network of physical and biological monitoring of oceanic systems is required to provide data for the robust development and testing of large-scale models. This will be achieved in conjunction with SOOS through more extensive measurement networks. ICED will also collaborate with the joint SOLAS-IMBER and International Carbon Coordination Project-Global Carbon Project (IOCCP-GCP) groups with a particular focus on the development of biogeochemical-ecological models. ICED will connect to groups such as Ecosystem Studies of Sub-Arctic Seas (ESSAS) to ensure that we aware of relevant Arctic modelling developments. A vital requirement of the ICED programme is to connect with groups working on global models to ensure that the Southern Ocean is correctly represented. The establishment of the ICED modelling group will bring in perspectives from other regions (e.g. via representatives from the GLOBEC and IMBER modelling communities, amongst others), ensuring a global perspective. The links made will be two-way relationships with ICED members being represented at workshops and in key collaborations with other relevant scientists and groups.

Summary of ICED model development plans

- A coordinated approach is required to advance Southern Ocean ecosystem modelling studies. In particular, integration of knowledge from research activities of groups focused on different aspects and regions of the Southern Ocean system is needed. Formation of a multidisciplinary Southern Ocean ecosystem modelling community expert Working Group is a priority for ICED;
- A strategic framework for ICED modelling will be developed which will include aspects of integrating the modelling work with field and data studies. This is outlined above, with additional details in Appendix III. The ultimate goal is the development of a circumpolar view of the operation of Southern Ocean ecosystems;
- The modelling work will be organised around the three ICED objectives with the following structure (leading eventually to integrated circumpolar models that link Southern Ocean models to Earth System models):
  - » models examining how ecosystem structure (including physical processes) influences responses to perturbation and change;
  - » models examining the influence of ecosystem structure on biogeochemistry;
  - » models to complement the development of management models by CCAMLR.
- A range of approaches involving workshops, timely publication of peer-reviewed scientific papers and reports, and establishment of a Southern Ocean ecosystem modelling community will be required;
- Ensuring that Southern Ocean modelling activities are undertaken in conjunction with global efforts, including those of GLOBEC and IMBER will be crucial.

Historical data synthesis

Background to historical data synthesis

Research over almost a century across wide geographical areas in the Southern Ocean has generated extensive data series for many aspects of marine system operation. A number of these individual datasets are now sufficiently extensive (>20 years duration) to start providing information on changes to ecosystem structure and function (e.g. demographic changes in predator populations described by Trathan *et al*., 2007b). Other individual datasets may not by themselves have sufficient temporal or spatial coverage to investigate long-term or large-scale changes; however, in combination they are able to provide unique insights, such as the revised view of the circumpolar distribution of krill (Fig. 14). Some physical and chemical data have been compiled and integrated analyses have been undertaken (e.g. Olbers *et al*., 1992). This has produced circumpolar maps of physical and chemical properties that can be used in the analyses of circumpolar ecosystem operation (e.g. the Hydrographic Atlas of the Southern Ocean; Olbers *et al*., 1992). Classification of habitat based on this type of data has begun (Grant *et al*., 2006) and will aid circumpolar analyses of the major controls on ecosystem structure and operation.

Historical datasets exist in a wide range of formats including original notebooks, individual data holdings and fully accessible electronic databases. All these different datasets are held at an individual, institutional, national or international level. Together they provide a valuable resource that has yet to be fully catalogued and utilised. The value of historical data syntheses is illustrated by the success of projects such as the History of Marine Animal Populations (HMAP) project which forms part of the Census of Marine Life (CoML) and the EUR-OCEANS Data Rescue Programme in which ICED is participating. The analysis of existing data using modern techniques and from new perspectives not only adds value to modelling initiatives but also ensures safe custody of, and access to, irreplaceable historical data. The ICED programme attaches a high priority to integrating existing datasets to enable investigation of long-term, large-scale ecosystem functioning, variability and change across the Southern Ocean. Focusing effort on identifying and developing access to such historical data archives, particularly those that can be used for validation, calibration and development of ICED models, will be an important task in the implementation of ICED.

The report of the first ICED workshop (Murphy *et al*., 2006) highlights a number of potential areas of focus for historical data synthesis; these areas are briefly discussed below.

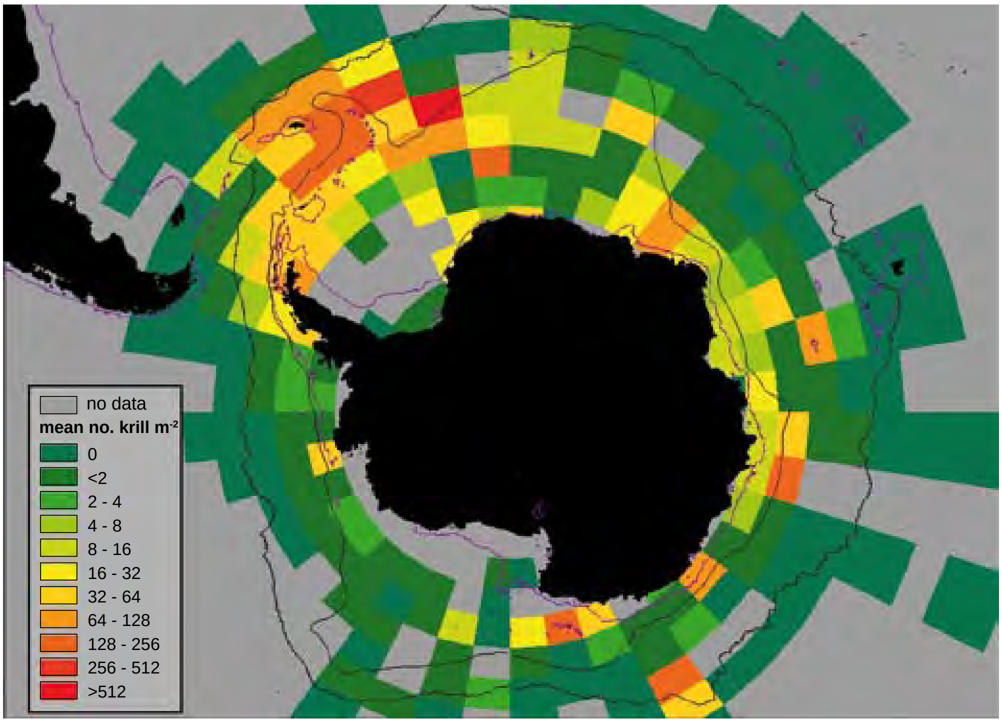


Figure 14. Mean density of postlarval Antarctic krill (*Euphausia superba*) in summer (updated from Atkinson *et al*., 2004). This plot is based on KRILLBASE, a historical database compiling all available net sample data for 1926-2004, standardised to a common sampling method. Source A. Atkinson, British Antarctic Survey.

Priority areas for data activities

Historical data synthesis activities are considered an essential and major component of the ICED programme. The following outlines just some of the areas where historical data syntheses are likely to have an important role in addressing issues fundamental to the ICED objectives. A more complete set of examples can be found in Appendix IV.

Key physical processes affecting the Southern Ocean

There is a need to better understand the regional and circumpolar response of the physical characteristics of the Southern Ocean to variability and change in climatic forcing. In particular, the role of sea ice and complex feedbacks with the cryosphere should be investigated. Some syntheses of long-term physical data have been undertaken generating important insights (e.g. Meredith and King, 2005; Murphy *et al*., 1995; Parkinson, 2002). However, developing circumpolar coverage is necessary, and retrieving data from studies through areas where least is known, such as the Bellingshausen Sea sector, is also considered important. A suite of consolidated, verified and integrated atmospheric, oceanographic and sea ice datasets would be extremely valuable in determining forcing, feedbacks and interactions.

Effects of interactions between physical and biological processes on nutrient dynamics and biogeochemical cycles in the Southern Ocean

- *Primary production*

Phytoplankton production is heterogeneous in the Southern Ocean, and often considered to be dependent upon the interaction between light and nutrient limitation, especially iron. Recent studies (e.g. Bertrand *et al*., 2007) have also shown the potential co-limitation of phytoplankton growth by vitamin B12. This potentially introduces additional complexity into the modelling of phytoplankton growth in the Southern Ocean as the supply and cycling of vitamin B12 is highly dependent on ecosystem processes. Environmental time-series data from remote sensing studies are now extensive, and as a result, inter-annual variability can be used to investigate some of the various controls on primary production. However, ship-based compilations of primary production and size-fractionated chlorophyll *a* data will be important for validating and calibrating remote sensing techniques and in providing some insights into primary production processes. Integration of compiled field data with ocean advection models will also be necessary to determine the physical-biological interaction effects that are important in the development and horizontal fate of blooms.

- *Mesopelagic zone*

Further information is needed to determine the potential of the mesopelagic zone as a sink (both magnitude and spatial extent) for organic matter, and to link this with mesopelagic community composition, not least to improve biogeochemical modelling capabilities in further understanding Southern Ocean ecosystem responses to climate change. Only limited data are currently available for this zone and retrieval of additional datasets for synthesis would be beneficial.

Structure and dynamics of Southern Ocean ecosystems

- *Regional habitat and community types*

Existing definitions of habitat and community type in the Southern Ocean are based on a series of concentric rings–e.g. the Seasonal Ice Zone (SIZ), the Antarctic Zone, the Polar Frontal Zone (Treguer and Jacques, 1992)–that do not account for major sector-based differences in productivity, such as those between the SIZ of the productive Atlantic and the unproductive southeast Indian sector. To improve our understanding, considerable effort is required in order to link numerous spatial databases from oceanography to higher trophic level predators. Such data integration would greatly improve our existing definitions of habitat and community types, but this will not be a simple mapping exercise. For example, the large upper trophic level predators may be important components of particular habitat types, but they often move between locations. This will require specific consideration of habitat definition at different trophic levels and how to link analyses across scales. Linking predator data and food web community data to other international programmes, such as the Ocean Biogeographic Information System-Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP), would facilitate analysis of their distributions in relation to satellite-observable features (e.g. eddies, ice edge and chlorophyll *a*). This type of whole ecosystem data integration would be a fundamental advance with wide implications, for example, in the context of fisheries management. A workshop was recently held to begin bioregionalisation of the Southern Ocean by dividing it into distinct spatial regions using a range of environmental and biological data (Grant *et al*., 2006). ICED fully recognises the importance and relevance of this work and will link closely with it.

• *Zooplankton life cycles*

Historical data synthesis of zooplankton life stage distribution and rate processes have provided critical insights into life cycles, in ways that are not possible from single field studies (e.g. Atkinson *et al*., 1997; Hirst and Bunker, 2003; Hirst and López-Urrutia, 2006; Tarling *et al*., 2004). Some effort has already been focused on copepod, krill and salp life cycles. Further work such as compilation of length-frequency data, and data from growth models, would be invaluable in improving life cycle predictions and defining population structure. There are extensive data on a wide range of zooplankton species in national and international databases. Developing syntheses of these data would be extremely relevant for ecosystem and biogeochemical studies. The geographical and historical scope of these data means they would also be useful in developing habitat definitions (see above), analyses of long-term ecological change, and in providing an important basis for development and validation of zooplankton life cycle models.

• *Predator-based indices*

A range of ongoing, long-term studies have been used to determine predator responses to environmental fluctuations. The analyses could be further enhanced, for example, by undertaking combined analyses with CCAMLR using their CEMP data. Extending these studies to include data on diet, foraging and detailed demographic and environmental data (e.g. satellite derived SST, sea ice extent and concentration) will also be important.

Southern Ocean ecosystem structure and dynamics in the context of sustainable management plans

Links with CCAMLR to explore CEMP and commercial fishery data in the context of sustainable management plans will be important. Fisheries data are particularly valuable in providing information where independent research data are lacking or insufficient.

Circumpolar models (predicting ecosystem response to climate change and harvesting)

Results from historical data synthesis will provide information for model parameterisation and validation (see modelling section above), and will highlight gaps for focusing future field activities (Fig. 9).

Methods for data synthesis

A data Working Group will be convened to further consider and develop priority areas, and devise plans for data mining, quality control, aggregation and analyses.

The following methods are amongst those envisaged:

- Linking existing datasets/databases

  This will involve linking datasets that are already operational (e.g. the relational database generated from the international BIOMASS programme (El Sayed, 1994)). This will include converting data formats, re-projecting data and harmonising datasets. Satellite-based data have yet to be used to their full potential for linkage with other datasets (i.e. with numerically-based spatial analysis);

- Locating and integrating existing data to compile working datasets

  This will involve data request and extraction from old logbooks, databases, etc, together with checking, reconfiguring, linking or merging of files (electronically or manually). For example, a EUR-OCEANS funded project (involving collaboration with ICED) to locate zooplankton datasets and produce Geographic Information Systems (GIS) summary maps has recently been initiated (Tancell and Cunningham pers. comm., 2007). Datasets that could be utilised include archived hardcopy datasets held by institutes in Russia and those resulting from the Discovery Investigations;

- Re-analysing historical samples

  This will involve the re-analysis of specimens (e.g. from plankton catches) that have not been fully analysed. The ICED Data Working Group will need to devise focused questions and conduct prior checks on sample condition and availability.

