Mid- to high-latitude oceans

Abstract
The mid- and high-latitude oceans influence climate change and variability by storing and transporting vast quantities of heat, freshwater and carbon dioxide. Australian researchers have played a leading role in discovery of the nature, causes and consequences of change in the mid- and high-latitude oceans of the Southern Hemisphere. Key science questions for the future include the sensitivity of ocean circulation to changes in climate, how and why Antarctic sea ice is changing, and the impact of a warming ocean on the mass balance of the Antarctic Ice Sheet. Progress requires an integrated program of theory, modelling, process studies and sustained observations, as well as more effective collaboration across Australia's innovation sector.

Background
Australian research into the mid- to high-latitude oceans is primarily focussed on the Southern Hemisphere oceans surrounding Australia and interactions of the Southern Ocean with the Antarctic Ice Sheet. Efforts are distributed between publicly-funded research agencies (PFRAs) and the university sector. PFRAs include the CSIRO and the Australian Antarctic Division (AAD), with some engagement from the Australian Bureau of Meteorology (BoM). Within the university sector, research programs at the University of Tasmania (UTas), the Australian National University (ANU), the University of Melbourne (UMelb) the University of Western Australia (UWA) and the University of New South Wales (UNSW, including UNSW Canberra) contribute to this area. Joint research programs between these institutions include the Antarctic Climate & Ecosystems Cooperative Research Centre (ACE CRC: CSIRO, AAD, BoM and UTas) and the Australian Research Council Centre of Excellence for Climate System Science (ARCCSS: ANU, UNSW, UTas).

Australians are at the forefront of global research into Southern Ocean dynamics, and contribute to the international scene through membership of international panels. CSIRO is a world leader in observations of Southern Ocean processes, while AAD/ACE CRC and UMelb have significant expertise in the distribution, properties, biogeochemistry and climatic role of Antarctic sea ice and processes affecting it. The Australian university sector (ANU, UNSW and UTas) have made world-leading contributions to the development of models of the Southern Ocean. The interaction between processes involving the ocean and cryosphere is a rapidly maturing research field, and Australia is well-placed to make a leading contribution to this field in the short-term through the efforts of the ACE CRC, which is funded until mid-2019 and UNSW Canberra.

Australian expertise in mid-latitude oceanography is focussed largely on the Indian Ocean (UTas, CSIRO, UWA) and Southwestern Pacific Ocean (CSIRO, UNSW Canberra, SIMS/UNSW). Both of these regions play an important role in regional climate, and are incorporated into ocean forecasting as well as seasonal prediction models (BoM).

Funding comes directly to institutions noted above, with external funding through the Australian Research Council (ARC), the ACE CRC, the Australian Climate Change Science Program (ACCSP) – now part of Natural Environment Science Program (NESP) – and the Australian Antarctic Science Programme. Research is underpinned by the National Computational Infrastructure (NCI) high-performance computational facilities, the Marine National Facility (MNF), the Integrated Marine Observing System (IMOS) and logistic support from the Australian Antarctic Divison (RSV *Aurora Australis*, Antarctic Bases). There is no significant private investment for this research area within Australia.

Relevance

Interpretation of past changes and projections of future changes in climate depends on understanding the ocean circulation and properties at mid- and high-latitudes and its sensitivity to change. As climate change and variability can directly impact Australian life, this research area is of relevance to a broad community of end users and decision makers in government, industry and the community. Because of their importance for sequestration of heat and carbon, the mid- to high-latitude Southern Hemisphere oceans are of particular significance for sea level rise (including both thermal expansion and melt of ice sheets), for the overall sensitivity of the climate system to greenhouse gases, atmospheric aerosols and ozone depletion., and for ocean acidification.

The Southern Indian/Pacific Oceans also influence Australia's climate on shorter timescales, making these priority areas for seasonal prediction. Models used to forecast seasonal climate are founded on understanding and observations of the ocean and its interaction with the atmosphere. Ocean forecasting systems (e.g. BLUElink) also rely heavily on ocean observations. Improved sea-ice forecasting capability is essential to ensure safe operations in the Southern Ocean and requires better observations and understanding of the coupled ocean, ice, atmosphere system at high latitudes.

