Day 1: Introduction

Southern Ocean Sentinel – an overview

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Dr. Andrew Constable has a background in experimental marine ecology, with an emphasis on the application of science in the management of marine resources. He spent six years as an academic teaching marine ecology and management before joining the Australian Antarctic Division in 1997 and most recently the Antarctic Climate and Ecosystems Cooperative Research Centre in 2005 where he is currently leader of the Antarctic Marine Ecosystems Program. He has been involved in the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) since 1986. His research now focusses on ecosystem simulation models to evaluate the potential consequences of climate change on Antarctic marine ecosystems and for evaluating the efficacy of management procedures and monitoring programs for Antarctic marine living resources.

The Southern Ocean ecosystem will be the first part of the global marine system to experience the full suite of physical changes expected from enhanced greenhouse gases in the atmosphere (hereafter termed ‘climate change impacts’). As a result, there will be concomitant changes in productivity and food web dynamics but what those specific changes might be and where and when they might occur remains uncertain. The Southern Ocean is also not likely to be substantially impacted by other human activities, notwithstanding the historical changes to the Southern Ocean food web wrought by whaling, sealing and fishing. An important question for managers and policy makers is whether a cost-effective program to estimate the rates of change in the Southern Ocean marine ecosystem arising from climate change impacts can be designed and used as a sentinel of future conditions and impacts on natural environmental services and success of mitigation strategies. A key challenge for designing such a program is the large uncertainty surrounding our knowledge of ecosystem structure and function. In addition, there are likely to be multiple types of direct and indirect impacts in different parts of the ecosystem along with associated feedbacks. This paper will introduce the workshop and describe the top-down process envisaged to be used both as a means of structuring the workshop and for developing a Southern Ocean Sentinel Program (hereafter termed the Sentinel). A set of indicators will need to be identified, perhaps measured in different locations and at different temporal frequencies. The Sentinel need not be a static monitoring regime. It will likely need to be dynamic, adaptive and capable of shifting emphasis to different indicators over time, as measurements from early indicators will enable learning and the distinguishing between critical alternative hypotheses and models on ecosystem structure and function. In order to be efficient and cost-effective, the Sentinel will necessarily be collaborative, multinational and multidisciplinary. In total, the results of the Sentinel Program should be able to triangulate towards a predictive model that provides the best forecasts of changes due to climate change impacts.

Setting the scene: The Southern Ocean's evolving state over the last three decades inferred from ocean salinity, temperature, oxygen and altimetry data

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Nathan Bindoff is Professor of Physical Oceanography at the University of Tasmania, and CSIRO Marine Research Laboratories, Director of the Tasmanian Partnership for Advanced Computing and Project Leader of the Antarctic Cooperative Research Centre's Modelling Program. Nathan is a physical oceanographer, specialising in ocean climate and the earth's climate system. He was the coordinating lead author for the ocean chapter in the Inter-Governmental Panel on Climate Change (IPCC) Fourth Assessment Report. His current interests are primarily in understanding how the changing ocean can be used to infer changes in atmosphere, and separately the interactions of the Antarctic Circumpolar Current and its eddies. He has served on 12 international committees, six of which are still current, invited speaker at ten conferences and workshops, co-chaired 2 workshops and was guest editor on two special volumes of Deep Sea Research, and convened Oceans session of the Climate Change Congress, Copenhagen March 2009.

Projections of climate change indicate increased precipitation in the equatorial region and at high latitudes and decreased precipitation in the subtropics, and a general increase in ocean stratification. We use the available temperature, salinity and oxygen profile data for the period 1970 to 2005 and satellite altimetry to examine the evidence for such Southern Ocean changes on a range of time scales including eddy time scales. Globally we find increased salinities near the upper-ocean salinity maximum and decreased salinities in the Southern Ocean surface waters and intermediate salinity minimum (~700m deep). These salinity changes imply about a 1% decrease in the precipitation-minus-evaporation over the mid-latitudes oceans and about a 5% increase in the precipitation-minus-evaporation in the Southern Ocean since 1970. These new and independent ocean derived estimates of changes in precipitation-minus-evaporation extend the growing evidence for an acceleration of the Earth's water cycle. An analysis of oxygen changes through out the Southern Ocean shows a coherent decrease in zonal averages at almost all latitudes above 1500m. Sub-ducting mode and salinity minimum waters in Southern Ocean have reduced oxygen concentration, and the upwelling circumpolar-deep water is also reduced (up to 10%). These changes are most simply explained by increased biological consumption resulting from reduced renewal rates. The inventories of oxygen, heat and sea-level show that these Southern Ocean outcropping density surfaces are driving these decreases in oxygen and increases in heat and sea-level. We compare these changes with projections of future climates for the Southern Ocean.

Southern Ocean Acidification: a tipping point at 450 ppm atmospheric CO_2

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Dr. Richard Matear is a Senior Research Scientist at CSIRO Marine and Atmospheric Research and works as a member of the Australian Community Climate and Earth System Simulator team. He is an oceanographer who specializes in the role the ocean plays in modifying both our climate and the atmospheric levels of CO_2. He has pursued many studies that investigate how global warming and rising CO2 levels in the atmosphere affect the oceans' carbon cycle and marine ecosystems. Richard recently co-authored a paper with Ben McNeil (Proceedings of the National Academy of Science, 2008), which showed given our projected human emissions of CO_2 there will be significant acidification of the Southern Ocean by 2045.