It should be noted that syntheses of the datasets should include production of maps (GIS based) and the use and development of statistical methods for ecosystem structure analyses (typology, structural network, inverse modelling, etc.) in a spatial context. Bioregionalisation of the Southern Ocean has begun (Grant *et al*., 2006), furthering our understanding of spatial ecosystem characteristics in the region and with a wide range of applications including ecosystem modelling and management.

Data sources

Appendix IV lists data sources that are likely to be important for historical data synthesis activities in addressing the ICED objectives.

Data management

ICED will develop a data management policy under the guidance of IMBER and GLOBEC. A draft of the principles is included in Appendix V. This will be refined and published in due course on the ICED website. This ICED Data Policy (Appendix V) is intended to facilitate the full exploitation of data resources available to the programme, whilst respecting the intellectual property rights of contributors and reducing duplication of fieldwork and research effort. The term 'data' includes raw and processed field and laboratory data and model output. ICED may also record information to facilitate the simultaneous development of models by ICED partners, such as model code components.

Linkages–an ICED data community

ICED intends to work closely with data management teams from related projects to ensure inter-operability of datasets where possible. Significant value will be added to data mining and syntheses by linking and collaborating with other programmes at national and international levels in different parts of the ocean science community. As an example, linking predator data and food web community data to other international programmes, such as OBIS-SEAMAP, would facilitate analysis of their distributions in relation to satellite-observable features (e.g. eddies, ice edge, chlorophyll *a*).

Amongst many others, ICED activities will form an important contribution to, for example, the Census of Antarctic Marine Life programme (CAML), CLIVAR, SOLAS, IOCCP-GCP, SCAR-Marine Biodiversity Information Network (SCAR-MarBIN) and the Global Ocean Observing System (GOOS). In addition, ICED will promote linkages with other long-term international programmes operating in the Southern Ocean, such as CCAMLR and IWC, to share historical data and to achieve goals of importance to each programme. The ICED Data Working Group will also integrate its activities within the programme with those of the modelling and fieldwork groups. For example, modelling efforts will benefit from the compilation and synthesis of existing datasets to produce circumpolar, biological distributions for model initialisation, calibration and verification (see integration section below).

Summary of ICED data activity plans

- Developing access to historical data archives will be an important activity for ICED;
- An ICED Data Working Group will be convened to consider available data and develop priority focus areas;
- The ICED Data Policy outlined in Appendix V will be applied through the ICED Data Working Group which will oversee all aspects of ICED data management;
- Development of circumpolar maps of biogeochemical and biological distributions will be a key activity;
- Data syntheses will be an important component of all aspects of ICED research and will be addressed by each of the implementation activities.

Fieldwork coordination and development

Background to fieldwork coordination and development

The existing and planned field activities of national and international programmes represent a major effort and commitment to address a wide range of scientific issues in the Southern Ocean. Many of these build on the programmes mentioned in the Historical context section (p.4) and range from studies on the effects of climate on upper ocean physics and the role of iron on ecosystem structure and biogeochemical cycles, to the abundance and dynamics of key mid- and upper-trophic level species such as krill, penguins and seals. These activities will utilise a range of fieldwork platforms and equipment and will, in many cases, be focused on a specific part of the ecosystem. It is likely that a field study of biogeochemistry may not include detailed specification of parts of the ecosystem larger than zooplankton; equally a study of cetaceans may not expressly concern itself with iron concentration. Some studies may only require ship-based fieldwork and others will operate from land-based facilities. There will also be integrated studies that use a combination of platforms in order to characterise the interactions of biogeochemistry and ecosystems from end-to-end. In addition, observing systems are being increasingly developed, utilising automated approaches combined with remote measuring and communication systems such as moorings, gliders, floats and autonomous underwater vehicles. These technologies vastly increase the potential to collect in situ data for combination with satellite data and that measured directly by scientists in the field.

Southern Ocean fieldwork is currently in the spotlight due to the IPY (2007–08) with over 200 projects being conducted in the Polar Regions. These involve thousands of scientists from over 60 nations examining a wide range of physical, geochemical, biological and social research topics (http://www.ipy.org). ICED leads the IPY consortium Ecosystems and Biogeochemistry of the Southern Ocean (see below). Despite all these activities, this remote region is logistically difficult to work in, particularly during the winter, and as such is one of the least sampled regions on Earth. Ensuring that field activities are planned and undertaken in such a way as to facilitate their integration is a huge challenge requiring the cooperation of groups operating throughout the Southern Ocean. Such cooperation is necessary to achieve improved geographical coverage of the Southern Ocean, streamlining of scientific objectives, integration of physical, biogeochemical and ecological processes, identification of key gaps, and effective future planning. The interest in comparative studies with the Arctic Ocean is another factor to consider. The main role of ICED in this early phase will be to facilitate improved fieldwork coordination to address these issues and the gaps in knowledge identified through historical data analysis, IPY activities and modelling; and to maximise subsequent international efforts to begin to fill the gaps.

Priority areas for fieldwork coordination and development

During the programme's early phases, ICED will improve the integration of existing and planned field studies; an activity considered of high priority since several field efforts are planned simultaneously across the same areas. This includes increasing the promotion of cross-cutting science activities and the exchange of personnel, expertise, methodology, data and equipment, in order to maximise the standardisation of field data. This should increase the efficiency and scientific value of integration of the outcomes of the individual programmes. These fieldwork efforts will be an integral part of the parallel initiatives of data syntheses and model development (see above and Fig. 9).

Existing field activities broadly encompass the various biogeographic areas of the Southern Ocean but national programmes often target restricted geographical regions such as the Antarctic Peninsula, Scotia Sea, Weddell Sea and Ross Sea. A particular focus of ICED will be ensuring that there is an international field effort to provide improved geographical coverage of the Southern Ocean, both coastal and open ocean areas. This will be facilitated by increasing the use of satellite data and by remote instrumentation. Remote instrumentation will include both fixed location devices, such as oceanographic moorings or penguin weighbridge/logging devices, and those on mobile platforms, such as animal-borne devices and oceanographic drifters.

In terms of planning future field efforts, regions that have been the focus of a number of national and international efforts during the last decade (such as the East Antarctic sector: (Nicol *et al*., 2004), and proved of significant interest, will continue to provide data critical for synthesis and modelling. Other regions, which have received much less attention (such as the Pacific sector from the Ross Sea to the west Antarctic Peninsula, and many of the more open ocean areas) and for which data on ecosystem dynamics are lacking, should be the focus of future coordinated field efforts.

The development of circumpolar genetic studies of key species, including krill, copepods, fish, seabirds, seals and whales, to determine genetic diversity and the potential for adaptation to environmental change will also be enhanced through improved fieldwork coordination through ICED.

Priority areas are thus:

- Improved circum-Antarctic integration of land-based and pelagic studies during and subsequent to the IPY period;
- Coordination and integration of fieldwork across major sectors where fieldwork is currently conducted;
- Planning and delivering new fieldwork in important regions that are currently data poor, including open ocean areas;
- Enhanced use of satellite and remote instrumentation;
- Development of circumpolar genetic studies.

Phases of fieldwork coordination and development

ICED fieldwork will be based on the main ICED objectives (see above) and focused on multidisciplinary interactions rather than any single discipline. Two phases of fieldwork are currently envisaged for ICED: 1) Coordination of a series of Southern Ocean research cruises during the IPY and continued development of existing activities along well-defined transects in order to collect biological, biogeochemical and physical information; 2) Process-oriented studies following IPY that will focus on particular systems the comparisons of which will allow further insights into the mechanisms controlling biogeochemical cycles and ecosystem structure. A planning workshop will be a useful first step in identifying key spatial/process knowledge gaps to focus and structure the field components of the ICED programme following the IPY phase.

Phase 1: ICED-IPY

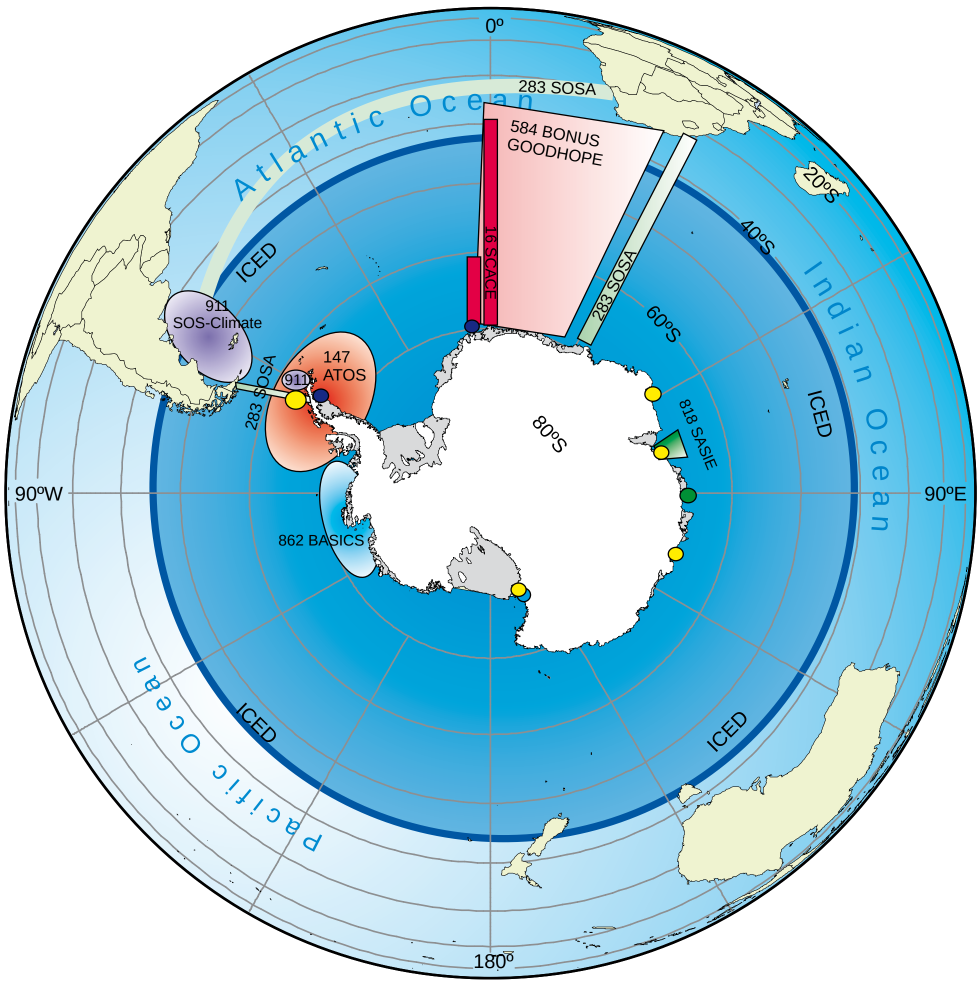
ICED submitted a proposal for IPY that became officially endorsed as ICED-IPY, and is coordinating nine IPY projects grouped within an assigned consortium entitled Ecosystems and Biogeochemistry of the Southern Ocean (see Fig. 15 and Appendix I for further details). To broaden the scope beyond this consortium, ICED-IPY is also linking to many other relevant IPY programmes (see Linkages sub-section p.36).

Within the ICED-IPY consortium, a number of research cruises and other field activities are planned or underway (Fig. 15). This information has been made centrally accessible via an interactive map on the ICED website (http://www.iced.ac.uk). This is the first in a series of maps through which ICED will build visual representations of Southern Ocean ecosystem and related activities. These maps will depict relevant Southern Ocean fieldwork (existing and planned), providing links to the project homepages, databases and contacts. It is envisaged these maps will be used as online tools by related groups; increasing the wider-reaching effects of field efforts, addressing gaps in coverage and knowledge, and promoting collaborations. The maps will form the basis for the development of coordinated field activities towards achieving the ICED objectives.

Phase 2: ICED fieldwork following IPY

Following IPY, ICED will be in a position to plan, execute and coordinate process studies within key regions. Field planning workshops after IPY will benefit from parallel developments in data synthesis and modelling (see above). These workshops will consolidate the outcomes from IPY field activities, and focus and structure the next phase of ICED fieldwork. A field planning Working Group should also be established.

This section refers to plans for ICED to develop fieldwork following IPY. It is beyond the scope of this document to set out a specific fieldwork plan in terms of exact locations and science. This will be developed in due course based on consolidation of IPY outcomes and expert opinion (including those from the modelling and data aspects of ICED) as noted above.



