

Centre for Southern Hemisphere Oceans Research Science Plan 2017 to 2022

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青岛海洋科学与技术国家实验室
Qingdao National Laboratory for Marine Science and Technology



UNIVERSITY of
TASMANIA

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A message from the Director

I am pleased to introduce the Centre for Southern Hemisphere Oceans Research (CSHOR) Science Plan which outlines the fundamental scientific research the Centre will carry out over five years commencing July 2017.

CSHOR is an exciting partnership between the Qingdao National Laboratory for Marine Science and Technology (QNLM) and the Commonwealth Science and Industrial Research Organisation (CSIRO) along with university partners the University of New South Wales and the University of Tasmania.

I look forward to learning more about our Earth's complex climate system as the CSHOR projects begin to reveal: how the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) occur and interact, and how they vary on decadal timescales; the multifaceted behaviour of the Indonesian Throughflow and its impact on the interaction between the Pacific and Indian Oceans and their modes of variability (ENSO and IOD); if air-sea coupling in the Indian Ocean warm pool holds the key for improved sub-seasonal and interannual climate predictions in the Indo-Pacific; what role the Southern Ocean and the Antarctic ice sheet play in sea-level change; the underlying mechanisms driving change in oceanic temperatures around Antarctica and the associated changes in Southern Ocean carbon uptake; and the sensitivity of circulation and water mass formation to changes in forcing of the Southern Ocean.

Since CSHOR commenced its research in July 2017, we have demonstrated our excellent science and impact on several fronts including extreme El Niño and extreme positive IOD in a 1.5 °C warming world; heat uptake in the Southern Ocean through changes in subantarctic mode water; and accelerated sea-level rise over the last decades. CSHOR and Antarctic Climate and Ecosystem Cooperative Research Centre researchers aboard the RV *Investigator* discovered a shift in a decades-long trend towards fresher less dense water off Antarctica. Also during this voyage 11 deep Argo floats supplied by collaborators from the USA, Japan and France were deployed and all are working successfully. This is the first deployment of deep Argo floats in the Southern Ocean. By tackling the most fundamental questions in southern hemisphere ocean climate research, CSHOR will help to inform an effective response to the challenges of climate change and variability.

Kind regards,



Dr Wenju Cai

CSHOR Director

August 2018

1 Introducing the Centre for Southern Hemisphere Oceans Research (CSHOR)

1.1 Inception



CSHOR Launch 22 May 2017 (photo by Francois Fourie)

The Centre for Southern Hemisphere Oceans Research (CSHOR) was launched in May 2017, with the aim of improving our understanding of the southern hemisphere oceans and their influence on global and regional climate. The Centre’s research will inform the development of information, products and services to assist Australia, China and the world to better manage the impacts of climate variability and climate change.

The Centre builds on CSIRO’s strong history of research leadership in the southern hemisphere oceans, and on our long history of international collaboration, including over 40 years of collaboration with China.

The Centre is contributing to the advancement of international climate science by exploring models of collaborative funding. If it is successful, it could be a template for other nations to follow. Nations with insufficient resources to conduct research on their own could be involved in joint international research efforts similar to CSHOR.

It is also hoped that the Centre will further contribute to the development of internationally coordinated ocean and climate science research in the southern hemisphere by supporting collaboration with international initiatives, such as the World Climate Research Programme.

Dr Lixin Wu, QNLM’s President, in describing CSHOR has stated that, “China and Australia share common challenges that require fundamental understanding of global climate system, their impacts and their possible changes under greenhouse condition. Understanding southern hemispheric oceans is key to global ocean heat and carbon uptakes. Partnership between research organizations with globally recognised research capability in southern oceans, such as CSIRO and QNLM, will achieve greater science impact, better value and return on investment, and addressing bigger issues

than individual institutions can. I am confident that the centre has a good prospect of generating long-lasting legacies to the southern oceans research.”

The Centre’s governance structure comprises a Steering Committee, Advisory Committee, a Director who reports to the Steering Committee, and a Research Leadership Team. A list of Steering and Advisory Committee members is on the CSHOR website at <https://cshor.csiro.au/>.

The CSHOR office is situated at CSIRO’s Marine Laboratories in Hobart, Tasmania and is managed by a project support officer, employed by CSIRO.

The total budget for the Centre is AU \$20M over five years.

1.2 Partners

1.2.1 Key partners

The Centre is a collaborative research partnership between the Qingdao National Laboratory for Marine Science and Technology (QNLN) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), along with the University of New South Wales (UNSW) and the University of Tasmania (UTAS).

QNLN, approved by the Ministry of Science and Technology in December 2013, is a joint initiative of national ministries and departments, Shandong Province and Qingdao City. Based in Qingdao with a national and global vision, QNLN conducts both basic and cutting edge research in line with China’s national marine development strategy. A world-class, comprehensive marine science and technology research centre, QNLN is also an open platform for collaborative innovation. The Laboratory brings in resources and researchers to expand independent innovation and take the lead in China’s marine science and technology.