Southern Ocean acidification via anthropogenic CO_2 uptake is expected to be detrimental to multiple calcifying plankton species by lowering the concentration of carbonate ion (CO_3) to levels where calcium carbonate (both aragonite and calcite) shells begin to dissolve. Natural seasonal variations in carbonate ion concentrations could either hasten or dampen the future onset of this undersaturation of calcium carbonate. We present a large-scale Southern Ocean observational analysis that examines the seasonal magnitude and variability of CO_3 and pH. Our analysis shows an intense wintertime minimum in CO_3 south of the Antarctic Polar Front and when combined with anthropogenic CO_2 uptake is likely to induce aragonite undersaturation when atmospheric CO_2 levels reach 450 ppm. Under the IPCC IS92a scenario, Southern Ocean wintertime aragonite undersaturation is projected to occur by the year 2030 and no later than 2038. Some prominent calcifying plankton, in particular the Pteropod species Limacina helicina, have important veliger larval development during winter and will have to experience detrimental carbonate conditions much earlier than previously thought, with possible deleterious flow-on impacts for the wider Southern Ocean marine ecosystem. Our results highlight the critical importance of understanding seasonal carbon dynamics within all calcifying marine ecosystems such as continental shelves and coral reefs, because natural variability may potentially hasten the onset of future ocean acidification.

How could rates of changes in biodiversity that result from climate change be measured in the short term and monitored over longer terms?

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Dr. Colin Southwell is a research scientist with experience in the broad-scale assessment and monitoring of wildlife populations in both terrestrial and marine environments. His current focus is on finding cost-effective designs and methods to extend the CCAMLR Ecosystem Monitoring Program in east Antarctica to cover greater spatial scales and to allow the differentiation of fishing impacts from climate change impacts. He has previously worked on population monitoring programs of commercially harvested kangaroo species across Australia at state and continental scales, and on population surveys of pack-ice seal populations across east Antarctica.

Monitoring change in Southern Ocean biodiversity would require measurement of numerous physical and biological parameters at broad spatial and temporal scales. These large scales would require adequate replication of measurements in space to take account of natural spatial variability, and repeated measurement over time to take account of natural temporal variability. Distinguishing change due to climate change from changes caused by other impacts such as fishery operations would also require either the manipulation, within a spatial design framework, of those impacts over which we have some control, or the development of a priori hypotheses about how the different impacts would affect biodiversity. In both cases, attributing the cause of any change would also require careful selection of appropriate parameters to collectively represent the system state. Ideally, these design-related decisions that should drive the choice of the specific methodologies that are used for taking measurements, or if no suitable methods exist, to drive the development of new methods to meet the design requirements. From a practical perspective, measurement methods also need to be cost-effective in order for monitoring to survive long term funding vagaries, as well as robust technological improvements that may confound long term time series measurements.

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Day 2: Change in Antarctic and Southern Ocean marine ecosystems – past, present and future

Changes in the Antarctic marine ecosystem

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Professor Eugene Murphy is Science Leader of the British Antarctic Survey's Ecosystems programme and a Visiting Professor at the University of Newcastle (UK). He has over 20 years experience in analyses and modelling of ocean ecosystem processes he has led the BAS ocean ecosystem programmes for over 10 years undertaking interdisciplinary analyses of the operation of oceanic ecosystems involving a multi-disciplinary team of scientists. He has interests in the physical and biological processes interactions determining the operation of large-scale ocean ecosystems and his studies have encompassed analyses of the spatial operation of populations and ecosystems and the impacts of climate variability and fisheries, which have been underpinned by a range of modelling approaches.

The Southern Ocean is undergoing major and rapid physical change, but there is marked regional variation in the form and magnitude of these changes. Here we discuss how the Southern Ocean ecosystem is responding to these physical changes. We highlight some of the contrasting effects being observed, for example, the different responses in areas of rapid regional warming and sea-ice reduction as opposed to those where sea-ice extent is increasing. We draw on extensive studies of interannual variability to consider how variation generated through large-scale climate-related processes affects both individual species and the overall structure of Southern Ocean ecosystems. These studies highlight, firstly, the importance of understanding the links between large-scale physical and biological processes that generate change, and secondly, the need to consider the historical effects of both climate and harvesting driven change. Finally, we consider issues in predicting the responses of Southern Ocean ecosystems to physical and chemical changes over the next century.

Antarctic Sea Ice – Complexities and Patterns in Distribution and Properties, and Their Physical and Ecological Implications

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Dr. Rob Massom has been involved in both Antarctic and Arctic sea ice research since 1980, and is currently a senior research scientist with the Australian Antarctic Division and Antarctic Climate and Ecosystems CRC in Hobart. His current research interests include large-scale spatio-temporal change/variability in sea ice and snowcover distribution; fast ice and penguins; validation of key satellite-derived sea ice geophysical/climatic data products; and sea ice-ice sheet interactions – all with a strong multi-disciplinary focus. He is the author/co-author of three books on remote sensing of polar regions, and two recent book chapters on snow on sea ice and polynyas.