Specific end users include government departments responsible for climate change policy; state and local planners responsible for built infrastructure; and decision makers in climate-sensitive industries such as agriculture, water, energy, health, and fisheries. The insurance industry relies on projections of climate change and sea level and has a strong interest in improved reliability of predictions on shorter timescales.

Engagement of end users in government is demonstrated by the long history of support for programs like ACCSP, the ARCCSS, and IMOS. Research and development corporations have invested in climate variability research for many years. Scientists investigating the impacts of climate change and variability (including research into water availability, health, ecosystems, biodiversity and marine resources) are also end users of research into the mid- and high-latitude oceans.

The relevance to end users is illustrated by the high priority given to mid- and high-latitude ocean research in recent national and international research strategies. These include the Plan for Implementing Climate Change Science in

Australia, the Australian Antarctic Science Strategic Plan 2011-12 to 2020-21, Marine Nation 2025, and international programs such as those of the World Climate Research Program (Grand Challenges, the Climate Variability and Predictability [CLIVAR] and Climate and the Cryosphere [CliC] projects), the Southern Ocean Observing System (SOOS), the 2014 Scientific Committee on Antarctic Research (SCAR) Antarctic and Southern Ocean Science Horizon Scan and the National Plan for IMOS.

Science Needs

The mid- to high-latitude ocean's profound role in climate change, weather patterns and global sea level rise motivates the need for continued development of Australian scientific programs and capabilities in this area. This development requires a combination of modelling (and theory), process studies and sustained observations. Specifically, critical research questions which will be the focus of Australian research in the coming decades include:

- *How will the ocean's overturning circulation respond to current and future changes in surface forcing?*
  High-latitude oceans (modulated by seasonally-varying sea-ice coverage) help to govern the ocean's overturning circulation to control oceanic heat and carbon storage on long timescales (Talley 2013). However, the response of the overturning circulation to changes in winds and buoyancy forcing remains poorly understood (Downes and Hogg 2013; Bracegirdle et al. 2013).

- *How and why is Antarctic sea ice coverage changing?*
  While sea ice coverage in the Arctic has reduced dramatically in recent decades, Antarctic sea ice extent has increased overall, with strong regional differences (Maksym et al. 2012). The causes of the changes observed in Antarctic sea ice are not yet understood. Better knowledge of the physics of Antarctic sea ice formation, extent and thickness is needed to allow improved projections of sea ice change and its impacts on the ocean, atmosphere, ice shelves, and ice sheet.

- *To what extent do interactions between the ocean, atmosphere, sea ice and the Antarctic ice shelves control the rate Antarctic ice loss?*
  The rate of discharge of grounded continental ice loss from Antarctica is regulated by the buttressing effect of ice shelves. This buttressing effect is diminished by reductions in ice-shelf thickness and/or areal extent (Thomas et al. 2004). Ultimately, basal melting of floating ice-sheet margins is driven by the supply of ocean heat onto the Antarctic continental shelf and into the sub-ice-shelf cavities (Rignot et al. 2013); this process is therefore sensitive to both ocean warming and circulation changes in and around the under-ice cavity. However, understanding of changes in ocean heat supply to the base of the ice shelves and the resultant ocean/ice-sheet interactions and changes in ice sheet flow remain rudimentary. Furthermore, basal melting of the ice shelves is dependent on baroclinic tides (Robertson 2013), with baroclinic tides increasing basal melt rates by 20-50 % in some regions, even with small

tidal velocities (Robertson 2013). This is a serious shortcoming in climate and ocean circulation models, where baroclinic tides are ignored or poorly simulated primarily due to resolution requirements.

- *How have important regional currents (the East Australian Current, the Leeuwin Current) changed in recent decades, and will these changes continue?*
  Major current systems close to the Australian continental shelf have a significant effect on both marine ecosystems and regional climate (Ridgway and Hill 2012). Considerable advances have been made in understanding the natural variability of these systems (Hill et al. 2011), but continued long-term monitoring and improved dynamical models will allow the causal attribution of observed changes, with a view to predicting future evolution of these currents.