KEY

Numbers = IPY project number
Sectors and zones = oceanographic study areas
Circular symbols = field station or dive sites

16	SCACE	Synoptic Circum-Antartic Climate-processes and Ecosystem study Dr Volker Strass, AWI, Germany
147	ATOS	Atmospheric inputs of organic carbon and pollutants to the polar oceans: rates, significance and outlook. A Spanish component of the OASIS programme
232	CLIMANT	Climate change in Antarctica: A pelagic-benthic coupling approach to the extremes of the Weddell Sea. Dr Enrique Isla, Instituto do Ciencias del Mar, CSIC, Spain
283	SOSA	Physical and biogeochemical fluxes in the Atlantic Sector of the Southern Ocean during the IPY (Southern Ocean Atlantic Box SOSA). Contribution to CASO Dr Brian King, SOC, UK
406	$CaCO_3$	The potential decline in rates of $CaCO_3$ accretion and primary productivity in cold waters due to elevated CO_2 content Dr John Runcie, University of Technology, Sydney, Australia
584	BONUS-Goodhope	Biogeochemistry of the Southern Ocean: interactions between nutrients, dynamics and ecosystem structure Dr Marie Boye, Laboratoire des Sciences de l'Environnement Marin (LEMAR), France
818	SASIE	Study of Antarctic Sea Ice Ecosystems Dr Igor Melnikov, Moscow, Russia
862	BASICS	A year-round study of Antarctic Sea Ice Biogeochemistry (Biogeochemistry of Antarctic Sea Ice and the Climate System) Prof Jean-Louis Tison, Universite Libre de Bruxelles, Belgium
911	SOS-Climate	Southern Ocean Studies for Understanding Global Climate issues

Figure 15. Map of approximate fieldwork locations for projects within the ICED-IPY consortium Ecosystems and Biogeochemistry of the Southern Ocean. The sectors and zones represent oceanographic study areas and the circular symbols represent field stations or dive sites. This map is interactive if accessed via http://www.iced.ac.uk. Note that ICED links to numerous other relevant projects; this map depicts only those within the consortium assigned by IPY, and is the first in a planned series of maps representing Southern Ocean ecosystem field activities (see main text and Appendix 1). Source C. Tancell, British Antarctic Survey.

Recommendations from the ICED science planning workshop (Murphy *et al*., 2006) are that potential priorities for ICED fieldwork post IPY should include:

- A comparison of the current end-to-end characterisation of the ecosystem at locations where sea ice is increasing or decreasing in both extent and duration;
- A comparison of the neritic system, where there is marked bentho-pelagic coupling (especially over shallow banks), and a deep shelf/slope system;
- Biogeochemical processes and ecosystem structure of a polynya-dominated system compared to a system with no major polynyas;
- An examination of the potential role of top-down and bottom-up forcing through a comparison of a system that has been substantially altered by harvesting and a system with little historical exploitation.

Discussions at the ICED Science Planning Workshop (Murphy *et al*., 2006) highlighted four regions that would potentially benefit from major efforts to harmonise study approach and techniques, share resources, personnel and equipment (Fig. 16). The regions, described in more detail below, reflect the assessment of priorities during the ICED workshop (Murphy *et al*., 2006). ICED is a circumpolar oceanic (with a focus on the pelagic) ecosystem programme. The regions of focus will be subject to re-assessment and revision as the programme develops and relevant factors are considered in tackling the ICED objectives. ICED will welcome input from individuals and groups in determining priorities and strategies. We include these four highlighted regions as examples below to illustrate potential areas, scope and focus:

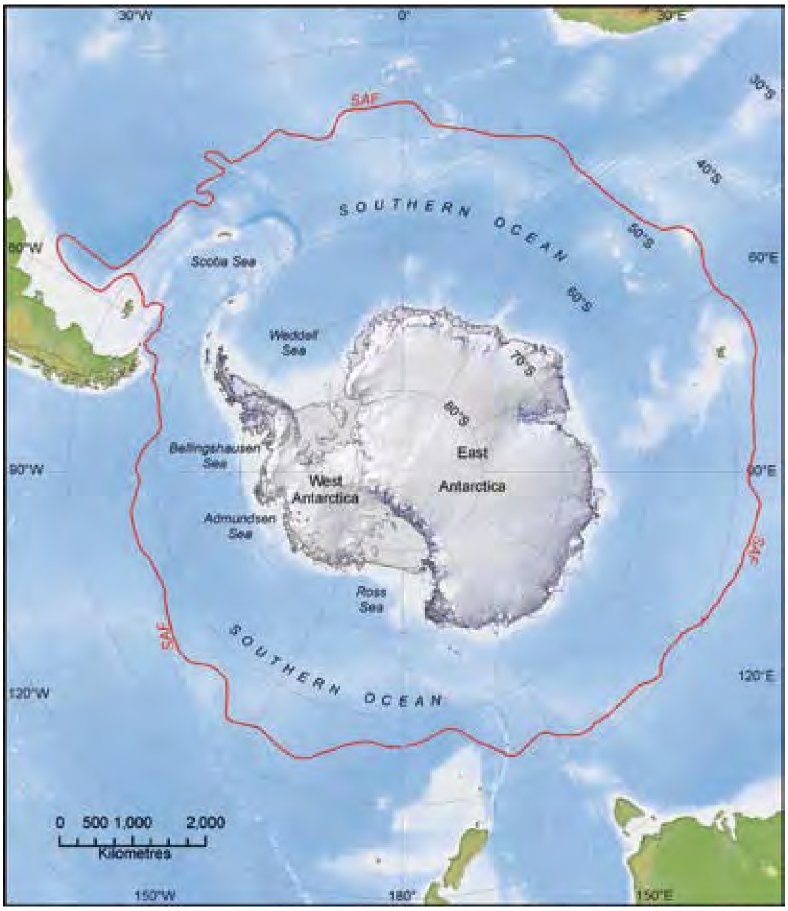


Figure 16. Four areas of the Southern Ocean (Scotia/Weddell Seas; Amundsen/Bellingshausen Seas; Ross Sea and East Antarctica) were highlighted at the ICED workshop as suggested priorities for field efforts. Proposed activities include: improving coordination and integration of fieldwork in areas where detailed studies are currently occurring (e.g. Ross Sea); investigating areas that are data poor (e.g. Amundsen/Bellingshausen Seas); and conducting comparative studies across these areas. The regions reflect the assessment of priorities during the ICED workshop. ICED is a circumpolar pelagic and coastal ecosystem programme and is by no means limited to these areas. They are included here as examples and will be subject to re-assessment as the programme develops. ICED is concerned with research throughout the Southern Ocean, defined here as the area encompassing the Antarctic Circumpolar Current (ACC) and regions to the south. This map shows the Subantarctic Front (SAF), considered to be the northern boundary of the ACC for this purpose. Source P. Fretwell, British Antarctic Survey.

Suggestions for potential process studies

- *Amundsen-Bellingshausen Seas (ABS)–80° to 140°W*

As there are so few data from this region, it was suggested that it could be a focus of process-oriented studies to investigate the extant food web and the potential changes induced by regional or global climate change. The ABS is the site of a CLIVAR transect and is being affected by regional climate change. Such changes are especially rapid around the west Antarctic Peninsula, but the gradients in changing air temperature (Vaughan *et al*., 2003), winter sea ice duration (Parkinson, 2002), and water temperature (Meredith and King, 2005) extend into the ABS. At the west Antarctic Peninsula these changes are affecting the population dynamics of krill and the fish *Pleuragamma*, which in turn affect the reproductive success of Adélie penguins (Fraser and Hofmann, 2003). There is reason to suspect that similar changes are occurring in the ABS region, but this area has received little attention to date. The ABS is also known to have direct linkages to globally significant perturbations such as ENSO events. Therefore, understanding the ecosystem responses to long-term climate-induced changes as well as shorter-term impacts would lead to a more complete understanding of the temporal variability and its driving forces.

- *Ross Sea–150° to 170°E*

This has been the site of much biogeochemical research in the past 15 years (e.g. JGOFS and Research on Atmospheric Variability and Ecosystem Response in the Ross Sea–ROAVERRS), and a substantial database exists on its hydrography, currents, nutrient and chlorophyll *a* distributions in both space and time (Dinniman *et al*., 2003; Smith *et al*., 2003). Parts of the Ross Sea have also been the location of extensive studies on the food web, including higher-trophic levels (e.g. Ainley *et al*., 1995; Smith *et al*., 2007; Wilson *et al*., 2001). The Ross Sea would provide an excellent comparison to the west Antarctic Peninsula. Critically, the Ross Sea is apparently changing almost as much as the west Antarctic Peninsula but ice cover is increasing here rather than decreasing (Gloersen *et al*., 1992; Stammerjohn *et al*., 2008). Increased ice concentration is predicted to alter primary production and energy transfer within the food web but the direction of such changes is unclear. It has been suggested (Arrigo *et al*., 1998) that increased stratification might initiate a shift in phytoplankton assemblage composition, which would in turn alter the biogeochemical cycles. Such changes would also be expected to have dramatic food web consequences. The Ross Sea is also impacted by ENSO events but to a lesser degree than in the ABS. Finally, the Ross Sea has not been subjected to the same level of harvesting across the different elements of the food web as the west Antarctic Peninsula-Scotia-Weddell Seas area has over the last 200 years.

- *East Antarctica–0° to 150°E*

Unlike the other three regions, East Antarctica is more clearly representative of the classic latitudinally-zoned ecosystems of the Southern Ocean described by Tréguer and Jacques (1992). This area comprises nearly half of the longitudinal extent of Antarctica, but is not punctuated by the huge embayments and peninsulas as in the Ross Sea or the Antarctic Peninsula regions. These latitudinally-zoned regions, albeit with some longitudinal variation (Nicol *et al*., 2004), provide the necessary comparison with the other areas. East Antarctica is a region where recent changes in ice concentrations are not apparent, and it has been hypothesized that it is more directly impacted by increases in the circumpolar wind field, which would in turn increase the velocity of the ACC. More recent studies have suggested that the effects of a changing wind field will be complex, generating changes in eddy activity (Meredith and Hogg, 2006). The ecosystem has been studied recently but not all components have been studied over sufficient spatial and temporal scales. ENSO-related effects are apparently weak in this area. Comparative field studies in this sector, with approaches harmonised to those in the other three regions, would further our understanding the role of climate change (as mediated by ice) on ecosystems of the Southern Ocean.

- *West Antarctic Peninsula–Scotia-Weddell Seas–10° to 70°W*

This is a large and important area and the reasons for suggested focus here are several, not least because it is changing substantially through regional warming. There are major differences in ecosystem dynamics within the region. The Scotia Sea region is one of the most productive oceanic areas of the Southern Ocean with consistently large diatom blooms making it an ideal region for analyses of biogeochemical cycles. This area is also considered to be one of natural iron fertilisation associated with the flow of the ACC over the rugged bathymetry of the Scotia Arc providing an important contrast with much of the rest of the oceanic ACC where iron levels are naturally very low. Further south, within the Weddell Sea, the dynamics are more complex: primary productivity is generally low but there is a lot of variation associated with the annual formation and retreat of sea ice which has major consequences for the food web dynamics. The Scotia Sea region is also the site of a number of long-term investigations of krill dynamics that will be a good basis for developing ICED studies. Together with the consistently studied extensive predator populations, these factors make the region ideal for studying the links between climate, biogeochemical and ecosystem processes. This region has been affected by the historical harvest of seals and whales; it is where the greatest current fishing effort occurs; and, where the CCAMLR ecosystem-based approach to management is most advanced.

- *Open ocean sampling*

The Southern Ocean is vast, remote, logistically difficult to access (particularly during winter months) and one of the least sampled regions on Earth. The need for open-ocean studies in understanding the major questions in marine ecosystem processes is widely acknowledged, not least to provide data for the robust development and testing of large-scale models. Enhancing the measurements undertaken on standard ocean transects and base supply tracks will be a focus of ICED. A wider network of multidisciplinary monitoring of oceanic systems is required. ICED is a focal point in the development, implementation and utilisation of a circumpolar network of remote measuring and communications in the Southern Ocean, particularly in collaboration with SOOS. The SOOS is currently being developed to address the challenge of developing comprehensive coverage of this remote ocean. This will be achieved by utilising a diverse array of tools and methods, including oceanographic moorings, profiling drifters such as Argo floats, operations by ships and from bases. Physical, biological, optical and meteorological sensors deployed on marine mammals will supplement these measurements.

- *Links and comparative studies*

The fieldwork required to elucidate the links between physical processes, biogeochemistry and ecosystem structure and dynamics in the Southern Ocean will be a combination of region-specific and circumpolar efforts. Studies in key regions need to be linked together to build a more coherent picture. In those regions where extensive historical datasets exist, such as the Ross Sea and the west Antarctic Peninsula, Scotia and Weddell Seas, it may be possible to address very specific issues, for example, what environmental elements of the marine system are the principle drivers of top predator distribution and abundance? In the other regions, especially in the Amundsen-Bellingshausen Seas, it may be necessary to focus efforts towards providing a more general characterisation of the biogeochemistry and ecosystem of the region.

Existing fieldwork conducted under national programmes is already providing many of the datasets for comparative studies, with sites around Antarctica encompassing the complete spectrum of ecosystems: from the sub-Antarctic islands in the north down to the continent in the south (Hunt and Hosie, 2005). A priority of ICED is therefore to provide a link between these existing programmes and a common analytical resource, based on circumpolar datasets on environment and distributions of key species. ICED will also focus on expanding the current scientific capacity of long-term ecosystem monitoring programmes to utilise remotely deployed physical, chemical and biological monitoring instrumentation, much of this will be achieved in close collaboration with SOOS and related programmes (see below).

- *Genetic studies*

ICED encourages the development of a series of circumpolar genetic studies of species of krill, copepods, fish, seabirds, seals and whales to determine genetic diversity and the potential for adaptation to environmental change. Understanding the genetic variability of sub-populations within their circumpolar populations is crucial to the development of predictive models of ecosystem dynamics. Technological and analytical improvements to the efficiency of genotyping procedures (allowing the production of multi-locus molecular datasets for 1000+ individuals) are facilitating such studies. Such large datasets will provide the fullest possible insights into population structure and history for effective management and conservation strategies for Southern Ocean species. They will enable the genetics of co-occurring species to be compared, and allow a community-based approach to exploring distribution and diversity. Our understanding of the potential for Southern Ocean species to adapt to periodic or long-term changes in their environment will also be taken to a new level through such work. Such large-scale goals are best achieved through communication and cooperation between research institutes, for which ICED can play an important role.