Covering approximately 19 x 10^6 km^2 of the Southern Ocean at maximum annual extent (September-October) and diminishing to 2-4 x 10^6 km^2 each February, sea ice plays a profound, complex and highly variable role in the global climate system through its impact on high latitude atmosphere-ocean interaction processes. Given its intimate relationship with oceanic and atmospheric forcing and the rapidity of its response to changes in such forcing, Antarctic sea ice also represents a sensitive indicator and modulator of climate variability and change. Moreover, it plays a dominant physical role in structuring high-latitude Southern Ocean ecosystems over a range of scales. Indeed, the seasonal cycle of sea ice advance and retreat is one of the major drivers of ecological (and physical) processes in the Southern Ocean. This talk will first give an overview of recurrent large-scale patterns that recur in Antarctic sea ice distribution and the reasons for these patterns. For this purpose, the largely seasonal sea ice cover is broken down into a series of zones or régimes (each with distinctive characteristics), with particular attention being paid to the coastal marine zone. Here, the distribution and characteristics of both pack and fast ice are strongly affected by coastal configuration and the presence of grounded icebergs. The talk will then draw upon regional case studies to illustrate the complex nature and consequences of recent change and variability in sea ice distribution and properties around Antarctica. These include the physical and ecological impacts (both positive and negative and at times unexpected) of extreme sea ice conditions in the Antarctic Peninsula region in response to anomalous patterns of large-scale atmospheric circulation. "Positive" ecological impacts include a major phytoplankton bloom, while "negative" impacts include a disastrous Adélie penguin (Pygoscelis adeliae) breeding season. In addition, variability in coastal fast ice and iceberg distributions are shown to have a first-order impact on the breeding success of Emperor penguins (Aptenodytes forsteri). The results underline the complexity of the Antarctic system and the need to more fully understand the links between different components of the cryosphere i.e., sea ice and the Antarctic Ice Sheet, as well as the impacts of variability and change in large-scale patterns of atmospheric and oceanic circulation.

Dynamics of mesopelagic species and assemblages

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Dr. Dirk Welsford has had over 10 years experience as a fish biologist and ecologist, working in southeastern Australia and the Southern Ocean, from shallow reef, to pelagic and deep ocean habitats. Much of his field research has been orientated at understanding the biology, ecology and population dynamics data of target and bycatch species in fisheries, as well as quantifying and mitigating the impacts of fishing. He is also particularly interested in methods of bringing scientific and logical rigour to decision making frameworks used in resource and environmental management.

Mesopelagic fishes, such as myctophids, Pleurogramma and icefishes, and squids, play a crucial role in pelagic ecosystems in the Southern Ocean. Concentrations of mesopelagic biota are a characteristic of the outer shelf and slope areas of the sub-Antarctic Island groups and the Antarctic continent, as well as in frontal systems. They form a critical energy pathway, whereby diverse smaller zooplankters are consumed by these mesopelagic predators, concentrating them into a form that can be readily and efficiently consumed by higher order predators such as seabirds and mammals. Large scale diurnal migrations of these mesopelagic species also link the mixed layer and deeper waters. Hence mesopelagic communities are a useful integrator of many ecosystem processes, and are likely to be responsive to predicted climate change impacts on the physical environment, such as changing depth of the mixed layer, and the alteration of frontal systems in relation to islands and submarine topography.

Southern Ocean Continuous Plankton Recorder Survey.

Graham Hosie

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Dr. Graham Hosie is a Principal Research Scientist at the AAD leading the Ocean Biodiversity & Global Change unit within the Environmental Protection & Change programme. He has been with the AAD 25 years studying krill and zooplankton ecology. Currently, he is Director of the SCAR Southern Ocean Continuous Plankton Recorder Survey, a plankton monitoring programme involving 15 nations, as well as co-Director of the Australian AusCPR Survey for the Integrated Marine Observing System. He is a governor of the Sir Alister Hardy Foundation for Ocean Science which runs the northern hemisphere CPR surveys and is involved with a number of other relevant committees; chair of the SCAR Expert Group on CPR research, a member of the SCAR-SCOR Expert Group on Oceanography which coordinates SOOS, and invited expert on the SCAR-MarBIN and CAML steering committees.

Antarctic plankton are expected to be particularly sensitive and vulnerable to climate change. Global warming will affect sea ice patterns and plankton distributions. Increased UV levels, ocean acidification, invasive plankton species, pollution and harvesting impacts are also potential major threats. These effects may act synergistically. The SO-CPR Survey was established in 1991 by the AAD to map the spatial-temporal patterns of zooplankton and then to use the sensitivity of plankton to environmental change as early warning indicators of Southern Ocean health. Several nations tow CPRs in the Southern Ocean providing a near circum-Antarctic Survey. The CPR is towed 100m behind a ship at 10m depth, at normal cruise speed. Plankton are trapped between two sheets of 270μm silk mesh representing 450 nmiles. Underway oceanographic and meteorological data, e.g. sea surface temperature, salinity, fluorometry, light, are collected at the same time and combined with the plankton data. More than 27,000 samples of 5 nmile resolution have been collected since 1991for 200+ taxa. Most data comes from October to April. Some winter tows south of Australia have been made. CPRs are used globally to readily distinguish regional, seasonal, annual and long-term variation in plankton patterns. The SO-CPR Survey has already identified two major changes in zooplankton composition in eastern Antarctic waters: first around 2000 in the sea ice zone (SIZ) when meso-zooplankton became more dominant; second, in 2004/05 when pelagic foraminiferans numbers increased by more the 25 times.