The Laboratory has 22 consortium partners. Five of these partners lead the consortium, including the Oceans University of China, which also has a long-standing relationship with UTAS and UNSW.

The university partners, UNSW and UTAS, are the two leading Australian universities in oceanographic research and among the national leaders in climate research. UNSW has particular strengths in ocean and climate modelling, Southern Ocean dynamics, ENSO, and investigations of the drivers of Australian climate. UTAS has particular strengths in ocean-cryosphere interaction, observations and models of the Southern Ocean, sea level research, and the ocean’s role in climate. These capabilities are needed to deliver on the research goals of the Centre.

Both universities have strong and growing engagement with QNLN and its partner institutions. Deepening their research collaborations with QNLN is a high strategic priority for both UNSW and UTAS. QNLN, in turn, has identified UNSW and UTAS as their preferred university partners for deeper engagement in Australia, and encouraged CSIRO to include them in the CSHOR partnership.

1.2.2 Research collaborators

In addition to the main partners in CSHOR, many international organisations contribute to CSHOR’s research infrastructure, activities and partnership. These are listed in Table 1. The list is current at the time of writing.

Table 1 CSHOR collaborators. Agencies in bold type also contribute research activities and those in blue type contribute research infrastructure.

Australian	<p>Antarctic Climate and Ecosystems Co-operative Research Centre (ACE CRC)</p> <p>Australian Antarctic Division (AAD)</p> <p>Australian Bureau of Meteorology (BoM)</p> <p>Australian Marine National Facility (MNF)</p> <p>Integrated Marine Observing System (IMOS)</p> <p>Australian Research Council Centre of Excellence for Climate Extremes (ARC CoECC)</p> <p>National Environmental Science Program –Earth System and Climate Change Hub (NESP ESCC)</p> <p>Australian Institute of Marine Science (AIMS)</p> <p>Geosciences Australia</p>
Chinese	<p>China Sea Institute of Oceanology (CSIO CAS)</p> <p>Chinese Academy of Sciences (CAS)</p> <p>Institute of Oceanology (IO CAS)</p> <p>First Institute of Oceanography (FIO SOA)</p> <p>Ocean University of China (OUC)</p>
International	<p>Florida State University, USA</p> <p>Institute of Research for Development, Laboratory of Oceanography and Climate: Experiments and numerical Approaches, France (LOCEAN)</p> <p>Japan Agency for Marine-Earth Science and Technology (JAMSTEC)</p> <p>Lamont-Doherty Earth Observatory, Columbia University, USA</p> <p>National Oceanic and Atmospheric Administration, USA (NOAA)</p> <p>New Zealand National Institute for Water and Atmosphere Research (NIWA)</p> <p>Rutgers University, USA</p> <p>Scripps Institution of Oceanography, USA</p> <p>University of Exeter, UK</p> <p>University of Washington, USA</p> <p>Woods Hole Oceanographic Institute, USA (WHOI)</p>

1.3 Strategic priorities

The southern hemisphere oceans have a massive influence on regional and global climate, but remain poorly observed and understood. The fundamental research carried out by CSHOR will underpin the next generation of climate projections needed to inform an effective national and international response to climate change and variability.

Both Australia and China are strongly influenced by climate variability and change (Figure 1), so have a strong common interest in better understanding how the southern hemisphere oceans influence the climate of our region and the rest of the globe.