Linkages–through fieldwork activities

The IPY is providing an unparalleled opportunity for polar researchers to forge new and multidisciplinary links between individuals, projects and programmes. ICED is coordinating nine IPY projects grouped within the Ecosystems and Biogeochemistry of the Southern Ocean consortium (see above and Fig. 15). However, it is important to note that there are many other IPY projects related to ICED that we will be linking with, including some of the projects focused on the Arctic. For more details see Appendix I and visit http://www.ipy.org and http://www.iced.ac.uk. A number of research cruises and other field activities are planned and ICED will play a major role in coordinating these. However, working with these projects will not be exclusively through fieldwork; related data and modelling activities will also be closely linked.

Links will be established and maintained with relevant IPY projects together with other existing and developing programmes. Links will be made with existing long-term monitoring programmes, national programmes and CCAMLR. These are too numerous to include here, but some of the key examples are mentioned in this section. Details of linkages will be updated on the ICED website as the programme develops. To ensure links between physics, biogeochemical and ecosystem field studies ICED will actively work with programmes such as CLIVAR, CliC and the Ship Of Opportunity Programme (SOOP; http://www.ifremer.fr/ird/soopip/). Enhancing the biological analyses undertaken on standard ocean transects through developing these and other links will be a focus of ICED. It will be important for ICED to link to national operators in order to enhance ocean transects and base supply tracks to include biogeochemical and ecological measurements.

ICED will collaborate with the joint SOLAS-IMBER carbon group and the IOCCP-GCP groups to: i) identify common research themes with a special focus on the development of biogeochemical-ecological models; ii) identify and implement key measurements to monitor the evolution of the Southern Ocean CO_2 sink in the coming decades; iii) highlight potential hot-spots for ocean-based mesocosm work and ocean carbon/ecological time series; and, iv) consider how ocean acidification fieldwork and process studies can be embedded into core plans for the science. During the IPY, links with the Synoptic Antarctic Shelf-Slope Interactions Study (SASSI, a scientific research project planned by the International Antarctic Zone Programme (iAnZone)) will provide a suitable framework for logistical and scientific collaboration between ICED-IPY, SOLAS and IMBER. Links have also been proposed to paleo-oceanographic activities planned by the International Marine Past Global Changes Study (IMAGES) programme in efforts to relate water column analyses of ecosystem structure and function to vertical flux and deep-water sedimentation processes.

In terms of improving circumpolar monitoring, ICED has been involved in the SOOS since its inception and will remain closely linked. As such, aspects of the SOOS have been purposely developed to address some of the key challenges for ICED. SOOS is a key component of the SCAR Pan Antarctic Observing System (PAntOS) and the need for sustained observing system in the Antarctic and Southern Ocean is recognised by the parties to the Antarctic Treaty.

Many existing programmes are going some way to providing important measurements although much more effort is needed to expand present observations into a viable SOOS (Summerhayes *et al*., 2007). For example, the Marine Mammal Exploration of the Oceans: Pole to Pole (MEOP) project is attaching satellite tags to animals to provide data on location, dive patterns, and water temperature and salinity. During IPY, CASO aims to obtain a synoptic circumpolar snapshot of the physical environment of the Southern Ocean by using sea-ice drifters, profiling floats, current-meter moorings and bottom pressure gauges to name just some of the methods. The CAML programme is investigating the distribution and abundance of Antarctic marine biodiversity and how it will be affected by climate change through a major ship based research programme. The IPY project Circumpolar Population Monitoring will fit penguins with powerful yet tiny state-of-the-art transponders and data recorders. To provide a wider context for these remote instrumentation studies ICED will also draw on available satellite data series including SST, chlorophyll *a*, sea ice concentration and sea surface height. Acoustic Recording Packages will be used to construct an observational network to record seasonal distribution of baleen whales; this work will benefit from collaboration with the IWC on whale survey data. These studies will provide the basis for analyses of inter-annual and sub-decadal circumpolar variability. Other possibilities will be explored through the SOOS and other connections such as expanding the Antarctic Weather Station network, improving mesoscale atmospheric models for Southern Ocean regions and developing a network of standard sampling transects and moorings systems.

In terms of links within ICED itself, the collective expertise embodied in ICED will serve as a valuable resource to guide the planning and implementation of field programmes. The experts on model development will be able to identify specific areas where work is needed to improve models; for example, in establishing the sensitivity of ecosystem parameters to changes in particular physical or chemical conditions. Close links will also be made with those involved in historical data synthesis activities. Through ICED they will make recommendations for field programmes to address such needs. The efforts of modellers, field observationalists and those synthesising and analysing data will be integrated to design field programmes explicitly for this purpose (Fig. 9 and the integration section, p.38).

Summary of ICED fieldwork coordination and development plans

- In the early phases, ICED will coordinate and improve integration of existing and planned field studies primarily through ICED-IPY and by developing other relevant linkages;
- Field planning workshops during and following IPY will consolidate the outcomes of IPY field activities and will help focus and structure subsequent ICED fieldwork. This will be aimed at filling the gaps in knowledge identified through IPY and the early phases of ICED;
- Field efforts focused on a number of integrated studies in the key regions, involving ship- and land-based fieldwork together with remote measurements, will be developed to further understanding of the structure and function of Southern Ocean ecosystems on a circumpolar scale;
- ICED will seek to address the gaps in knowledge that have and will be identified through historical data analysis and modelling, and maximise international field efforts to fill them.

INTEGRATION

Planning and integrating activities

The core of the ICED programme will be the integration of ecosystem, biogeochemical and climate research in order to meet the three multidisciplinary objectives (see p.16). The activities planned under ICED will be carefully integrated from the outset. This integration will be an ongoing process that will escalate over the course of the programme (Fig. 17). Models will provide the basis for integrating Southern Ocean ecosystem data, and generating and testing relevant hypotheses. These will be iterative and integrated with the whole research programme, including field and data analyses. Modelling will help focus research effort efficiently by identifying gaps in data availability, clarifying important areas of uncertainty, and determining strategies for the most efficient and effective collection of data.

At the same time, modelling efforts will benefit from the compilation and synthesis of existing datasets to produce circumpolar biological distributions for model initialisation, calibration and verification. Sufficient data exist to produce circumpolar maps of many biological quantities, such as plankton species biomass and abundance, although these are often not easily available or in the correct formats (as discussed in the data section, p.26 onwards). One of the first integration exercises during the initial phase of model development will therefore be a consideration of available data in collaboration with the relevant scientists. This will help clarify priorities for data retrieval and compilation.

During the development stages of ICED it will be important to establish links between scientists involved in modelling and data activities, and those involved in planning field studies (including process studies and survey and monitoring programmes). This will be achieved through electronic communications, meetings and workshops and will help in identifying gaps and prioritising sampling effort. Flexible Working Groups will be formed (see below). Regular workshops will be organised by theme and/or activity and will unite members of the Antarctic science communities in addressing particular aspects of the science as the ICED programme develops.

In addition to the ongoing integration and synthesis throughout the programme; towards the later stages of ICED, a Synthesis Working Group will be established and a focused integration and synthesis phase will be entered. This will draw together observations and results from the various components of the ICED programme in order to develop the global synthesis that must be its legacy. This will provide a comprehensive understanding of the functioning of the Southern Ocean circumpolar ecosystem, its interactions with biogeochemistry and its responses to physical forcing.

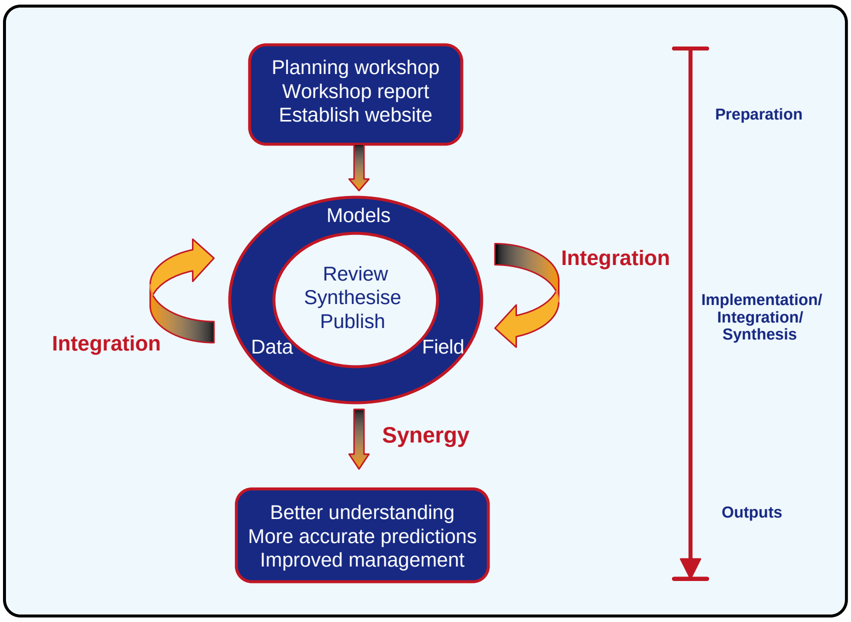


Figure 17. Simplified representation of the integration and synthesis of ICED activities that will gather pace during the course of the programme. Towards the later stages, a specific integration and synthesis phase will be entered to bring all the results together. Comprehensive outputs on Southern Ocean ecosystem functioning will be produced.

The ICED SSC will take the lead in guiding the integration process. This will require the early development of a framework to facilitate effective interaction between the SSC and the Working Groups (see p.40). This framework should be focused on enabling the effective interaction between ICED participants, Working Groups and national and regional programmes. Ensuring that Southern Ocean ecosystem research under ICED is also developed in parallel with global efforts, as part of IMBER and GLOBEC, is imperative.

Linkages

ICED has been developed in conjunction with SCOR and IGBP. Directed jointly by IMBER and GLOBEC, and through national and international programme activities, it is envisaged that ICED will further the understanding of Southern Ocean systems as part of the Earth System. ICED will generate multidisciplinary links between biologists, oceanographers, biogeochemists, climatologists and fisheries scientists from the international community, building upon the research and experience of projects such as SO JGOFS and SO GLOBEC.

In the earlier stages, ICED will lead and coordinate international research together with the Southern Ocean System of EUR-OCEANS and ICED-IPY. The IPY offers a unique opportunity to mobilise the required international effort for a step-change in analyses of polar ocean ecosystem dynamics for input into the next generation of Earth System simulations. As detailed in the Fieldwork section (p.30), ICED is coordinating nine IPY projects within the Ecosystems and Biogeochemistry of the Southern Ocean consortium (Fig. 15), and will form links to other related IPY projects (e.g. see Appendix I).

Collaboration with other relevant programmes will be vital to the success of ICED. ICED will establish links and integrate activities with related groups such as those shown in Figure 18 and many others as noted throughout this document (see particularly the links sections of each of three activity areas above and Appendix I) and on the ICED website. ICED will need to be aware of the activities of other Southern Ocean research programmes and integrate with them where appropriate. For example, as mentioned in the fieldwork section, ICED will collaborate with CLIVAR and other surveys to integrate relevant data where possible. In terms of improving circumpolar monitoring, ICED has been involved in the SOOS since its inception and will remain closely linked. Limitations in our understanding of atmospheric transport, nutrient cycling and deposition processes will be improved by developing linkages with SOLAS and the multi-national programme to investigate the global marine biogeochemical cycles of trace elements and their isotopes: GEOTRACES. Also of relevance is the bioregionalisation approach underpinning the

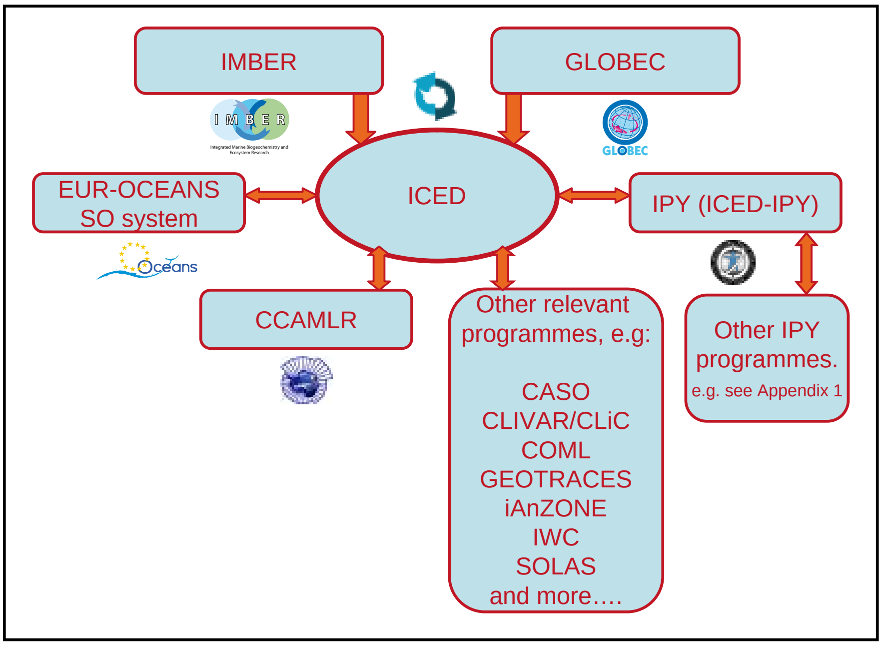


Figure 18. Collaboration with other relevant programmes is vital to the success of ICED (see Appendix I for acronyms). Directed jointly by IMBER and GLOBEC, ICED will generate multidisciplinary links between biologists, oceanographers, biogeochemists, climatologists and fisheries scientists from the international community.

development of a system of marine protected areas in the Southern Ocean, currently being coordinated by the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE) and the World Wide Fund for Nature (WWF; Grant *et al.*, 2006).