Long term changes in top predators in the Southern Indian Ocean and relationships with climate and human activities

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Dr. Henri Weimerskirch is a Research Director at the CNRS in Chizé France. He is Head of the "Marine Top predators" Unit, a research group of 30 persons working on the link between environmental variability, foraging behaviour and demography of marine mammals and seabirds. He is coordinator of the long term program funded by the French Polar Institute 'Seabirds and marine mammals as sentinels of climate change in the southern ocean'. Henri and several members of the group are also involved in conservation programs, in particular on the impact of fisheries and on comparative studies between tropical and polar marine systems. He published more than 200 papers in peer reviewed journals and is member of several national and international committees on research and conservation.

Worldwide ecosystems are modified by human activities and climate change. To be able to predict future changes it is necessary to understand their respective role on population dynamics. Populations of 22 species of seabirds and seals have been monitored on four sites in the Southern Ocean French territories over the past 50 years. Extensive changes have occurred with many populations having declined whereas others have increased or fluctuated with no clear trends. We show that several of these changes are related to environmental variability and that for some species especially in Antarctica a clear cyclicity in demographic parameters occurs and is directly related to variability in climate or sea ice extent. In the sub-Antarctic and sub-tropical waters, several species of albatrosses are affected by both human activities, especially longline fisheries, and climatic fluctuations. Using a comparative approach we assess the relative impact of climate and fisheries during and outside the breeding season on seven albatross and petrel species. We show that adult survival of almost all species was not affected by climate, and therefore probably canalized against climatic variations, but was negatively affected by tuna longlining effort whereas fecundity is affected by climate, and especially Southern Oscillation. Differences in demographic responses are related to the foraging ecology during and outside the breeding season. Using IPCC scenarios we show that future climate changes will have contrasted effects on several species of seabirds.

Responses of Southern Ocean whales to climate change

Nick Gales

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Dr. Nick Gales has a background in applied marine mammal conservation science. Originally graduating as a veterinarian and then moving to applied science through a PhD program on Australian sea lions, he has enjoyed working on the science that underpins the policy and management of marine mammal and human interactions in many arenas. He has conducted detailed physiological, reproductive and movement studies of seals, dugongs, whales and dolphins in a range of environments including Antarctica, Australia, New Zealand and many of the subantarctic islands. Nick is now the Leader of the Australian Marine Mammal Centre, based at the Australian Antarctic Division in Hobart. Among other roles he also heads up Australia's delegation at meetings of the International Whaling Commission's Scientific Committee, and is the Oceania coordinator for the IUCNs cetacean specialist group.

Whales and other marine mammals in the Southern Ocean were almost extirpated in the 19th and 20th centuries. Although some whale populations are recovering well since industrial whaling ceased, and the species which are evident on our coasts are increasingly well studied, others remain at only remnant population sizes and are poorly studied and understood. Consequences of the near complete removal of much of the biomass of these higher level predators, along with changes in food web dynamics arising from climate change mean that expectations that the community structure and biomass of whales and other predators will return to historic patterns are likely naïve. The concomitant effects on Southern Ocean ecosystems of recovering predator populations and modern climate effects mean that forecasting plausible future scenarios for populations is difficult, and highlights the need for integrated ecosystem-scale studies and well designed, long-term monitoring strategies. This paper will outline recent advances in research on understanding the recovery of whales, and the role of environmental factors in influencing the future recovery and dynamics of these species. In particular, the paper will outline the outcomes of discussions at the recent IWC Workshop on Cetaceans and Climate Change and the Workshop to develop a Southern Ocean Regional Partnership which aims to improve our understanding of the status, health, dynamics and environmental linkages of whales and the threats they face. It will then provide an integration of those outcomes to identify possible directions for research in understanding the response of Southern Ocean whales to climate change. For example, a range of single-species studies expected to be focussed on IWC outcomes could be embedded within larger, international research efforts into Southern Ocean ecology and change. In conclusion, it will be proposed that some whales lend themselves most effectively to sentinel roles and could be utilised in a Southern Ocean Sentinel program, including the humpback and Southern Right whales. Research underway indicates that these species might provide useful signals of different changes occurring in different regions of the Southern Ocean.

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Day 3: Measuring change – populations, species and ecosystems

Measuring change in krill abundance

Steve Nicol

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Dr. Steve Nicol joined the Australian Antarctic Division in 1987 to lead the krill research team. He was acting Program Leader for the Biology Program from 1992-1995 and since 1999 has been Program Leader for the Antarctic Marine Living Resources Program (later renamed the Southern Ocean Ecosystems Program). His research interests include all aspects of the biology and ecology of krill, Antarctic fisheries, and the dynamics of Southern Ocean ecosystems. He has been a member of Australia's Delegation to the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) since 1987 and has served as office holder in CCAMLR as well as in a number of international scientific organizations. Steve is on the Steering Group of the Southern Ocean Global Ecosystem Dynamics (GLOBEC) and the Integrated Circumpolar Climate Interactions and Ecosystem Dynamics (ICED) Programs. He has produced a smorgasbord of around 150 scientific papers.