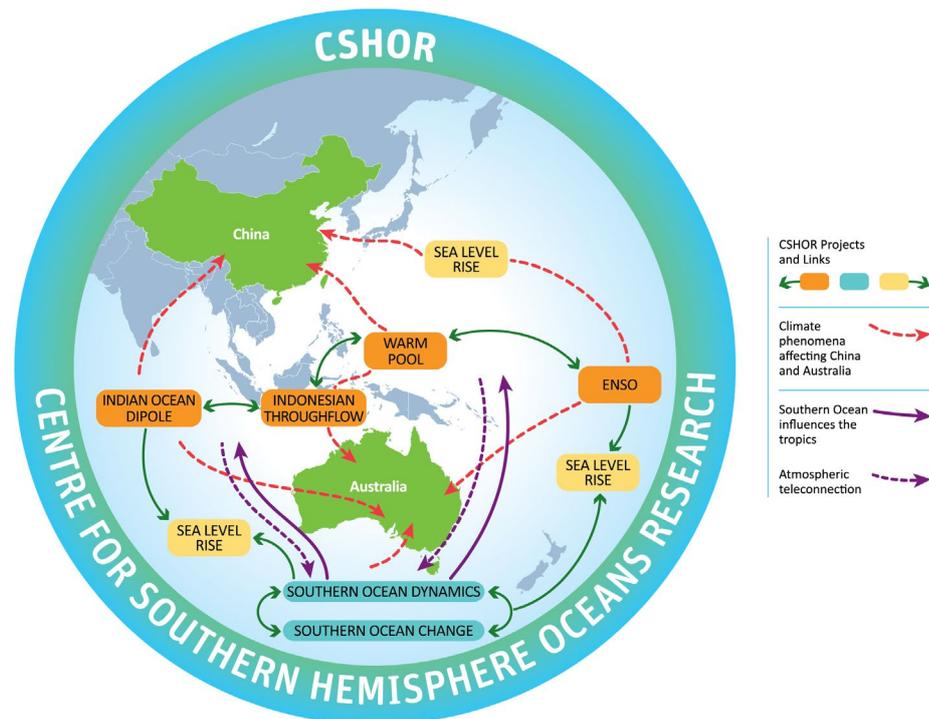


Figure 1 CSHOR projects

CSHOR will tackle the fundamental science challenges limiting our ability to identify and respond to the risks and opportunities of climate variability and change. Effective adaptation requires an ability to anticipate future change with a level of detail and confidence that can only be achieved through an improved understanding of the climate system.

Open questions to be addressed by CSHOR are:

- How will the El Niño – La Niña cycles that bring floods and drought change with climate change, including extreme events?
- How do the Pacific, Indian and Southern Oceans interact to drive variability in the climate of Australia, China and the rest of the globe?
- How does the ‘warm pool’ north of Australia influence regional and global climate, and can better understanding of warm pool dynamics enhance weather and climate predictions?
- How will changes in the ocean, including warming and interaction with Antarctic ice shelves, impact sea-level rise?
- Will the southern oceans continue to slow the pace of climate change by taking up heat and carbon dioxide at the same rate in the future?
- What is driving rapid change in the abyssal ocean?

1.4 Capacity building, outcomes and outreach

The Centre is supporting the next generation of internationally trained scientists through recruitment of early career researchers, the majority of whom are postdoctoral fellows. Our early career researchers are provided the opportunity to work across a number of different disciplines.

They have access to world-class research training and development to ensure they are productive and successful contributors to the Australian and international research effort. Early career researchers add value to CSHOR's research activities through original insights, new knowledge and innovative techniques.

CSHOR scientists are encouraged to contribute to international research efforts by:

- Attending, and assisting in the organisation of, international conferences (2018 conference plans are listed in the Communication section 3.5).
- Joining international committees, such as the CLIVAR Scientific Steering Group and CLIVAR regional panels, including the Southern Ocean Panel.
- Engaging with international programs, such as the WCRP grand challenge and the UN Decade of Ocean Science for Sustainable Development (2021–2030).

It is hoped that in the final years of CSHOR a major conference and/or assessment of the impact and connectivity between the project themes will be conducted. It is difficult to be specific at this early stage, but it could be a major conference on ice-sheet contribution to global sea-level variability and change or on the teleconnection between the tropics and the Southern Ocean. Such an undertaking will build the capacity to share knowledge by bringing what we have learned together in a more integrated sense, hence, enhancing the outcomes, which include:

- more useful and reliable projections of future climate provided by models that better represent the influence of the southern hemisphere oceans on global and regional climate
- synthesis of the research findings, in the form of a conference or/and a review paper
- identification of the next major challenges in the field of climate science research and also where CSHOR could expand to address those challenges
- more effective national policies and strategies for mitigating and adapting to the effects of climate change by providing decision-makers with the best possible scientific knowledge in a form that is useful to them
- advancement of internationally coordinated ocean and climate research in the southern hemisphere by supporting collaboration with international initiatives, such as the World Climate Research Programme
- provision of a tested and proven protocol of multi-investor collaboration to fund international science, enabling more nations to potentially contribute.

These outcomes will benefit a wide range of end-users in Australia, China, and the rest of the global community. These include policy makers responsible for the national response to climate change and its impacts, at the federal, state and local level; local planners and managers of infrastructure; climate-sensitive regional industries such as agriculture and tourism; sectors with long planning horizons like energy, water and transport; and global assessments such as those of the Intergovernmental Panel on Climate Change.

2 CSHOR research projects

CSHOR's research portfolio is constructed in line with the Centre's strategic priorities (Section 1.3) and comprises six research projects.

2.1 Understanding present and future dynamics of ENSO, the IOD

2.2 Indo-Pacific interbasin exchange

2.3 Coupled warm pool dynamics in the Indo-Pacific

2.4 Southern Ocean dynamics, circulation and water mass formation

2.5 Southern Ocean observations and change

2.6 The role of the Southern Ocean in sea-level change.

Three of the projects focus on processes and impacts of the tropical phenomena, modes of tropical variability, and the relationship among them (projects 2.1 to 2.3). The remaining three aim to understand the dynamics, and observe changes, of the Southern Ocean, with a focus on the contribution of Southern Ocean heat uptake and melting of the Antarctic ice sheet to global sea-level rise. These projects target the southern hemisphere ocean phenomena of greatest relevance to the climate of Australia, China and the globe (projects 2.4 to 2.6).