- *How is mid-latitude climate variability influenced by oceanic processes?*
  The decadal variability of the mid-latitude ocean-atmosphere system influences Australian water availability and agriculture. As modelling capabilities progress to higher resolution, ocean variability at decadal timescales increases (Penduff et al. 2011), implying that oceans may generate mid-latitude climate variability. A clear understanding of the ocean's role in driving such variability would enhance our ability to predict climate at seasonal and longer timescales.

The primary goal in mid- to high-latitude oceanography and sea-ice science is to improve the understanding of fundamental processes that underpin predictions of the future evolution of the ocean, and hence climate. These predictions are essential for management of future risks due to climate change and variability.

Perspective

Ocean-Cryosphere Interactions

A significant challenge facing the ocean-climate community is modelling and observing the interaction between the Southern Ocean and the Antarctic Ice Shelves, mediated by sea ice coverage. These interactions control the rate of mass loss from the Antarctic Ice Sheet and hence rates of future sea level rise. Inflow of glacial meltwater also influences ocean circulation and sea ice. A major limitation on the development of this research field is the paucity of observations near the ice-sheet margins and in critical regions where the ice sheet is showing rapid change.

Key priorities are:

- Coincident and simultaneous measurements of the glacial ice, sea ice and ocean properties near the Antarctic margin.
- Improved measurements of bathymetry on the continental shelf, within ice shelf cavities and below grounded ice.
- Quantification of the spatial and temporal distribution of sea ice and ocean properties and ice sheet basal characteristics for use in coupled ice-sheet/ocean models.

- A climatology of baroclinic tides for the circumpolar Antarctic waters, providing estimates of tidally induced changes in basal melting, mixing, dense water formation, and sea ice lead formation.
- Development of coupled models (including ice sheets, sea ice ocean, glacial isostatic adjustment and climate) for assessment of the ice sheet response to changes in floating ice shelves.

The difficulty of making ice/ocean observations in this region means that international cooperation is required to make progress in this field. Australia is well-placed (both geographically and scientifically) to contribute to such international programs, and indeed lead those programs in East Antarctica. This area of research will continue to remain a high priority over the coming decades.

In concert with extending the observations, Australian efforts to model the complexity of ocean-ice interactions will play a critical role in future projections of sea level rise. The technical challenge in this area is to couple ice sheet models with ocean-sea ice models and to evaluate these models against observations. Australia is one of just a few nations with coupled model development programs, making an internationally-recognised contribution to the Climate and Cryosphere (CliC) project of the WCRP and their involvement with the SCAR/IASC/CliC Expert Group on Ice Sheet Mass Balance and Sea Level (ISMASS).

Ocean's Role in Mid-latitude Climate Variability and Change

The dynamical understanding of mid-latitude oceans has developed rapidly over the last decade, with large-scale modelling at higher resolution revealing the role of the ocean in generating climate variability over continental regions (Penduff et al. 2011) and governing the response to climate change. Over the next 5 years, global high-resolution ocean models will allow better prediction of regional variations in ocean change, feeding into seasonal prediction of Australian climate variability.

Warming of the ocean accounts for more than 90% of the extra heat energy stored by the planet since 1970 (Rhein et al., 2013). Measurements of ocean heat content are therefore essential to quantify the earth's energy budget and to track the evolution of climate change (Church et al. 2011). Broad-scale measurements of temperature and salinity are also needed to quantify the thermosteric contribution to sea level rise (e.g. Domingues et al. 2008). Measurements of salinity have been used to assess changes in the global water cycle (e.g. Durack and Wijffels 2010). Sustained measurements of the mid- and high-latitude oceans are needed to identify and understand low-frequency modes of climate variability. Finally, broad-scale measurements of the mid- to high-latitude oceans provide a key tool for the detection and attribution of climate change.

Long-term monitoring of important regional currents, in particular the East Australian and Leeuwin Currents, is an essential component in diagnosing changes in, for example, low-frequency climate variability which have a major impact on Australian climate. Such long-term records form the basis of our understanding of climate change: recent change can be put into context using longer records. There is a strong imperative to maintain these programs.