It is becoming increasingly apparent that links need to be strengthened between those working in Antarctic and Arctic regions. Some of the strongest regional expressions of global climate change have occurred in the Polar Regions and these are predicted to continue or indeed increase. Comparative views of marine ecosystem operation in both Polar Regions are essential to determine the responses to climate change and potential feedback effects. Developing links with Arctic (and sub-Arctic) Ocean ecosystem scientists and programmes is important from the ICED perspective, particularly in developing comparative analyses and models of the operation of polar marine ecosystems. ICED has begun this process through working with EUR-OCEANS scientists involved in Arctic Ocean research and with the ESSAS programme. Linking with scientists and groups from non-polar regions is also important in areas such as model development where certain concepts and methods will be applicable or adaptable regardless of geographic focus. This will be achieved in the first instance by inviting non-polar scientists from relevant fields to participate in ICED Working Groups, meetings and workshops. At least one non-polar scientist and one Arctic scientist should sit on the SSC. There are many other examples of linkages and collaborations detailed or mentioned throughout this document and on our website. An important role for ICED scientists will be to ensure that the Southern Ocean is adequately represented in Earth System models. This will be achieved primarily through working with GLOBEC and IMBER.

Structure of ICED

ICED will be organised around Working Groups, workshops and meetings focused on the ICED objectives. Since the first workshop, ICED has been operating under an interim committee. The SSC will be formally appointed by IMBER and GLOBEC and this will change at frequent periods over the life-span of ICED. This committee will consist of active scientists who have specific and broad expertise in the major disciplines covered by the ICED Science Plan and who provide broad geographical representation. The SSC will have overall responsibility for the direction and management of ICED activities on behalf of the IMBER/GLOBEC Joint Scientific Steering Committee (JSSC). A sub-set of the SSC will form an Executive Committee (EC). Flexible and interacting Working Groups (WG) will be formed to focus on, and lead, the work in specific areas (both theme-based and activity-based as appropriate, together with a synthesis WG). The SSC, EC and WGs together with the Programme Officer will organise the ICED work programme to maximise efforts in securing the necessary financial resources, international expertise and time to achieve the programme objectives. Terms of reference for the SSC, EC and WGs are currently being drafted and will be available on the ICED website in due course. The British Antarctic Survey (BAS) has provided the initial funding for a Programme Officer, currently based at BAS, to facilitate communications, workshops and other activities. It is envisaged that ICED will develop funding bids as the programme develops, particularly through coordinated efforts with both national and international programmes.

The institutes currently involved in the ICED programme include those associated with participants from the launch workshop (Appendix II) and the ICED-IPY projects (Appendix I). These include many leading polar research institutes and groups. As the programme develops it is envisaged that the number of participants and institutes involved with ICED will increase. Readers are encouraged to visit the ICED website on a regular basis for updates to the structure of the programme.

Communication

Given the international nature of ICED communication is fundamental to its success, and central to this is the ICED website (http://www.iced.ac.uk). The site will coordinate and publicise the activities of ICED and associated programmes, provide the latest news and information on projects and progress, and provide a forum for communicating ICED science to the widest possible audience.

ICED will contribute articles to international newsletters, such as GLOBEC and IMBER, and in due course will develop its own newsletter. This will initially take the form of an electronic bulletin. A series of workshops is planned and these will be important for the development, implementation and integration of the programme. Reports from the workshops will also be published.

To develop and maintain communication from the wider Southern Ocean community, ICED science meetings and sessions will be organised. These may be linked to, for example, SCAR, IMBER, EUR-OCEANS and GLOBEC conferences and meetings planned over the next couple of years, as well as separate ICED meetings when the programme becomes more established. The first ICED science session was held at the SCAR Open Science Conference (OSC) in Hobart, Australia in July 2006. A second will be held jointly with CAML at the SCAR OSC in St Petersburg, Russia in July 2008.

The results from ICED will be published in scientific journals and reports. However, ICED will endeavour to ensure that the main results will also be accessible to a wider audience, including policy makers, managers and the public. Some input will therefore be required in producing summary fact sheets or brochures.

Training and education

ICED will help to stimulate research capacity in the international community by undertaking training courses to develop multidisciplinary science skills, workshops, summer schools and a programme of personnel exchange. These activities will initially be coordinated through EUR-OCEANS.

During the IPY the public will have the opportunity to experience polar science through school activities, the Internet, films and documentaries, special events and exhibitions. The biology of the Southern Ocean captures the imagination of the public and will provide a platform from which to address issues such as climate change: not only how this will affect the charismatic wildlife and environment of Antarctica but also wider impacts on a global scale. For example, through ICED-IPY, young people will be able to read about life aboard research ships in the Southern Ocean and contact scientists directly.

ICED will ensure that its activities reach as wide an audience as possible and have the greatest possible impact both during and beyond IPY.

ICED programme outputs and legacy

As this document has outlined, the Southern Ocean ecosystem is changing rapidly as a result of both climate and harvesting driven effects. These changes have profound consequences for populations, species, biodiversity and ecosystem structure and function. They affect biogeochemical cycles and influence the development of management strategies for fisheries. To fully understand the impacts of variability and change requires integrated end-to-end analyses of Southern Ocean food webs, from primary production systems through to top predators.

As has been noted throughout the document there are a wide range of distinct scientific challenges in analyses of ecosystem operation, climate impacts, biogeochemistry and fisheries that the ICED community will address. This requires a strong focus by the community on the large-scale operation of whole Southern Ocean ecosystems. Whilst a vast amount of focused data collection (field and experimental) and model development studies have already been undertaken, what we currently lack is a dedicated, multidisciplinary effort to bring these together more coherently. This forms the central focus of ICED and the basis for its outputs and legacy.

Over the next decade ICED will work towards determining the major controls on the dynamics of Southern Ocean ecosystems and the potential for feedbacks as part of the Earth System. Emphasis will be given to developing the basis for evaluating and predicting the impacts of climate and harvesting driven change on Southern Ocean ecosystems. To do this the major focus for ICED will be on integrated regional and circumpolar analyses of whole ecosystem operation, particularly at the interfaces between traditional disciplines of ecosystem, climate, biogeochemistry and fisheries science. The main activities will include: i) circumpolar data mining and syntheses activities to examine long-term, large-scale ecosystem functioning, variability and change; ii) coordination, planning and development of fieldwork activities to address gaps, undertake comparative studies and maximise the efficiency and scientific value of individual programmes; and, iii) development of circulation, biogeochemical and biological models to the circumpolar scale, and of integrated end-to-end ecosystem models.

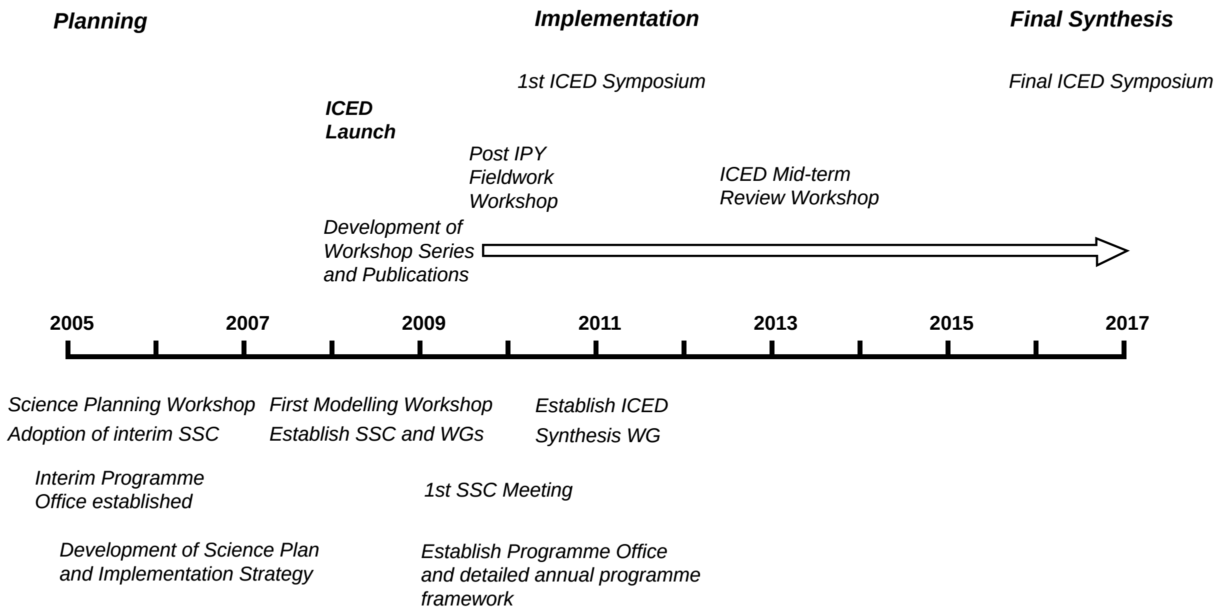


Figure 19. Preliminary draft timeline for the ICED programme. This will be revised as appropriate with later versions to be made available on the ICED website.

ICED is currently building a multidisciplinary network of experts that will grow throughout the programme. Through the SSC and WGs, ICED will convene regular Working Group and committee meetings, workshops, scientific sessions, and ultimately, scientific conferences. A preliminary timeline is shown in Fig. 19. This serves only as a draft outline and will be revised as appropriate with later versions to be made available on the ICED website.

The earlier meetings and workshops will serve to develop aspects of the work plan. Subsequent events will build on these to further develop new approaches and to step up the integration process. These events will occur at regular periods as noted in the draft timeline (Fig. 19). Other activities such as the direct research, development of online tools, publications and model development will take place throughout the programme and will feed into the workshops and meetings as appropriate. Some of the specific challenges, activities and outcomes envisaged are listed below as a guide. These are by no means exhaustive or definitive; new avenues of research will be continually developed through the outcomes of historical data research, the development of new field programmes building on the coordination phase, and through innovative, state-of-the-art modelling development.

Key research challenges include (for further details refer to the Science Background and Objectives sections of this document):

- Determining spatial and temporal operation of Southern Ocean ecosystems across a range of scales. For example:
  - » how ecosystems operate at regional and circumpolar scales and the physical and biological links across these scales;
  - » the controls (physical, biogeochemical and ecological) on the dynamics of Southern Ocean ecosystems and how variability affects structure and function;
  - » alternative food web pathways, trophic interactions and detailed life cycles of key species.
- Monitoring and interpretation of rapid and longer-term physical changes, particularly in oceanic and sea ice conditions, and linking these with:
  - » ecosystem and biogeochemical studies;
  - » Southern Hemisphere and global climate changes.

- Identifying, investigating and resolving key biogeochemical processes and their effects and feedbacks on Southern Ocean food webs over different spatial and temporal scales. For example:
  - » the biogeochemical and ecological impacts of ocean acidification in the context of physical and ecological change;
  - » the impacts of the combined changes in ocean physics and marine ecosystems on the Southern Ocean sink for CO_2;
  - » the role of iron availability.

- Determining how physical and harvesting driven changes affect the structure and function of Southern Ocean ecosystems and applying these to predict the effects of future change. Including:
  - » development of the ecosystem approach to management through inter-disciplinary analyses of physical and biological interactions in ocean systems;
  - » evaluation of uncertainties in our understanding of ecosystem operation and dynamics, and inclusion of levels of uncertainty in predictions of harvesting impacts;
  - » investigating and developing methods of integrating the results of regional studies into large-scale models.

Programme activities and outputs will include:

- Developing innovative approaches for modelling different scales and processes, towards building ecosystem models operating at regional and circumpolar scales;
- Developing coupled physical-biogeochemical models and their use with ecosystem models, to include state of the art parameterizations, data assimilative capabilities and the ability to interface with and inform climate and resource management models;
- Accessing (for the first time) and revisiting (from new perspectives) historical datasets (e.g. on abundance and distribution of key species) and adopting new analytical techniques to shed light on long-term, large-scale ecosystem functioning, variability and change;
- Developing coordinated, documented, quality-controlled and accessible data sets for Southern Ocean ecosystems;
- Producing circumpolar maps of biogeochemical and biological distributions;
- Producing a series of online interactive maps depicting ecosystem and related activities in the Southern Ocean, linked to detailed information and databases;
- Multidisciplinary exploration of data poor and unknown areas of the Southern Ocean to build up circumpolar coverage (involving ship- and land-based fieldwork together with remote measurements), including comparative studies with better known areas;
- Forging strong links with Southern Ocean, Arctic and relevant non-polar programmes.
- Producing collaborative papers for peer-reviewed journals on key scientific aspects of the ICED programme;
- Effectively disseminating information, advice and scientific analyses to inform global climate change projections (through the IPCC) and management strategies (through CCAMLR);
- Producing articles and reports for popular literature and online to provide relevant information to the wider community, policy makers and the general public;
- Developing educational tools including web-based material, print media and films.