The tropical projects are clearly linked by their dependence on the tropical trade winds and other atmospheric and oceanic teleconnections. The Southern Ocean projects will bring observational and modelling approaches to bear on the dynamics and change of the circulation of the Southern Ocean, and its impact on the Antarctic ice sheet. As sea level is affected by both tropical and high-latitude processes, each of the five regional projects contribute to the CSHOR goal of better understanding sea level change on regional and global scales.

In addition, recent research has shown that modes of tropical variability and their decadal changes affect the Southern Ocean, and the spatial inhomogeneity of surface warming and oceanic heat content change in the southern oceans in turn affect properties of tropical variability (Hwang et al. 2017), however, interaction between the tropics and southern oceans is poorly understood. It is envisaged that the six CSHOR projects will bring us closer to an understanding of how the Pacific, Indian and Southern Oceans interact to drive variability in the climate of Australia, China and the rest of the globe.

These projects together address key science challenges outlined in section 1.3, and in most cases, each question might be contributed from multiple projects (Table 2).

Table 2 A matrix showing how the six CSHOR projects will contribute to addressing the key science challenges.

Project 2.1: Future dynamics of ENSO/IOD	Project 2.2: Indonesian Throughflow	Project 2.3: Warm pool dynamics in the Indo-Pacific	Project 2.4: Southern Ocean dynamics	Project 2.5: Southern Ocean observations	Project 2.6: Southern Ocean and sea level rise
How will the El Niño – La Niña cycles that bring floods and drought change with climate change, including extreme events?					
Determine the factors regulating the frequency and magnitude of ENSO and IOD events, with an emphasis on extreme events	Assess the role of the ITF in ENSO and IOD	Assess how the dynamics of the warm pool contribute to ENSO, including extreme events			Quantify the contribution of ENSO and IOD to regional patterns of sea level rise
How do the Pacific, Indian and Southern Oceans interact to drive variability in the climate of Australia, China and the rest of the globe?					
Focus on factors influencing the frequency and strength of ENSO/IOD events and their influence on regional and global climate variability	Assess influence of ITF on regional and basin-scale teleconnections influencing regional and global climate	Quantify how warm pool dynamics influence climate phenomena relevant to Australian and Chinese climate, including MJO/ENSO/IOD	Explore the sensitivity of climate modes to Southern Ocean change, using a hierarchy of models	Determine the influence of oceanic teleconnections in linking the mid- to high-latitude southern hemisphere ocean to the mean state of the tropical ocean, and hence modes of climate variability	Quantify the contribution of modes of climate variability and large-scale ocean circulation on regional and global sea level rise
How does the ‘warm pool’ north of Australia influence regional and global climate, and can better understanding of warm pool dynamics enhance weather and climate predictions?					
Analysis of the role of the warm pool in influencing the frequency and magnitude of ENSO/IOD, and how ENSO/IOD influence the warm pool	Assessment of role of the Indonesian throughflow in regulating the temperature and dynamics of the warm pool	Observations and models used to understand the processes controlling the temperature of the warm pool and its teleconnections			
How will changes in the ocean, including warming and interaction with Antarctic ice shelves, impact sea level rise?					
			Models used to investigate the mechanisms carrying heat to the ice shelves and their sensitivity to changes in forcing	Observations used to assess where and how rapidly ocean heat reaches the Antarctic ice shelves	Models and observations used to quantify regional and global sea level rise and its contributions
Will the southern oceans continue to slow the pace of climate change by taking up heat and carbon dioxide at the same rate in the future?					
Investigation of role of atmospheric teleconnections in driving Southern Ocean change			Hierarchy of models used to assess sensitivity of Southern Ocean circulation and heat/carbon uptake to changes in forcing	Change in ocean uptake assessed from physical and biogeochemical observations	
What is driving rapid change in the abyssal ocean?					
Investigation of role of atmospheric teleconnections in driving Southern Ocean change			Model experiments with perturbed forcing	Quantify change in the deep ocean using measurements from ships and deep floats	

2.1 Understanding present and future dynamics of ENSO, IOD, and their interactions with the southern hemisphere oceans

Project leaders: Drs Agus Santoso and Guojian Wang

ENSO and the IOD (Figure 2) affect millions human lives in the tropical belt and beyond. The likelihood of extreme weather and climate such as drought, heatwaves, floods and cyclones is elevated during ENSO and IOD events. Understanding how ENSO and IOD occur, how they interact, and how they vary on decadal timescales is crucial to enhance our capacity to predict their occurrences and manage risks in a climate that is undergoing change.