Combined field-numerical studies targeting key areas (e.g. Kerguelen Plateau and Macquarie Ridge in the Southern Ocean) form an important part of Australian collaboration with the international scientific community (such as the recent SOFINE experimental program). In these studies, modelling can be used for both improving field planning, and for interpretation of results during the analysis phase.

Ocean Overturning Circulation

Recent studies have highlighted the Southern Hemisphere's important role in global ocean overturning circulation (Nikurashin and Vallis 2012; Shakespeare and Hogg 2012). The overturning circulation helps to set deep ocean stratification, thereby governing the ocean's uptake of heat and carbon on long timescales. These studies thus have implications for understanding past changes in climate, as well as providing constraints for models of the ocean carbon cycle.

Australia is a significant international player in measuring the deep ocean changes in stratification, and in formulating the theoretical/computational approaches to understanding the overturning circulation. Over the next decade, Australian contributions will enable a coordinated approach to reconcile observed change with that predicted by models.

The highest priority here is continued monitoring of changes in the properties of Antarctic Bottom Water (AABW) (Rintoul 2007), which flows off the Antarctic continental shelf to occupy the deepest levels of the ocean. These water masses are an integrator of surface and interior processes, and knowledge of long-term changes can be used to constrain the evolution of these processes (Purkey and Johnson 2013). In concert with next-generation ocean models being developed in Australia, the goal is to be able to properly simulate AABW processes within the next decade.

The other mode of overturning that is unique to the Southern Ocean is the mid-latitude upwelling, which is understood to have increased due to changes in Southern Ocean winds in recent decades (Le Quere et al. 2007). Upwelling of water in this region can ventilate the carbon-rich mid-depth ocean waters, thereby controlling ocean carbon content (Russell et al. 2006). However, upwelling systems are difficult to diagnose directly; their evolution must be inferred from the combination of tracer measurements and theory. Australia already has significant investment in such research programs, and is well placed to make world-leading contributions.

Sea Ice Change/Variability and its Effects

By forming a high-albedo, insulating blanket that covers ~4-19 million km^2 of the Southern Ocean each year and producing vast amounts of brine and meltwater (Maksym et al. 2012), sea ice (and its snowcover) strongly affects ocean properties and circulation and atmosphere-ocean interaction processes, and is both a sensitive indicator and modulator of climate change and variability. While we have reasonable understanding of the areal extent and seasonality of

Antarctic sea ice coverage (dating back to 1979), a major current gap is lack of information on the thickness distribution/volume of sea ice and its snowcover, and change with time. Accurate sea ice thickness information is critically important in that it provides an integrated measure of total sea-ice production and, hence, surface salinity flux to the ocean in winter and freshwater input in summer. Current uncertainties in these quantities, of 50-100%, significantly undermine our ability to evaluate models and limit confidence in the accuracy of future projections. Underpinning this uncertainty is another high-priority need: that is, to determine what processes and feedbacks are driving changes in sea ice distribution, mass and properties.

With the focus of international sea ice-climate research being largely on West Antarctica, Australia has a key role to play in leading research towards better quantifying/observing and modelling sea ice change and variability, and its effects on the coupled ocean-atmosphere-ice sheet system, in the East Antarctic sector. This research area presents a considerable challenge requiring cross-disciplinary process studies; sustained observations using novel state-of-the-art instrumentation and satellite remote sensing; and improvement of coupled ice-ocean-atmosphere models, including interactions with the ice sheet. Development of high-resolution regional models capable of resolving key local-scale processes (e.g., polynyas along the Antarctic coastal margin and their role in Antarctic Bottom Water formation), as well as models for forecasting sea ice extent and thickness, is also a high priority.

Realisation

Australia's Integrated Marine Observing System (IMOS) provides the foundation infrastructure on which much of the nation's research in the mid-/high-latitude oceans depends. Continued support for this infrastructure is essential. Platforms supported by IMOS that are critical for mid- to high-latitude ocean research include:

- the Argo profiling float array, which provides sustained, broad-scale sampling of the oceans of relevance to Australia;
- moored time series measurements of key currents of relevance to Australian climate and marine ecosystems, including boundary currents, deep water formation sites, and continental shelf circulation;
- direct air-sea flux measurements;
- instrumented marine mammals;
- underway measurements of physical and biogeochemical variables in surface waters; and
- gliders used to sample shelf and open ocean environments.