Krill (*Euphausia superba*) abundance data are available from a number of sources: from net surveys (the longest historical series of available date), from acoustic surveys, from fisheries data and from the distribution of krill predators. Each of these forms of data collection has its own biases and limitations and our current understanding of krill abundance comes from utilising the various forms of data to the maximum extent possible. Time series data are really only available from the South Atlantic where scientific netting programs and annual acoustic surveys have been carried out annually. The South Atlantic is also the area where the fishery has concentrated for the last 20 years. There have been suggestions of changes in the abundance of Antarctic krill, based mainly on analysis of available scientific net data. There is also evidence of intense inter- and intra-annual variability of krill abundance within regions. These fluctuations in abundance make it difficult to detect long-term trends.

Measuring change in marine habitats

Daniel Costa
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Daniel Costa is a Distinguished Professor of Ecology and Evolutionary Biology at the University of California at Santa Cruz and holds the Ida Benson endowed Chair in Ocean Health. His research focuses on the ecology and physiology of marine mammals and seabirds and he has worked in almost every habitat from the Galapagos to the Antarctic and on a broad range of animals including penguins albatross, seals, sea lions, whales and dolphins. His first experience with Antarctic Research started when he assisted Dr. Gerald Kooyman with the deployment of some of the earliest time depth recorders on Weddell seals in the Ross Sea in 1978. Since that time he has worked on South Georgia Island and the Antarctic Peninsula. He was Chief Scientist for two U.S. Southern Ocean GLOBEC winter cruises and has been one of the pioneers in using animals as ocean sensors. In addition to his Antarctic Research, along with Barbara Block he founded the Tagging of Pacific Predators program, which is a multidisciplinary effort to study the movement patterns of marine predators in the North Pacific Ocean.

The foraging behavior of top predators can be used to measure both direct and indirect changes in the marine environment. Top predators integrate resources over time and space and depending on the particular species they represent different components of the marine environment. For example, southern elephant seals forage over very large distances and reflect changes in marine communities over large spatial scales; in contrast at least in the Western Antarctic Peninsula Crabeater seals forage widely along the continental shelf, while Weddell seals appear to forage in very restricted areas. Changes in their foraging patterns reflect changes in their preferred habitat and can be used to understand changes in their population trajectories. Foraging behavior can be monitored using a variety of techniques from biotelemetry to stable isotopes. While biotelemetry provides the most detailed analysis of behavior and patterns, variation in stable isotopes levels reflect changes in trophic patterns and can be applied to both modern and historic samples. Finally, sensors can be deployed on large marine predators to acquire information on the changing physical environment. The maximum depths recorded for the seals led to the discovery of several deep troughs that extend from the outer to inner continental shelf near the WIS. These troughs provide conduits for the across-shelf movement of warm (>1°C) Upper Circumpolar Deep Water (UCDW) (also identified from the seal temperature profiles) and for transport of water at all depths across the ice-shelf front. These data suggest that the thinning of the WIS during the two decades prior to the 2008 break-up events may be explained by a reduction in summer sea-ice distribution leading to increased solar heating of the upper ocean. The hypothesized influence of ocean warming on the ultimate break-up of the WIS in 2008, and the feedback from the WIS to the surrounding ocean, although speculative demonstrates the value of ongoing seal-based measurements as a mechanism for more routine monitoring of the oceans in such biologically active regions.

Measuring change in marine benthos

Martin Riddle and Jonny Stark

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Dr. Martin Riddle joined the Australian Antarctic Division in 1994 to develop and lead a program of research to understand and mitigate the impacts of people in the Antarctic on the Antarctic environment, in support of Australian policy of comprehensive environmental protection for Antarctica. The scope of the program was broadened in 2006 to include impacts of global change on Antarctic biodiversity. He trained as an applied marine ecologist with his PhD focusing on the cost-effective optimisation of benthic monitoring to identify impacts of the North Sea oil industry. He has published with a large network of co-workers on a wide range of environmental topics leading to practical measures to reduce impacts. His approach is to identify key processes in the Antarctic environment that influence its sensitivity to environmental perturbations and that should be accommodated when deciding how human activities are best managed to mitigate impacts.

Marine benthic communities are widely used throughout the world for environmental monitoring. The characteristics that make them particularly well suited to this purpose will be discussed. In planning any benthic monitoring there are a number of key decisions to be taken, including which component of the benthos to focus on, sieve and sampler sizes, number of replicates, stations and sampling times and taxonomic resolution. There is a trade-off between many of these factors, for example, for a fixed cost it may be possible to increase replication by reducing sampler size or taxonomic resolution.