Recent studies have found that extreme ENSO and IOD events may occur more frequently under greenhouse warming (Santoso et al. 2013; Cai et al. 2014, 2015a, 2015b). However, the mechanisms for how extreme ENSO and IOD events occur are still not fully understood and are likely to be complex. It is also not clear how the processes and their interplay could be influenced by greenhouse forcing. These overarching issues will be addressed by the project using observational products and several climate models, toward more accurate future projections of these impactful climate events.

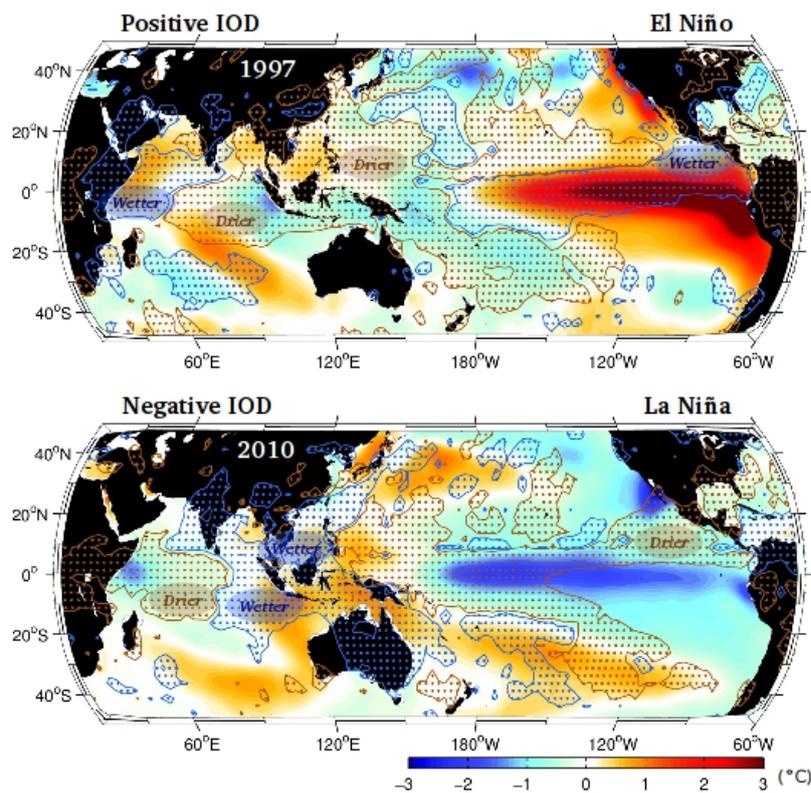


Figure 2 Sea surface temperature and rainfall anomaly during austral spring of 1997 extreme El Niño and extreme positive IOD (top), and 2010 extreme La Niña and negative IOD (bottom). The SST (colour shading) and rainfall (stippled) anomaly data are based on ERSST version5 and CMAP rainfall. (Image source: A. Santoso)

2.1.1 Project aims and objectives

a) How do extreme ENSO and IOD events occur?

It is not entirely clear why ENSO and IOD events can grow to extreme amplitude in a particular year (e.g. 1997) and not in others. For instance, a strong El Niño was expected to occur in 2014, but it did not materialise. Instead, an extreme El Niño unexpectedly occurred in 2015 (McPhaden 2015; Santoso et al. 2015). What are the factors that influence the growth of ENSO and IOD events, and what kind of interplay is involved in the process? What are the mechanisms that give rise to differences in the characteristics across events?

b) What is the role of southern hemisphere extra-tropical oceans in ENSO and IOD genesis?

ENSO is known to be influenced by modes of variability sourced in the northern hemisphere extra-tropics (e.g. Chang et al. 2007), as well as variability in the Atlantic (e.g. Wu et al. 2005; Kajtar et al. 2017) and Indian Oceans (Santoso et al. 2012). However, much less is known about the potential influence of modes of variability in the southern hemisphere extra-tropics, particularly on the IOD and its interactions with ENSO.

Objective 1: To increase our understanding of how ENSO and IOD events are generated, in particular, how they attain extreme amplitude, how they interact with each other and with the southern hemisphere oceans.

c) What are the processes controlling decadal variability in ENSO and IOD?

Decadal variability in ENSO has been linked to the Interdecadal Pacific Oscillation (IPO), though it is unclear which one more strongly influences the other and how this may affect the IOD (Han et al. 2014). Understanding the mechanisms for their decadal variability will also need to take remote processes into account.

d) How do ENSO and IOD, their event diversity, and decadal variability interact with Southern Ocean circulation and Antarctic sea-ice processes?

The Southern Ocean connects the Indian, Pacific, and Atlantic basins, allowing oceanic anomalies created in one basin to be transmitted into another, eventually affecting the tropical climate (e.g. Timmermann et al. 2007). In addition, complex air-sea-ice interactions along the Antarctic ice margin could give rise to inter-decadal variability (Santoso et al. 2008). ENSO and IOD can also impact high-latitude processes and water-mass formation (e.g. via the Southern Annular Mode and the Pacific-South American mode), which may in turn influence ENSO and IOD.