Conclusion and legacy

ICED will develop a coordinated, circumpolar approach to determine the major controls on the dynamics of Southern Ocean ecosystems and the potential for feedbacks as part of the Earth System;

ICED will focus on developing models to improve the reliability of predictions of future ecosystem dynamics in the Southern Ocean, including responses to climate change and harvesting;

ICED will work towards integrating and analysing existing datasets to facilitate investigation of long-term, large-scale marine ecosystem functioning and change;

ICED will help to bring together the scientific outcomes of existing studies, identify priority areas for research, and develop and coordinate future field studies to fulfil spatial and temporal gaps in Southern Ocean data;

ICED will coordinate and link existing national and international programmes with a Southern Ocean focus, maximising their effectiveness and providing added value.

The integration and coordination of Southern Ocean ecosystem research and analyses through ICED will improve our predictions of the impacts of global change on Southern Ocean ecosystems, creating a lasting legacy on which future research can build. Much of what we learn may also be transferable to other regions and research areas. The reports and papers produced will inform scientists in the international community and provide a focus for future research on important regional, circumpolar and global issues. These outputs will also be presented in forms that provide policy makers with the sound scientific basis upon which to make decisions on ecosystem-based management in the Southern Ocean. In the global context, ICED will complement GLOBEC and IMBER in developing and inspiring a new generation of international, multidisciplinary polar marine scientists with a systems approach to their research.

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APPENDIX I. GLOSSARY (INCLUDING ICED PROGRAMME LINKS)

SCIENTIFIC GLOSSARY

ABS	Amundsen-Bellingshausen Sea
ACC	Antarctic Circumpolar Current
ACW	Antarctic Circumpolar Wave
AWS	Automatic Weather Station
CPR	Continuous Plankton Recorder
CTD	Conductivity/Temperature/Depth
CZCS	Coastal Zone Color Scanner
DMS	Dimethyl sulfide
ENSO	*El Niño* Southern Oscillation
GIS	Geographic Information Systems
HNLC	High-nutrient low-chlorophyll
IUU	Illegal, Unregulated and Unreported fishing
PF	Polar Front
SAF	Subantarctic Front
SAM	Southern Annular Mode
SeaWiFS	Sea-viewing Wide Field-of-view Sensor Project
SIZ	Seasonal Ice Zone
SODB	Southern Ocean Database
SOI	Southern Oscillation Index
SST	Sea Surface Temperature

PROJECT, PROGRAMME AND ORGANISATION GLOSSARY

■ Member of ICED-IPY consortium ‘Ecosystems and Biogeochemistry of the Southern Ocean’

□ IPY project linked through ICED-IPY

‡ Other IPY project relevant to ICED

For further details visit http://www.ipy.org/ and http://www.iced.ac.uk

AAD	Australian Antarctic Division
ACE	Antarctic Climate and Ecosystems Cooperative Research Centre
‡ AMES	Integrated Circumpolar Studies of Antarctic Marine Ecosystems (an IPY project)
‡ ANDEEP-SYSTCO	Antarctic benthic deep-sea biodiversity: colonisation history and recent community (an IPY project)
□ Antarctic Sea Ice	Antarctic Sea Ice in IPY Links with this Consortium will be made primarily through BASICS. *Leader*: Stephen Ackley. *Email*: sackley@pol.net *Web*: http://www.aspect.aq/
□ Arctic and Antarctic Sea Levels	Arctic and Antarctic Sea Level Network Development and Studies of Polar Sea Level Variability. *Leader*: Philip Woodworth. *Email*: plw@pol.ac.uk
ASAID	Antarctic Surface Accumulation and Ice Discharge (an IPY project)
ASPeCt	Antarctic Sea Ice Processes and Climate

■ ATOS	Atmospheric inputs of organic carbon and pollutants to the polar ocean: rates, significance and outlook: a Spanish component of the OASIS programme: *Leader*: Carlos Duarte, IMEDEA, CSIC, Spain *Aims*: To investigate the role of air-sea exchanges of materials in the polar oceans by determining: (1) atmospheric inputs of organic carbon and key organic pollutants; (2) role of sea ice cover in controlling these rates and the inputs associated with sea ice melting; (3) fate of these material through food webs; and (4) effects on microplankton as the entry points of the materials in the food web. *Email*: carlosduarte@imedea.uib.es *Web*: http://www.oasishome.net/ *Proposal*: http://classic.ipy.org/development/eoi/details.php?id=147
AWI	Alfred Wegener Institute, Germany
BAS	British Antarctic Survey, UK
■ BASICS	Biogeochemistry of Antarctic Sea Ice and the Climate System *Leader*: Jean-Louis Tison, Universite Libre de Bruxelles, Belgium *Aims*: Year-round study of Antarctic sea ice physics and biogeochemistry to budget the exchanges of energy and matter across ocean-sea ice-atmosphere interfaces. This will help quantify impacts on fluxes of climatically important gases (CO_2, DMS) and carbon export to the deep ocean. *Email*: jtison@ulb.ac.be *Web*: http://www.utsa.edu/lrsg/Antarctica/SIMBA *Proposal*: http://classic.ipy.org/development/eoi/details.php?id=862
BIAC-IPY	Bipolar Atlantic Thermohaline Circulation-an IPY project
BIOMASS	Biological Investigation of Marine Antarctic Species and Stocks
■ BONUS-GOODHOPE	Biogeochemistry of the Southern Ocean: interactions Between NUtrients, dynamics, and ecosystem Structure *Leaders*: Marie Boye/Sabrina Speich, Technopole Brest-Iroise, France *Aims*: To carry out multidisciplinary oceanographic research at the intersection of GEOTRACES and Chokepoints/GOODHOPE. It will integrate and extend observations by GOODHOPE and will focus on the subduction zone of the Mode Waters and on the African continental margin. *Email*: marie.boye@univ-brest.fr or sabrina.speech@univ-brest.fr *Web*: http://www.univ-brest.fr/IUEM/BONUS/ *Proposal*: http://classic.ipy.org/development/eoi/details.php?id=584
■ CaCO3-IPY	The potential decline in rates of $CaCO_3$ accretion and primary productivity in cold waters due to elevated CO_2 content *Leader*: John Runcie, University of Sydney, Australia *Aims*: To study the impacts of elevated CO_2 concentration on marine algae, in particular the extent to which elevated CO_2 levels influence rates of carbonate accretion and oxygen evolution (~carbon fixation, photosynthesis) in relation to water depth. This project will develop predictions for the response of primary producers in Polar Regions to elevated CO_2 under future CO_2 scenarios. *Email*: jruncie@usyd.edu.au *Proposal*: http://classic.ipy.org/development/eoi/details.php?id=406
□ CAML	Census of Antarctic Marine Life-to be conducted under the auspices of the international Census of Marine Life. *Leader*: Michael Stoddart. *Email*: michael.stoddart@aad.gov.au *Web*: http://www.caml.aq/news/
□ CASO	Climate of Antarctica and the Southern Ocean-Role of Antarctica and the Southern Ocean in Past, Present and Future Climate: a strategy for the International Polar Year 2007/08 Links with this Consortium will be made primarily through SOSA. *Leader*: Steve Rintoul *Email*: Steve.Rintoul@csiro.au *Web*: http://www.clivar.org/organization/southern/CASO/about.htm
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources

□ CCAMLR 2008 Survey	International CCAMLR 2008 synoptic survey of krill, pelagic fish and plankton biomass and biodiversity in the South Atlantic (Area 48). *Leader*: Volker Siegel *Email*: volker.siegel@ish.bfa-fisch.de
CEMP	Ecosystem Monitoring Program
‡ Circumpolar Population Monitoring	Circumpolar monitoring of the biology of key species in relation to environmental changes
CliC	Climate and Cryosphere
‡ CliC-OPEN	Impact of climate-induced glacial melting on marine and terrestrial coastal Antarctic communities.
■ CLIMANT	CLIMate change in ANTarctica: A pelagic-benthic coupling approach to the extremes of the Weddell Sea *Leader*: Enrique Isla, Instituto de Ciencias del Mar CSIC, Spain *Aims*: To study aspects of climate change in Antarctica through a pelagic-benthic coupling approach to studying the extremes of the Weddell Sea. *Email*: isla@cmima.csic.es *Web*: http://www.recercaenaccio.cat *Proposal*: http://classic.ipy.org/development/eoi/proposal-details.php?id=232
CLIVAR	Climate Variability and Predictability
CoML	Census of Marine Life
CS-EASIZ	Coastal and Shelf Ecology of the Antarctic Sea-Ice Zone
CSIC	Consejo Superior de Investigaciones Científicas, Spain
‡ EBA	Evolution and Biodiversity in the Antarctic: The Response of Life to Change
ECMWF	European Centre for Medium Range Weather Forecasts
EPOS	European Polarstern Study
EUR-OCEANS	European Network of Excellence for Ocean Ecosystems Analysis
□ GEOTRACES	A collaborative multi-national programme to investigate the global marine biogeochemical cycles of trace elements and their isotopes Links with this Consortium will be made primarily through Effects of CO_2 on $CaCO_3$ accretion and primary productivity, ATOS and BONUS-GOODHOPE. *Leader*: Hein de Baar *Email*: debaar@nioz.nl *Web*: http://www.ldeo.columbia.edu/res/pi/geotraces/
GLOBEC	Global Ocean Ecosystem Dynamics
GLOBEC-ESSAS	Ecosystem Studies of Sub-Arctic Seas
GCP	Global Carbon Project
GRACE (Ice and snow mass change)	Ice and snow mass change of Arctic and Antarctic polar regions using GRACE satellite gravimetry (an IPY project)
iAnZone	International Antarctic Zone Program
ICED	Integrating Climate and Ecosystem Dynamics in the Southern Ocean
ICED-IPY	Integrating Climate and Ecosystem Dynamics in the Southern Ocean-International Polar Year
IGBP	International Geosphere-Biosphere Programme
IMAGES	International Marine Past Global Changes Study
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
IMEDEA	Mediterranean Institute for Advanced Studies, Spain
IOCCP	International Carbon Coordination Project
IPCC	Intergovernmental Panel on Climate Change
IPY	International Polar Year
ISOS	International Southern Ocean Studies program
IWC	International Whaling Commission
IWC IDCR	International Whaling Commission’s International Decade of Cetacean Research
IWC SOC	International Whaling Commission’s Southern Ocean Collaboration (IWC SOC)

IWC SOWER	International Whaling Commission's Southern Ocean Whale and Ecosystem Research (SOWER) programme
JARPA	Japanese Whale Research Program under Special Permit in the Antarctic
JGOFS	Joint Global Ocean Flux Study
‡ MEOP	Marine Mammal Exploration of the Oceans-Pole to Pole
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
□ OASIS-IPY	Ocean-Atmosphere-Sea Ice-Snowpack Interactions Links with this Consortium will be made primarily through ATOS and Carbon in Sea Ice. *Leader*: Harry Beine *Email*: harry108@gmail.com *Web*: http://www.oasishome.net/
OBIS-SEAMAP	Ocean Biogeographic Information System-Spatial Ecological Analysis of Megavertebrate Populations
OCCAM	Ocean Circulation and Climate Advanced Modelling Project
PAL	Palmer Long Term Ecological Research
ROAVERRS	Research on Atmospheric Variability and Ecosystem Response in the Ross Sea
SAHFOS	Sir Alistair Hardy Foundation for Ocean Science
■ SASIE	Study of Antarctic Sea Ice Ecosystems *Leader*: Igor Melnikov, P.P. Shirshov Institute of Oceanology, Russia *Aims*: Multidisciplinary research in the Antarctic sea ice zone to understand environmental changes in the Southern Ocean. Field observations in key pelagic and coastal regions will be undertaken to examine large-scale and long-term modes of variability. *Email*: migor@online.ru *Proposal*: http://classic.ipy.org/development/eoi/details.php?id=818
□ SASSI	Synoptic Antarctic Shelf-Slope Interactions (an IPY project from iAnZone) *Leader*: Karen Heywood *Email*: K.Heywood@uea.ac.uk *Web*: http://roughy.tamu.edu/sassi/sassi.html
■ SCACE	Synoptic Circum-Antarctic Climate and Ecosystem study *Leader*: Volker Strass, AWI, Germany *Aims*: To examine the role of the Southern Ocean in the global climate: SCACE aims at welding together a broad range of ocean science and climate disciplines in order to address currently elusive questions such as: which physical, biological and chemical processes regulate the Southern Ocean system and determine its influence on the global climate development? How sensitive are Southern Ocean processes and systems to natural climate change and anthropogenic perturbations? *Email*: vhstrass@awi-bremerhaven.de *Web*: http://www.polarjahr.de/SCACE.257+M52087573ab0.0.html *Proposal*: http://classic.ipy.org/development/eoi/details.php?id=16
SCAR	Scientific Committee on Antarctic Research
‡ SCAR-MarBIN	Linking, Integrating and Disseminating Marine Biodiversity Information
SCOR	Scientific Committee on Oceanic Research
SOC	Southampton Oceanography Institute, UK
SO GLOBEC	Southern Ocean Global Ocean Ecosystem Dynamics
SOIREE	Southern Ocean Iron Release Experiment
SO JGOFS	Southern Ocean Joint Global Ocean Flux Study
SOLAS	Surface Ocean-Lower Atmosphere Study
SOOP	Ship Of Opportunity Program
SOOS	Southern Ocean Observing System
SOPHOCLES	Southern Ocean Physical Oceanography and Cryospheric Linkages