The objective of all monitoring is to identify meaningful change against the background of natural spatial and temporal variability. All benthic systems are subject to some common patch generating processes, but the benthos of polar-regions is subject to additional processes unique to regions influenced by ice. The interactions of ice and benthos are only beginning to be understood and will be discussed. As well as being a significant source of variability in the benthos now, ice also has the potential to be an important mechanism for climate change to impact on benthic systems in the future (50-500+ years). Over medium time-scales (10-50 years), ocean acidification caused by increasing atmospheric CO_2 may have major and widespread impacts on benthic calcifiers, particularly those that rely on the more soluble aragonite form of calcium carbonate. Over the shortest time-frame (1-10 years), the most likely impacts are from local pollution caused by accidental spills and poor waste management practices and physical disturbance of the sea-bed from fishing with trawls and long-lines.

Sites may be subject to the simultaneous, interacting effects of more than one of the above processes. Measuring change in marine benthos is easy, attributing change to a particular cause is very much more difficult and requires understanding of how the benthos functions and how it interacts with its environment.

Monitoring the response of marine predators to climate change

Phil Trathan

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Dr. Phil Trathan is a senior research scientist with an extensive publication record on the biology, ecology, and sustainable management of marine resources in the Antarctic and South Atlantic. He has wide experience and an established track record of interdisciplinary research, commissioned research, and international collaboration. Phil carries out fundamental research into the marine ecosystem of the Southern Ocean, in particular studies that identify the causes of spatial and temporal variability in ecosystem relationships. His current focus is on developing an understanding of natural predators and the way that they exploit resources. He also has an interest in the sustainable use of marine living resources and the ways ecosystems can be managed. He therefore also has a natural interest in the overlap between dependent species and commercial fisheries that target the same resource. Phil is currently the senior research scientist leading the British Antarctic Survey's core-funded science that is investigating predator–prey–fishery interactions in the Scotia Sea. Other research activities focus on the foraging activity of predator species and their interactions with the physical environment, particularly relating organisms to the mesoscale and large-scale hydrographic features of the Southern Ocean and how they respond to ocean and climate variability. He is also interested in inter-disciplinary studies on the Antarctic krill population in the Scotia Sea. This includes studies of krill and their predators, and of the oceanographic environment of the Southwest Atlantic and beyond. Through the Convention for the Conservation of Antarctic Marine Living Resources, Phil has worked with numerous collaborators on questions relating to how the krill-dependent Southern Ocean ecosystem should be managed.

The impacts of climate change are likely to affect higher trophic levels in a variety of ways. For seabirds and marine mammals most responses will be evident as changes in behaviour, phenotypic expression or in genotype that result in one or more of the following:

- Changes in distribution. At its simplest, a pole-ward shift in ranges may be evident;
- Match-mismatch changes. The matching of the timing and distribution of reproduction for many higher trophic level animals is critical to successful breeding;
- Changed patterns of movement. If the distribution of important prey species are also altered by changes in the climate, then regular commuting between breeding sites and feeding grounds may be affected. Similarly, migration routes between summer and winter feeding grounds may be altered;
- Changes in population density. Population sizes and densities may change due to the direct effects of extreme environments, through impacts on vital rates (such as survival, fertility, breeding success). Populations may fragment, and genetic diversity may be reduced;
- Changes in phenology. As a consequence of changed environmental conditions, a wide variety of processes could alter in their absolute timing over the course of a year;

- Changes in behaviour. Diurnal patterns of activity and behaviour may also change as a consequence of altered environmental conditions;
- Change in community interactions. If climate change impacts upon a number of trophic levels, then wholesale community changes may become evident. This may be apparent as a 'regime shift' or as changes in the foodweb as new species interactions or predator-prey interactions develop;
- Changes in morphology or physiology. As environmental conditions alter, animal populations may respond by changes in morphology, such as changes in body mass or breeding performance, either as a result of energetic constraints, or because of altered physiological efficiencies.

Detecting these changes in the context of other environmental signals requires dedicated field monitoring. In this paper I examine examples from the literature and explore some of the issues associated with the monitoring effort necessary.

Practical examples on deciding how to measure change in biota

Beth Fulton
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Dr. Beth Fulton is a Principal Research Scientist and holds a CSIRO CEO Science Leader fellowship. Beth began her science career at James Cook University in Townsville (where she did a Bachelor of Science). She graduated with first class Honours (jointly in Mathematics and Marine Biology) in 1997. Beth then moved to Hobart to do her PhD on "The effects of the structure and formulation of ecosystem models on model performance" at the University of Tasmania (in the School of Zoology and the Tasmanian Aquaculture and Fisheries Institute). From there she moved into CSIRO where she now leads the marine ecosystem modelling team. Beth is also an Honorary Associate at the Centre for Marine Science, University of Tasmania. Beth developed the Atlantis modelling framework, which has been used to provide strategic advice to the Australian Fisheries Management Authority and has been applied to 19 marine ecosystems around the world. Beth also co-developed InVitro, which allows users to explore the impacts and management of the myriad of pressures on marine and coastal environments. These models are some of the first to give equal attention to biophysical and human components of marine ecosystems. They underpin CSIRO's research into managing potentially competing uses of Australia's marine environments and have been used in Australia and North America to consider the most effective means of monitoring marine ecosystems.