Objective 2: To examine the causes for decadal modulation of ENSO and IOD characteristics, and the potential role of southern hemisphere oceans.

e) How would these processes operate under greenhouse forcing?

The southern oceans are projected to change under greenhouse warming (e.g. Sen Gupta et al. 2009). The impact of these changes on ENSO and the IOD needs to be investigated, while taking into consideration the projected changes in the atmospheric Walker circulation (Vecchi et al. 2006). How different emission scenarios may impact on the mechanisms is also an open question.

Objective 3: To project changes in ENSO and the IOD under greenhouse warming, as well as their interactions and teleconnection, and assess uncertainty in the projected change.

f) To what extent do climate models simulate all of the aforementioned processes and how do model biases affect the future projections?

Climate models are used for future projections, so it is important to assess the representation of these processes and the associated atmospheric and oceanic teleconnection (e.g. the link between Indonesian Throughflow variability with ENSO and IOD), and how any model biases may impact the future projections of ENSO and IOD.

Objective 4: To improve understanding of model deficiencies in simulating processes of extreme ENSO and IOD events, and the ramifications on their future projections.

2.1.2 What will the project deliver over 3 to 5 years?

Year 1: An examination of the 2015/16 extreme El Niño for a better understanding of ENSO extremes; the links between the Indonesian Throughflow and ENSO and IOD in climate models; ENSO-IOD projections under different emission scenario; the impact of Pacific decadal variability on event diversity.

Year 2: Inter-model evaluation of extreme ENSO and IOD, including the teleconnection pathways for their interactions, and the impact of tropical ocean model biases on the future projections of these events.

Year 3: A mechanistic understanding of how extreme ENSO and IOD events are generated and respond to greenhouse forcing (e.g. on the role of stochastic wind surges, decadal mean state, and extra-tropical climate variations).

Year 4: An assessment on the potential role of southern hemisphere oceans in contributing to decadal mean state variations in the tropics and their effect on ENSO-IOD evolution.

Year 5: An evaluation of the impact of model biases, and future projections of the southern oceans, on the projected frequency of extreme ENSO and IOD events.

2.2 Indo-Pacific interbasin exchange

Project leader: Dr Bernadette Sloyan

The Indonesian Throughflow (ITF) is the complex filamented low-latitude boundary current that connects the Pacific Ocean and Indian Oceans. The ITF and Indonesian seas lie at the intersection of the two largest oceanic warm pools and the climatological centre of the atmospheric deep convection associated with the ascending branch of the Walker circulation and upward branch of the Hadley Circulation. As such, the region plays a central role in the coupled ocean-atmosphere climate system.

As the western Pacific water transits the Indonesian seas, the complex island geometry comprised of broad shallow shelves and deep basins, large tides and Asian-Australian monsoon wind variability all drive ocean mixing that modifies the water mass characteristics and regional sea surface temperature (SST). This mixing has the potential to strongly impact the marine environment in the Indonesian seas and the heat and freshwater transports to the Indian Ocean. The drawdown of heat into the ocean suppresses the region's SST and feeds back to impact the structure of winds and convection across the Indo-Pacific region. In addition, the strength and temperature and salinity property of the ITF is strongly influenced by ENSO and IOD.

A thorough understanding of the dynamical drivers of ITF transport and property variability and its impacts on regional and global climate remain poorly known. Currently, regional ocean and global climate models struggle to simulate the region due to the complex bathymetry, ocean processes and coupled ocean-atmosphere dynamics.

We aim to provide improved understanding of the intraseasonal, interseasonal, mean and interannual behaviour of the Indonesian Throughflow, including interaction between the Pacific and Indian Oceans and their modes of variability ENSO and IOD. We will address these issues through comprehensive observational and modelling studies, with observations of the inflow and outflow straits and passages and mixing in the Banda and Flores Seas, and development of a high-resolution model that resolves the complex bathymetry of the region, and explicitly includes tides that drive mixing along the pathway between the Pacific and Indian Ocean.

2.2.1 Project aims and objectives

We will use observational data and develop a high-resolution model to focus on the following:

- a) What are the drivers of ITF variability across intraseasonal, interseasonal, mean and interannual timescales? How do the ITF and regional seas respond to intraseasonal – interannual forcing?**

A number of in situ observational programs provide a variety of observations over a 20-year timeframe, yet there have been few studies that combine these data to investigate the variability of the ITF at various timescales. For example, the INSTANT program, 2004–2005, directly measured the full-depth volume, temperature and salinity transport in the two major inflows (Makassar Strait and Lifamatola Passage) and three major outflows (Timor Passage, Ombai Strait and Lombok Strait) of the Indonesian Throughflow. More recently, the Australian IMOS program monitored the Ombai Strait and Timor Passage between 2011–2015 and there is an ongoing US program to monitor the Makassar Strait (Gordon, pers coms). Additionally, there are ongoing XBTs and satellite SST, and

altimetry data. These programs provided valuable observations of the inflow and outflow passages, and the Indonesian seas.