IMOS should be supported more for exploratory activities and trials of emerging technologies, including the Antarctic continental shelf seas and accessing sub-ice-shelf ocean environments.

A form of the ACE CRC has been funded since 1991 with successful rebids occurring every 5 to 7 years, which give a transient workforce centred around short-term goals. Establishment of a permanent institute focussed on Antarctic, Southern Ocean and Climate processes, would aid long-term monitoring and model development projects, while also committing to investment in expert personnel.

Australian marine scientists must have access to new technologies for coordinated ocean and sea ice sampling. These include "deep Argo" floats capable of profiling the full ocean depth; profiling floats with new biogeochemical sensors; and ice mass-balance buoys providing simultaneous measurement of sea ice dynamics and growth/melt. A high priority is access to long-range autonomous underwater vehicles (AUV) and measurement packages capable of operating in regions inaccessible by ship, including to deep grounding zones beneath ice shelves, sea ice and fast ice.

Access to ship-time is needed to facilitate marine science voyages on the continental shelf, open ocean and in ice-covered seas. *RV Investigator* provides a much more capable ocean-going vessel than previously available in Australia, but must be operated for 300+ days/year to meet the demand from Australian researchers (the vessel is presently funded for 180 days of operation per year). The *RSV Aurora Australis* and future Australian icebreaker are crucial for work within the sea-ice zone, and sufficient funding to support marine science must be included in the Australian Antarctic Division budget. Present rapid access drilling capability is through the AAD and is limited to ice thicknesses of less than 1000 m, which is appropriate for accessing sub-ice/ocean environments, but expertise in its use is being lost due to staffing reductions.

Australia's national capacity for observations of ocean–ice interaction is limited. As some of the largest uncertainties in projections of future climate and sea level rise result from poor understanding of ocean–cryosphere interactions, enhancements to the high-latitude observing system are needed. Coordinated international deployment of autonomous platforms and moorings in key regions has the potential to revolutionise our understanding of the remote, challenging and under-sampled under-sea ice and –ice shelf environments. Continued access to satellite data is also crucial, and Australia has a leading role to play in algorithm development and calibration and validation of derived geophysical quantities.

Ocean model development in Australia is currently an *ad hoc* arrangement between the university community (focussed via ARCCSS) and publicly-funded research agencies (PFRAs) such as CSIRO, BoM and AAD. National (and international) coordination of these efforts is focussed on individual applications (e.g. ocean forecasting, climate prediction, ocean-ice interaction). Australia's oceanographic contributions would be enhanced by better coordination of these efforts, allowing the benefits of investment in each area to be spread across the community. Crucially, there is also a current gap in Australia's sea-ice modelling capability.

Ocean modelling has been limited by computational power, and this will continue to be a constraint for the foreseeable future. Continued secure funding for the current NCI, which entails a national approach to high-performance computing, is a necessity for Australian marine science. NCI facilitates both the research (through provision of computing power) and provides a common environment to facilitate collaboration between different parts of the research sector. In addition, in-house expertise within NCI provides invaluable high-level technical services to the sector. Modelling groups need to prepare for the significant increase in both storage and computing needs for running next generation coupled climate models and processing of satellite observations, including porting code to new types of computer architectures and maintaining state-of-the-art capability.

The Australian marine and climate science communities are relatively small and split across the university sector and PFRAs. It is essential that scientists in the two sectors collaborate effectively. At present, the shortage of funding sources that can support collaborative work between scientists based at universities and at PFRAs on the same project is a major impediment to research progress. Continued investment in personnel in both sectors is needed to ensure maintenance of Australian expertise.

Long-term logistics support for fieldwork is essential for monitoring slow changes at critical locations. Provision of such support needs to be funded as part of core funding to the agencies operating research vessels and other infrastructure, and not out of the funds available to support research. Such provision would allow the university sector to make meaningful contributions to field-based research, while also providing the long-term monitoring capacity that is essential for disentangling climate change in the mid-to high-latitudes.

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