Monitoring of marine systems is attracting increasing attention as its realised that longer term time series are required for detecting and unravelling climate impacts, but also for monitoring systems in the context of ecosystem-based management. Whole-of-ecosystem models are a useful platform for exploring monitoring options and pitfalls and have been used to identify the most informative and robust kinds of ecological indicators. Many of the most effective indicators are based on relative biomasses or size of animals. These model results are in accord with what has been found empirically in places, such as the northeast US, where there is a long history of multispecies monitoring. While sensor technology is in an a period of accelerated growth right now, many of these are years away from successful deployment in a polar environment. Consequently, older technology and methods will still be a significant component of Antarctic monitoring for years to come. Drawing on a combination of model output and real world experience it is possible to identify cost effective monitoring regimes that are based around the use of indicator species, simple measurement schemes and value-added sampling.

NOTES

Day 4: Requirements in designing a long-term field program to detect and estimate rates of change

Can we detect, interpret and predict Southern Ocean change?

Steve Rintoul

Antarctic Climate and Ecosystems CRC and Centre for Australian Weather and Climate Research, Private Bag 80, Hobart, Tasmania 7001, Australia.

Dr. Steve Rintoul is a physical oceanographer studying the role of the Southern Ocean in the Earth's climate system. He also has a keen interest in how ocean currents influence sea ice, biogeochemical cycles, and the distribution of biological productivity. He is an active sea-going oceanographer, who has led 10 expeditions to the Southern, Indian and Pacific oceans. In his role as co-chair of the SCAR Expert Group on Oceanography and member of the CLIVAR-CliC-SCAR Southern Ocean panel, he has been leading the development of a plan for a Southern Ocean Observing System. Steve leads the Climate Variability and Change program of the ACE CRC.

Detecting change in a system, by definition, requires measurements from different time periods. When the system, like the Southern Ocean, has energetic variability at many time-scales, the duration of the time series needs to be many times longer than the time-scale of the phenomenon one hopes to observe. In the case of climate change impacts in the Southern Ocean, this means the measurements must span many decades or more. We have very few physical oceanographic observations that are adequate for the task and arguably no biological or ecological time series that come close. So what can we do? We can make progress by: 1) securing a sustained future for the present "golden age" of Southern Ocean observations (mostly physical and biogeochemical), based on Argo, satellites, hydrography, underway sampling and animal-borne sensors; 2) starting now to establish time series of biological and ecological variables that are suitable for sustained measurements (eg underway measurements of phyto- and zooplankton); 3) detecting and understanding short-term variability, and use this mechanistic understanding to interpret short and incomplete historical records and to improve models used for future projections; 4) recovering as much historical data as possible; and 5) articulating the global significance of Southern Ocean change to ensure sustained commitment to the observing system. The presentation will summarise plans by the international community to use this strategy to design and implement an integrated, multi-disciplinary Southern Ocean Observing System.

Using remote sensing to monitor oceans and ice

Kevin Arrigo
Department of Environmental Earth System Science, Stanford University, Stanford, CA, USA

Assoc Prof. Kevin Arrigo has been using satellite remote sensing data to understand Southern Ocean physics and biology since 1992. While on a post-doc at NASA (Goddard Space Flight Center - Oceans and Ice Branch), he worked closely with both the ocean color and sea ice groups and helped develop algorithms leading to better correction schemes for atmospheric aerosols and improved retrieval of snow thickness from passive microwave data. His specialty now, however, is using remotely sensed ocean color, sea surface temperature, and sea ice distributions to estimate spatial and temporal variability in primary production in the Southern Ocean.

Due to its relative inaccessibility to research vessels for much of the year, satellite remote sensing of the Southern Ocean has proven to be a useful tool for characterizing its spatial and temporal variability. Since the late 1970's, sea ice concentration has been routinely quantified using passive microwave sensors, which have the advantage of being much less sensitive to cloud cover than sensors that operate within the near-infrared and visible portion of the electromagnetic spectrum. More recently, passive microwave sensors such as SSM/I and AMSR-E have been used to characterize sea ice motion and the thickness of snow cover overlying the sea ice in Southern Ocean waters. Sea surface temperature (SST) and sea surface height (SSH) are also routinely measured from satellite, although the former suffers somewhat from the high cloud cover in the Southern Ocean and the latter is of relatively course resolution. Biological properties amenable to quantification using satellite remote sensing tools include particulate organic carbon and phytoplankton chlorophyll a. Recent studies based on remote sensing technologies suggest that over the last decade, changes in ice cover and phytoplankton primary production in the Southern Ocean are relatively small compared to changes ongoing in the Arctic. Nevertheless, local impacts can be significant, particularly in the vicinity of the Antarctic Peninsula.

Understanding and monitoring climate change in the Southern Ocean mesopelagic environment

Eileen Hofmann
Center for Coastal Physical Oceanography, Old Dominion University, Norfolk, VA 23508, USA.