Objective 1: To use available ocean datasets and atmospheric reanalysis products to characterise the response of the ITF to intraseasonal – interannual forcing.

b) What are key ocean processes/dynamics of the ITF?

i) What are the controlling dynamics of the Indonesian seas?

The controlling dynamics of the mean and interannual behaviour of the Indonesian Throughflow remains a major research challenge. Understanding both the advection pathways and mixing patterns are important: Kida and Wijffels (2012) show that the ITF has a profound impact on the pattern of sea surface temperature in the region on seasonal timescales by suppressing seasonal upwelling via warm advection, which in turn will feedback to atmospheric patterns. Jochum and Potemra (2008) show that regional mixing rates can have strong feedbacks to the atmosphere.

Objective 2: To investigate the key ocean dynamics of the ITF using both the observational datasets and a high-resolution ocean regional model. The observations will be used to guide a number of model perturbation experiments specifically designed to investigate key dynamics that influence ITF characteristics.

ii) What is the strength and spatial patterns of tidally driven mixing and internal wave generation?

There have been limited studies of ocean mixing in the region. INDOMIX was one of the first projects dedicated to observations of ocean mixing in the Indonesian seas, with most of the microstructure measurements taken in the energetic Halmahera Sea. INDOMIX confirmed the importance of vertical mixing associated to internal tides in setting the vertical profile of the temperature and salinity of the ITF. Based on the mixing observations, theoretical studies have indicated possible resonance between coastal and internal waves which would lead to increase turbulent dissipation leading to enhanced ocean mixing (Reznik and Zeitlin 2011). Models (Koch-Larrouy et al. 2007, 2010; Nagai and Hibiya 2015) have shown that tidally-driven mixing within the Indonesian seas strongly modifies the temperature and salinity profiles and affects the overall character of the ITF. However, there is still a paucity of observations and realistic models of turbulence and mixing and more are needed from this region.

Objective 3: To understand the impact of ocean mixing. We will include tidal and internal wave generated mixing in our high-resolution model of the region, and the project will work with international partners to include ocean mixing observations in an intensive ocean field campaign.

c) How is the ITF influenced by Pacific and Indian Ocean climate variability such as the ENSO and the IOD (modulation of the ITF by external ocean forcing)?

Lee et al. (2015) suggest that a stronger than normal ITF has been transferring heat from the Pacific to the South Indian Ocean, helping to account for strong upper ocean heat content growth in that basin since 2003, compared to stasis in Pacific heat content over the same time. The relatively rapid intraseasonal variability (e.g. Madden Julian Oscillation, MJO) affects the evolution and predictability of seasonal signals. The MJO is a key phenomenon that spans and links both the areas in the Indian and Pacific Oceans and has a significant impact on the region's climate. Having a dominant time period near 50 days, and imbedded in the seasonally migrating inter-tropical convergence zones, the MJO is suggested to play a role in the initiation and evolution of ENSO and IOD events (McPhaden et al. 2006) and modulation of the Indonesian Throughflow (Sprintall et al. 2009). At present, coupled models do not capture this variability very realistically (Lin et al. 2006). Recognition of the importance of the MJO for both numerical weather prediction (Hendon et al. 1999) and seasonal climate forecasting is driving a demand for comprehensive process studies of the ITF – observation and high-resolution modelling – which resolve these phenomena and increase process understanding to improve their simulation in models.

Objective 4: To investigate the modulation of the ITF by these external forces using our comprehensive observational dataset and high resolution models. This will provide a more thorough understanding of the connections amongst the Indian and Pacific Oceans and the Indonesian seas.

2.2.2 What will the project deliver over 3 to 5 years?

Year 1: Collation of the existing observational datasets as possible, including mooring data (INSTANT, IMOS, and other mooring data), XBT, mixing datasets, and satellite sea surface temperature and salinity, and altimetry data. Development of a high-resolution model of the Indonesian seas region.

Year 2: Analysis of the observation datasets and high-resolution model investigating the interannual variability of the ITF. Development of target model studies investigating the influence of Pacific and Indian climate modes on the ITF variability. Submission of the ARC proposal for acquisition of shear-floats for deployment in the Indonesian seas during the international field campaign. Preparation and submission of journal papers.

Year 3: Inclusion of mixing in the high-resolution model. Participation in the international research voyage to deploy moorings and carry out the synoptic ship-based survey to characterise channel sidewall behaviour and capture internal wave trains near the sills, including deployment of EM-APEX floats to obtain mixing estimates in the Banda and Flores Seas.

Year 4: Processing of the EM-APEX shear float observation and beginning of analysis of the data to characterise mixing in the Indonesian seas and compare to high-resolution model simulations. Further publications based on model simulations of the external forcing influences on the ITF.