■ SOSA	Physical and biogeochemical fluxes in the Atlantic Sector of the Southern Ocean during the IPY (SOSA = Southern Ocean South Atlantic box) *Leader*: Brian King, SOC, UK *Aims*: to conduct a suite of near-synoptic physical and biogeochemical measurements in the Atlantic sector, including transient tracers and elements of the carbon system. *Email*: bak@noc.soton.ac.uk *Proposal*: http://classic.ipy.org/development/eoi/details.php?id=283
■ SOS-CLIMATE	Southern Ocean Studies for Understanding Global Climate Issues *Leader*: Carlos Garcia, Universidade Federal do Rio Grande, Brazil *Aims*: To conduct multidisciplinary oceanographic fieldwork (physics, nutrients, bio-optics, primary production, CO_2, DMS, etc.) in shelf and shelf-slope regions across the Polar Front from the Antarctic Peninsula region in the south to the Patagonian Shelf region in the north. Understanding of bloom dynamics in this region is needed to anticipate changes to the regional carbon budget that may occur as a result of climate change. *Email*: dfsgar@furg.br *Web*: http://www.goal.ocfis.furg.br *Proposal*: http://classic.ipy.org/development/eoi/details.php?id=911
WCRP	World Climate Research Program
WOCE	World Ocean Circulation Experiment
WWF	World Wide Fund for Nature
□ ZERO&DRAKE	Synoptic transects of trace elements and their isotopes in the Antarctic Ocean: A contribution to the international GEOTRACES programme. Links with this Consortium will be made primarily through Effects of CO_2 on $CaCO_3$ accretion and primary productivity. *Leader*: Hein De Baar *Email*: debaar@nioz.nl

APPENDIX II. ICED WORKSHOP PARTICIPANTS

Participants in the ICED Science Planning Workshop, British Antarctic Survey, 24-26 May 2005.

Name	Institute
David Agnew	Imperial College London, UK
Angus Atkinson	British Antarctic Survey, UK
Uli Bathmann*	Alfred Wegener Institute, Germany
Aike Beckmann	University of Helsinki, Finland
Stephane Blain	Université de la Méditerranée, France
Pavel Chernyshkov	Atlantic Research Institute of Marine Fisheries & Oceanography, Russia
Frank Dehairs	Vrije Universiteit Brussel, Belgium
Bill Fraser	Polar Oceans Research Group, USA
Julie Hall	National Institute of Water and Atmospheric Research, New Zealand
Gideon Henderson	University of Oxford, UK
Eileen Hofmann*	Old Dominion University, USA
Rennie Holt	Southwest Fisheries Science Center, NMFS, USA
Graham Hosie	Australian Antarctic Division, Australia
Nadine Johnston	British Antarctic Survey, UK
Christiane Lancelot*	Université Libre de Bruxelles, Belgium
Mike Meredith	British Antarctic Survey, UK
Eugene Murphy*	British Antarctic Survey, UK
Steve Nicol*	Australian Antarctic Division, Australia
Tsuneo Odate	National Institute of Polar Research, Japan
Evgeny Pakhomov*	University of British Columbia, Canada
Keith Reid	British Antarctic Survey, UK
Steve Reilly	Southwest Fisheries Science Center, NMFS, USA
Antonio Tovar Sanchez	University of the Balearic Islands, Spain
Geraldine Sarthou+	Technopole Brest Iroise, France
Hyoung-Chul Shin	Korea Ocean Research and Development Institute, Korea
Walker Smith*	Virginia Institute of Marine Sciences, USA
Colin Summerhayes,	Scientific Committee on Antarctic Research
Deborah Thiele*	University of Deakin, Australia
Phil Trathan	British Antarctic Survey, UK
Tom Trull	Antarctic Climate and Ecosystems Cooperative Research Centre/University of Tasmania, Australia
John Turner	British Antarctic Survey, UK
Jon Watkins	British Antarctic Survey, UK
Henri Weimerskirch	Centre d'Etudes Biologiques de Chizé-Centre National de la Recherche Scientifique, France
Tony Worby	Australian Antarctic Division, Australia

* = ICED Interim Steering Committee members

+ = Participants who contributed to the workshop but could not attend

NB: a number of scientists were invited but could not attend (including Kevin Arrigo, Carlos Duarte, Hugh Ducklow, Mitsuo Fukuchi, Catherine Jeandel, Mike Sparrow, Volker Strass, Vyacheslav Sushin, Sun Song, Paul Tréguer*, Maurizio d'Alcala)

APPENDIX III. ISSUES TO BE CONSIDERED FOR ICED MODEL DEVELOPMENT

This appendix is based on discussions held at the first ICED workshop (Murphy *et al.*, 2006) and is intended to assist in planning the forthcoming ICED modelling workshops. One of the first challenges to address is to define the theoretical and technical process required to model whole ocean ecosystems. Is it appropriate to rely on the ad-hoc assembly of building blocks that will, in some as yet undefined way, come together to provide models of ecosystem function? It is essential that construction of these building block models continues, in order to address specific issues that relate to parts of the system, however it may be necessary to consider different approaches to produce overarching views of the macro-scale response of ecosystems to change. Nevertheless, there remains an imperative to identify the main areas and building blocks required to provide the underlying understanding required to inform and evaluate macro-scale ecosystem models. The key science areas and associated model requirements are listed below; clearly this listing is intended to be indicative and cannot be considered exhaustive.

OBJECTIVE 1: TO UNDERSTAND THE STRUCTURE AND DYNAMICS OF ECOSYSTEMS IN THE SOUTHERN OCEAN AND HOW THEY ARE AFFECTED BY CLIMATE PROCESSES

Structure and dynamics of Southern Ocean ecosystems

Developing models of Southern Ocean ecosystems is still at an early stage and much of the work undertaken to date has been of restricted geographical or trophic scope. There are major questions regarding the criteria that should be used to develop realistic models of Southern Ocean ecosystems.

Model development should involve some consideration of the following issues:

- The development of integrated ecosystem models must be done in conjunction with experimental and field studies to provide the basis for model parameterisations.
- When considering the operation of Southern Ocean ecosystems (and to explore effects of climate processes) the use of static food web analyses will be insufficient given the importance of spatial heterogeneity and temporal variation. A range of approaches to food web representation will be required involving models with different spatial, temporal and trophic complexity. Specific issues include:
    - » the effects of horizontal advection of biological material in maintaining ecosystem structure;
    - » the effects of behavioural processes, such as vertical migration of plankton or predator-prey interactions, for multi-trophic system models;
    - » determining the importance of energy transfer to upper trophic levels via krill-dominated and non-krill pathways (e.g. mesozooplankton and fish) in structuring food webs;
    - » the spatial and temporal resolution required for coupling lower trophic level models with those developed for top predators;
    - » regional differences;
    - » the links between benthic and pelagic systems, particularly in coastal regions.
- Some energetic, growth and demographic model studies of Southern Ocean zooplankton, fish and predators have been undertaken (Constable, 2004; Fennel *et al.*, 2003; Murphy *et al.*, 1998; Murphy and Reid, 2001; Priddle *et al.*, 1988; Tarling *et al.*, 2006). A much more systematic and strategic focus is required to bring these models together and to develop models for other key species or groups of species, such as gelatinous zooplankton (e.g. salps) and their role in nutrient cycling and end-to-end food web operation.

- Ecosystem models need to include the explicit operation of the life history of key species of plankton, fish, seabirds and marine mammals. There is no existing model describing the full life cycle of a planktonic animal in the Southern Ocean. Much effort has gone into modelling different life stages of plankton (krill in particular), but these have yet to be combined in order to describe development from embryo through to adult. As an example, the incorporation of detailed life history models into circulation models will allow the effects of physical-biological processes on the distribution and abundance of organisms to be explored. Effort is required to develop Eulerian calculations to simulate changes in the density of stage or age structured populations so that populations, as opposed to individuals, can be tracked within circulation models. An important aspect of this integration of physical-biological processes will be a consideration of how to match the time-scales for coupling physical and biological processes to avoid errors in calculating population development.

Key physical processes

The development of coupled physical-biological models will require close collaboration with physical modelling groups. As a basis for ICED modelling efforts physical models are required that provide outputs relevant to the scales of operation of the biological processes under consideration, for example such models may include:

- Circumpolar scale atmospheric-sea and ice-ocean models.
- Coupled models for key regions of the Southern Ocean, such as the Ross Sea, west Antarctic Peninsula, Scotia Sea and East Antarctic.
- High resolution meso-scale (10s-100s km) models of shelf and cross-shelf processes, island and frontal regions and sea-ice/ocean processes in ice zones.

In order to develop these as a nested hierarchy of models will require explicit consideration of cross-scale links.

Model development should involve some consideration of the following issues:

- Sub-decadal physical fluctuations are crucial for determining inter-annual to decadal dynamics of ecological systems and provide an important and tractable scale for examining ecosystem responses to physical variation. Models are therefore required that include large-scale physical interactions (atmosphere-sea and ice-ocean) and their connections with Southern Hemisphere climate related processes (e.g. the Antarctic Oscillation, Antarctic Dipole, SAM and ENSO). Clarifying the interactive nature of these physical processes is required to determine the drivers of ecological change.
- Models predicting future climate driven change in the Southern Ocean have suggested that atmospheric warming will generate reductions in sea-ice distribution and thickness, increased ACC speeds may result from increased wind speeds and changes in freshwater budgets associated with precipitation changes will affect water column stability. However a high degree of uncertainty is involved-this needs to be accounted for in simulating future change scenarios in relation to biological systems.
- A wider network of physical and biological monitoring of oceanic systems is required to provide data for the robust development and testing of large-scale models. This could be achieved in conjunction with CASO/SOOS through more extensive measurements networks, e.g. by expanding the Antarctic Weather Station network, improving mesoscale atmospheric models for Southern Ocean regions and developing a network of standard sampling transects and mooring systems.
- Circulation models at circumpolar (such as the OCCAM Project) and regional scales are valuable as stand-alone systems for examining circulation effects on biological systems.
- Additional enhancement and development of circulation model frameworks for biological studies is required. For example the simultaneous calculation of particles with flow fields will improve the resolution of tracking studies compared to the use of archived simulated circulation fields.

- Observations of change in Southern Ocean systems have demonstrated the regional nature of the variation. Large-scale models do not generally capture that regional variation which will be crucial in determining the ecosystem responses. For example, dynamic sea ice models that provide realistic simulations at regional scales are needed to better understand biological responses to changing sea ice conditions.
- High-resolution models that include adaptive vertical mixing schemes, the ability to handle steep topography, tidal effects, processes under ice shelf cavities (to correctly simulate water mass structure and circulation), and dynamic sea ice models (especially models that include realistic coupling to ocean-atmosphere processes and that resolve the marginal sea ice zone) are needed.

Circumpolar models-predicting ecosystem response to climate and harvesting effects

Understanding the conceptual basis for the operation of Southern Ocean ecosystems is a fundamental requirement in developing circumpolar models (see above).

Model development should involve some consideration of the following issues:

- The development of conceptual models for Antarctic food webs will be an initial focus for ICED modelling activities. Much has been learned about the structure and function of Southern Ocean food webs from multidisciplinary oceanographic programmes that have taken place over the past 25-30 years (e.g. BIOMASS, SO GLOBEC), and there is a need to synthesise and integrate this information.
- The level of species aggregation or functional group definition required to resolve ecosystem dynamics is a priority area of research. There is a pressing need to increase the spatial coverage and trophic resolution of the available models, and a much more coordinated approach is required.
- Southern Ocean models are required that include links to the wider Earth System; including atmospheric connections to low-latitude regions and the inclusion of migratory higher predators that connect ecosystems across the globe. ICED needs to link to groups that are already developing global models that include the Southern Ocean to help clarify the major issues involved in developing appropriate models.
- The use of data assimilation (a form of inverse modelling) has been highlighted as worthy of exploration for use in synthesis and analysis of existing datasets and for future model development (see Model development section).
- Genetic modelling approaches have the potential to provide a stepwise improvement in the study of ecosystem dynamics of this region, from assessing levels of connectivity between circumpolar populations to determining the resilience of species to rapid regional environmental change (see Model development section).

Objective 2: To understand how ecosystem structure and dynamics affect biogeochemical cycles in the Southern Ocean

Development of biogeochemical models for the Southern Ocean is advancing and models that simulate circumpolar biogeochemical distributions are just beginning to be available. Acquisition of datasets that can provide evaluation of such model results will be an important focus for the next generation of Southern Ocean research programmes. Biogeochemical-based models have been developed for selected regions of, and across, the Southern Ocean, for example: Weddell Sea (Lancelot *et al*., 1991), Atlantic sector (Fennel *et al*., 2003; Lancelot *et al*., 2000), Indian sector (Pondaven *et al*., 1998), Ross Sea (Arrigo *et al*., 2003a; Hecq *et al*., 2000; Tagliabue and Arrigo, 2005) and the Antarctic Peninsula region (Walsh *et al*., 2001). Hense *et al*. (2003a, 2003b) used a coupled physical-biochemical model for oceanic regions of the Southern Ocean (south of 50°S). These models provide useful insights as a basis for ICED modelling studies.