Eileen Hofmann is a Professor in the Department of Ocean, Earth and Atmospheric Sciences and a member of the Center for Coastal Physical Oceanography, both at Old Dominion University, Norfolk, Virginia. She received a B.S. degree in Biology from Chestnut Hill College in Philadelphia, PA and M.S. and Ph.D. degrees in Marine Sciences and Engineering from North Carolina State University, and held a postdoctoral position at Florida State University. Her research interests are in the areas of understanding physical-biological interactions in marine ecosystems, climate control of diseases of marine shellfish populations, descriptive physical oceanography, and mathematical modeling of marine ecosystems. She has worked in a variety of marine environments, most recently the continental shelf region off the western Antarctic Peninsula. She was co-editor of two volumes of Deep-Sea Research II that are devoted to the results of the Southern Ocean GLOBEC program. She is Chair of the GLOBEC Southern Ocean Planning Group and the U.S. Southern Ocean GLOBEC Science Steering Committee and is Vice Chair of the Scientific Committee for Antarctic Research Southern Ocean Working Group.

The mesopelagic region of the Southern Ocean is dominated by a warm (2.0°C), salty (34.72), high-nutrient water mass, Circumpolar Deep Water (CDW), that has its origins in North Atlantic Deep Water (NADW). CDW is found at 1000 m to 2000 m in the Antarctic Circumpolar Current (ACC) and shoals to about 200 m near the Antarctic continent. Thus, in regions where the southern boundary of the ACC is along the shelf break, the mesopelagic environment comes into direct contact with the continental shelf environment through on-shelf intrusions of CDW. CDW dominates heat, salt, and nutrient budgets of the continental shelf, influences sea ice concentration, and affects the food web by its control on primary production, plankton species composition, and the success of Antarctic krill (Euphausia superba) reproduction. For the oceanic environment, CDW provides a unique deep-water habitat. The structuring of the Southern Ocean mesopelagic environment by a single water mass makes this region, and by association the continental shelf system, vulnerable to large scale climate changes that produce variability in the NADW source region, the transport of the ACC, and the location of the ACC fronts. Detecting changes in the mesopelagic environment requires a sustained, circumpolar Southern Ocean Observing System that includes oceanic and continental shelf sites and is linked to a larger global observing system. This presentation will provide a discussion of potential modifications to the Southern Ocean mesopelagic environment that may result from climate change, discuss the implications of these changes for the food web (oceanic and continental shelf), and propose measurement systems that allow detection and quantification of environmental and biological changes in this region.

Measuring change in marine ecosystems: theory and practice

Peter Fairweather

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Prof. Peter Fairweather has 30+ years experience working at Flinders, Deakin, Macquarie and Sydney Universities as well as CSIRO on a wide range of aquatic ecosystems. As a quantitative ecologist specialising in field or modelled assessments of ecological variation using well-designed sampling and manipulative experiments, Peter believes that sound environmental management of our seas must be based on understanding how such ecosystems work, and suggests that this can be achieved by co-operation among scientists from many disciplines and involving stakeholders from the wider public. To embrace this view he suggests we must be skilled in using arcane tools of trade such as experimental design, statistics, visualisation, epistemology, and scientific communication.

The detection of change in ecosystems and its measurement can pose daunting challenges and so considerable thought should be applied before implementing any sentinel program. Ecosystems and biodiversity tend to be multivariate concepts that are more involved than mere population dynamics, and so there is usually substantial effort required in just measuring their multiple components. Some useful indicators can be functional in nature but the majority are still purely structural. Changes may go in several divergent directions and so we need to be clear about what we presume for any system. There is a role for clear predictions made beforehand (often from modelling) that allow us to then fine-tune what we are trying to detect. Such careful design will maximise the chance of detecting what is meaningful. In addition, we need to prepare for surprises occurring via serendipity (because we know little of some systems, especially offshore). In such cases we should back up the first hint of such findings with more in-depth examinations once agreed trigger points have been reached. Examples will be drawn to illustrate such points from extensive environmental programs, e.g. the Coorong, and the state system of marine protected areas in South Australia.

Approaches for matching objectives, monitoring and decision making in the face of uncertainty?

Bill de la Mare
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Dr. Bill de la Mare is Leader of the Marine Nation Theme in CSIRO's Wealth from Oceans Flagship. He has worked on a wide range of topics of broad interest in marine resource management and has been very influential in international and national conservation and management bodies, both in science and policy development. He has specialized in the development of management methods for marine living resources, including extensive experience in the development of statistical methods for the scientific assessment of marine mammals, fish and seabirds. He was an early developer of the precautionary approach to the management of capture fisheries.

Planning long-term programs to measure change can benefit from a number of advances in designing science programs to support marine ecosystem management over the last two decades. The development and management of complex systems in industrial control provides a source of practical guidance on how to approach the ideals of marine ecosystem management. Industrial control systems focus on objectives and outcomes, are hierarchical and localise and distribute control tasks. The principles of hierarchical control systems and focusing on outputs helps overcome the conceptual difficulties associated with designing research programs when ecosystem theory is poorly developed. An important factor in these considerations is how to accommodate learning in updating monitoring and research activities.

Prospective evaluation of management systems has been shown to be a very successful way for designing such field programs, so that they are cost-effective and likely to meet their objectives. This involves the use of computer simulations and the development of performance measures that demonstrate the likely success of a monitoring system at meeting its objectives. This process is advocated for designing the Southern Ocean Sentinel Program. Given the potentially large range and scales of monitoring that may be proposed, a qualitative decision support framework is presented that could narrow the options for developmental research and monitoring before exploring candidate options with more complex ecosystem simulations.