Model development should involve consideration of the following issues:

- Circulation-biogeochemical models:
  - » a focus for ICED is to foster the development of regional coupled circulation-biogeochemical models, especially for areas identified as priority regions for field studies (see Fieldwork section, p.32);
  - » sea-ice models exist that are adequate for coupling with biogeochemical models. However, further development (requiring finer vertical resolution) is likely to be required to improve their use in conjunction with biogeochemical and food web models. Sea ice biological processes also need to be incorporated;
  - » the interaction of the large-scale flow of the ACC with steep bathymetry around the Southern Ocean is critical in resolving regional biogeochemical processes and presents methodological modelling challenges. A nested model structure will provide the space and time resolution for local scales as well as maintaining the larger scale connections between regions. A circumpolar view could be developed by embedding high-resolution regional biogeochemical models into larger-scale circulation models;
  - » inclusion of sediment transport into circulation models, especially for coastal and continental shelf regions needs to be considered. The importance of re-suspension events to material cycling, for example, has not been examined in models developed for Antarctic continental shelf regions.

- Development of generic models to determine how ecosystem structure influences biogeochemistry will be useful because potential feedbacks and control processes need to be specifically explored before attempts are made to construct complex simulations. Specific points for consideration in developing biogeochemical-ecosystem models:
  - » the importance of iron in regulating primary production should be incorporated into models of Southern Ocean primary production (Arrigo *et al*., 2003b) to begin to address questions regarding links between biogeochemical cycles and food web structure;
  - » impacts of ocean acidification will require a specific focus on impacts at different levels of the ecosystem: stress changes on organisms through pH changes, changes in calcification rates of autotrophic species (hence impacts on production and phytoplankton community composition) and changes in calcification rates of molluscan species, (particularly pteropods) that are present but make an unknown contribution to material flow in Southern Ocean food webs. Models are required that quantitatively assess these impacts and examine potential food web effects;
  - » the next generation of biogeochemical models should include explicit food web dynamics. Validation and testing of such models will require appropriate data (that are not often collected simultaneously) at the required scales. This presents a challenge to the development of the field programmes;
  - » most biogeochemical models developed for the Southern Ocean are focused on the euphotic zone. Depth-related vertical links in food webs, for example links to the mesopelagic layer and its role in controlling biogeochemical cycles are largely unexplored in models studies. The biogeochemistry and ecosystem dynamics of this large and important zone, where organic material is mineralised, are largely unknown;
  - » coupling of pelagic-based biogeochemical models to benthic models will be important for some Antarctic coastal regions to build up a more complete picture of the processes.

- There has been little modelling of the importance of very fine scale (<1 km) physical-biological process interactions in biogeochemical cycling. This type of parameterisation of sub-grid scale processes may be extremely important. For example, the patchiness of krill distributions will affect biogeochemical cycling and may have implications for larger-scale simulations.

Objective 3: To determine how ecosystem structure and dynamics should be incorporated into management approaches to sustainable exploitation of living resources in the Southern Ocean

Model development should involve consideration of the following issues:

- Much of the management related modelling has tended to focus on single species harvesting based models. In recent years there has been an increasing emphasis on the ecosystem-based approach, incorporating food web interactions and environment links.
- ICED will complement and contribute to the work of CCAMLR and IWC in developing modelling approaches for sustainable management of Southern Ocean resources, providing a broad ecological perspective. A range of models have been developed to examine upper trophic level food web interactions with a particular focus on the effects of harvesting (see Hill *et al*., 2006). CCAMLR's current work programme includes the development of ecosystem dynamics models for resource management (SC-CAMLR, 2005, 2006).
- Specific areas of focus for ICED include:
    - » how should the structure and dynamics of Southern Ocean ecosystems be represented in ecosystem models used in resource management?
    - » how should the complexity and uncertainty in our understanding of the functioning of these ecosystems be reflected in the preparation and delivery of management advice?
    - » what are the principles required to utilise data from ecosystem monitoring programmes as part of management?
- A key aspect for ICED will be addressing the appropriate scales at which biological populations/ meta-populations need to be managed. This will be an ongoing and iterative process involving explicit consideration of the implications of model uncertainty on the delivery of management advice.

APPENDIX IV. DATA TYPES FOR ICED HISTORICAL DATA SYNTHESIS (WITH EXAMPLE SOURCES AND EXPLANATORY NOTES)

Note that all acronyms in this table are fully detailed in Appendix I.

Data type	Examples	Notes
Atmospheric	• Air temperature records (e.g. from Heard Island, South Georgia, the South Orkneys, the Antarctic Peninsula, as well as improved recent regional coverage). • Climate indices, e.g. SOI, SAM index etc., data and derived indices of climatic sub-decadal periodicity. NCEP/NCAR and ECMWF reanalysis datasets. • Weather station records, including from AWS.	
Oceanographic	• British Oceanographic Data Centre, Liverpool, UK. • National Oceanographic Data Centre, NOAA, US. • *Discovery* Reports. • Pathfinder SST data (from 1982 onwards). • Altimetry data for resolving eddies. • Southern Ocean Database (SODB; Orsi). • Repeat hydrographic sections (e.g. WOCE transects). • Argo float data. • SEaOS/MEOP CTD profiles. • Drifter datasets. • Historical and ongoing moorings records.	
Sea ice	• NOAA satellite data (from mid 1970s onwards). • Local indices pre-dating NOAA, satellite data (e.g. Signy fast ice (Murphy *et al*., 1995). • Larger-scale historical observations (e.g. de la Mare, 1997). • Chemical proxies in sea ice within the Indian sector (e.g. Curran *et al*., 2003). • ASPeCt sea ice data.	Station journals may be invaluable for at least rough reconstruction of the west Antarctic Peninsula/Scotia Sea sea ice variability prior to the remote sensing record.
Nutrients	• Circumpolar synthesis of Sarmiento *et al*. (2004).	Large majority of data collected by various nations over last 20 years are probably compatible for circumpolar and seasonal distributions.
Microplankton composition	• *Discovery* Investigations (e.g. Hart, 1942). • Scattered recent data (but taxonomic problems may hinder analysis of long-term trends).	It should be possible to at least update the large-scale regional view of the major taxa. Chemical (e.g. high performance liquid chromatography) taxonomy and size-fractionated chlorophyll *a* (Chl *a*) are probably of more use for data synthesis than shipboard bulk Chl *a* values (see below). However this would be a major effort and cost/benefit analysis would be required before proceeding.
Chlorophyll a	• CZCS and SeaWiFS.	These data provide a basis for examining issues of inter-annual variability and assessing causes of blooms, e.g. by linking with other remotely sensed datasets. However, there are uncertainties regarding the ease and benefit of compiling all available bulk Chl *a* data from shipboard studies.
Mesozooplankton	• *Discovery* Investigations data from vertical net hauls (e.g. at South Georgia (Hardy and Gunther, 1936) and 80ºW (Mackintosh, 1937). • Datasets with large-scale coverage (e.g. by Russian, Australian, Japanese, British, and South African research vessels). • CPR datasets for Southern Ocean are now developing through SAHFOS/BAS/AAD links.	Much of these data are available in notebook form; data are dispersed, collected with non-standardised gear. Other issues include: Net mesh selection, net clogging, and consistency of identifying copepodite or larval stages. Research questions may be best focused on specific sectors or on long-term changes along well sampled transect lines/study areas. Looking at the ratios of easily identified co-occurring warm/cold water species groups of similar size may help circumvent some of the sampling problems. As an illustrative example, investigating the relative abundance of increasingly warm-tolerant calanoid copepod species (*Calanus propinquus*→*Calanoides acutus*→*Rhincalanus gigas*→*Calanus simillimus*) with respect to time and space in order to assess their response to temperature change.

Krill and salps	• An historical database of krill and salp abundance has already been constructed (Atkinson *et al*., 2004). This needs updating and can be re-analysed. • Large datasets are available on length frequency distribution-wide coverage and spanning 80 years, which should not have too many problems in compiling. • Acoustic data from international programmes (BIOMASS, CCAMLR), established national programmes (e.g. Australia, Germany, USA, UK) and individual surveys to look at large-scale distribution. • Long-term data from predator diet studies in some sectors of the Antarctic now span 30 or more years. • Fisheries-based assessments of krill biomass and/or size composition (CCAMLR).	The lack of a standard methodology hampers the synthesis of early acoustics data. Ample evidence that predator diets are excellent proxies for what is available in the marine environment. Issue of access to commercial sensitive fishery data will need to be resolved through CCAMLR.
Fish, squid and mesopelagic fauna	• Archived Russian datasets and CCAMLR-derived data, including ground fish surveys (including fish diet studies) may be accessible	Data coverage for these groups is scarce. Data synthesis will be valuable given the paucity of knowledge and current lack of any integration.
Higher predators (excluding whales)	• Population censuses and other demographic/ ecological data for land-breeding species are available • Long time-series are available for seabirds for three or four locations • Line-transect survey data for air-breathing predators (birds and seals) can be accessed for at-sea distributions • SCAR Group of Experts on compilation and analysis all available Southern Ocean seabird data.	Linking and organising these data at a circumpolar, multi-national level likely to be challenging. International cooperation and linking of datasets needed to determine population size and trajectories for higher predators.
Whales	Whale catch and sighting data held by the IWC have potential for integration into whole food web analyses in relation to large-scale habitat types and modelling of ecosystem change effects at regional and circumpolar scales using historical and recent data. Antarctic whale data held by IWC includes: • Antarctic whaling records 'catch data' for 1913 to 1987 all areas, coverage primarily austral summer; • Antarctic whale sighting records from the circumpolar IWC IDCR/SOWER population surveys. Comprises three decades of whale sighting surveys with coverage across all regions at least once each decade from 1978-present (surveys all in the austral summer); • IWC SOC database which holds whale sighting, wildlife biodiversity and ASPeCt sea ice data collected 2000-2006 on multidisciplinary surveys (e.g. CCAMLR and SO GLOBEC) of many national programmes across most regions of the Antarctic, coverage all seasons (currently held by D. Thiele, Deakin University, Australia).	Other Southern Hemisphere whale sighting data, such as JARPA are also available from the IWC under specific data availability agreements.
Paleoecological/ paleoclimatological	The Antarctic has played a critical role in the global climate system for tens of millions of years. Paleoecological/paleoclimatological data show patterns in ecosystem response (diatoms to top predators) to past warming and cooling periods, hence may serve as a useful proxy in developing and implementing aspects of ICED, including its field programmes and models.	
Rate process/ecosystem structure data-notes:		
Primary production	Possibly a priority area if a standardised currency (e.g. gross or net) is used, as it is a key measurement and one which is especially useful when synthesised in relation to environmental datasets.	
Isotopic composition of food web components	Particularly valuable may be the $\Delta^{13}C$ and $\Delta^{15}N$ values of a wide range of consumers to give a broad picture of organic dietary sources and trophic level within regional food webs. This is a fairly standardised measurement, and further benefits from a large-scale data synthesis approach given imprecision (largely due to variable food web baseline). Efforts are already underway in Germany, South Africa and Canada to compile such databases.	

APPENDIX V. ICED DATA POLICY–DRAFT PRINCIPLES

1. A Data Working Group (ICED DWG) will be established by the ICED Scientific Steering Committee in order to identify priorities and oversee and monitor the effective synthesis and management of data under the ICED programme;
2. ICED will manage relevant data, according to the recommendations of the ICED DWG, via a de-centralised structure, utilising existing pathways for management and dissemination (e.g. national data centres, international initiatives such as the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) and subject oriented initiatives such as the World Meteorological Organisation (WMO), the Ocean Biogeographic Information System (OBIS) and the Global Change Master Directory (GCMD);
3. The ICED DWG will identify and recommend appropriate conventions and standards in order to ensure maximum compatibility of ICED data with international data and metadata standards;
4. During the IPY, the ICED DWG will work closely with the International Council for Science (ICSU)/WMO Joint Committee for the IPY to ensure data are made available according to the IPY Data Policy;
5. The ICED DWG will provide guidance for small projects or individuals requiring information about the most appropriate data centre for long-term safe custody of data;
6. The ICED DWG will consider the issues around standardisation of model input and output in order to facilitate comparison between modelling methods, and make recommendations accordingly;
7. ICED will provide a central point of reference for ICED partners through its website. This will provide links to all relevant data sources. This may be in the form of interactive maps (see field section, p.30 onwards);
8. ICED partners must provide information about the chosen long-term location of data they hold or generate during the lifetime of the ICED Programme;
9. The ICED DWG will include individuals concerned with data mining, rationalisation and synthesis to provide a balance of expertise within the group;
10. The ICED DWG will, in consultation with ICED partners, identify key historic data sets, in electronic or any other format, which should be targeted for data rescue activities. These activities will be considered as discrete projects that may necessitate further dedicated funding;
11. The ICED DWG will integrate its activities with those of the modelling and fieldwork Working Groups.