Year 5: Combined analysis of observations and model to further understand the interior and external drivers of variability of the ITF and Indonesian seas at various timescales and coupling to atmospheric circulation. Participation on the international voyage to recover moorings.

2.3 Coupled warm pool dynamics in the Indo-Pacific

Project leaders: Drs Ming Feng and Susan Wijffels

The Indo-Pacific warm pool hosts the largest global centre of deep convection, the dominant source of latent heating and moisture for the global atmosphere. The warm pool enables important coupled climate modes, such as ENSO, IOD, and MJO (Figure 3), which are likely the most important sources of enhanced weather and climate prediction on the globe.

The Indo-Pacific warm pool is separated by the Indonesian Archipelago into the western Pacific warm pool and the eastern Indian Ocean warm pool, connected by the Indonesian Throughflow (ITF). Climate mode variability of the Indo-Pacific influences the ITF transport and modulates the exchanges between the Indian Ocean and Pacific warm pool on interannual and decadal timescales. The warm pool has warmed and grown substantially during the past century due to anthropogenic climate change, which may have profound implications for regional and global climate.

An improved understanding of air-sea coupling in the Indian Ocean warm pool may hold the key for improved sub-seasonal and interannual climate predictions in the Indo-Pacific. There is a growing understanding of how coupling at high frequencies and small spatial scales can be important for climate modes, even the mean climate. We aim to advance this frontier through new observations and modelling, grounded in the largescale context of the ITF and its role as a warm pool connector. In addition, better quantification of upper ocean heat balance of the Indian Ocean and associated ocean transport are important in pinpointing the anthropogenic heat uptakes in the global ocean. Poleward heat transport of the Indian Ocean into the Southern Ocean may play a role in the oceanic pathway of tropical ocean-Southern Ocean interaction.

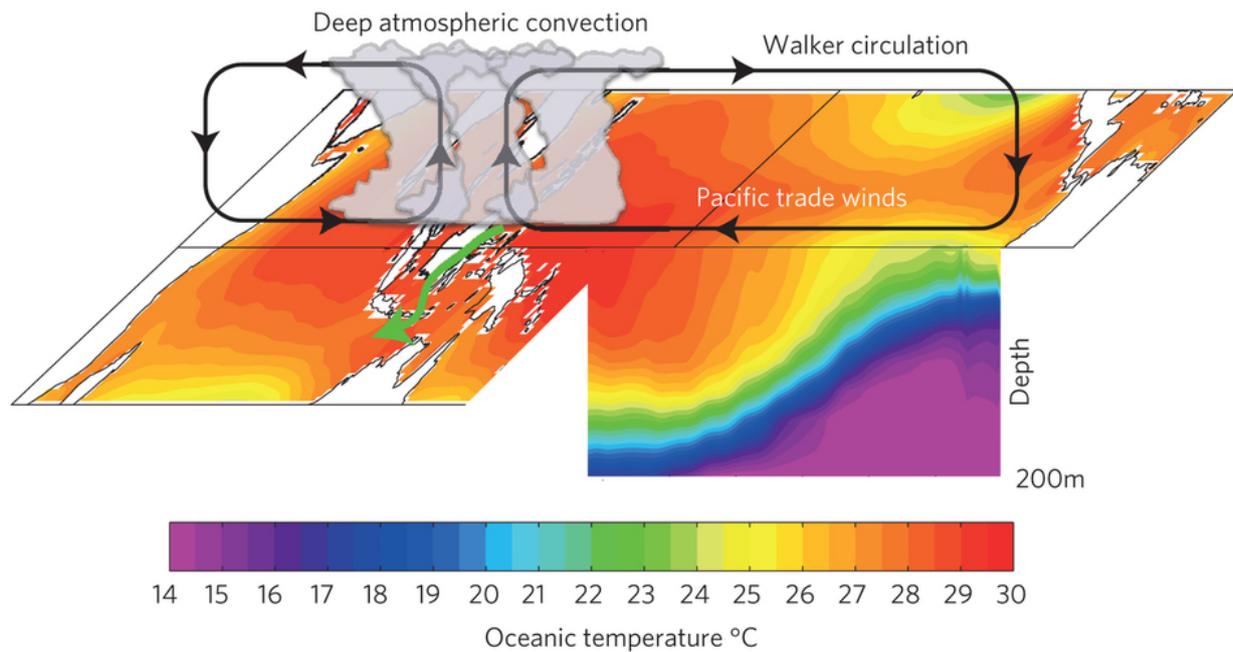


Figure 3 Deep atmospheric convection over the Indo-Pacific warm pool drives the Walker circulation (from Vialard 2016). The green arrow denote the ITF connecting the warm pools.

2.3.1 Project aims and objectives

- a) How important is the fast air-sea coupling in the southeast Indian Ocean in the evolution of the MJO events?**

Over the past decade, there has been growing recognition of the importance of fast coupling (~hours) between the atmosphere and upper ocean to major weather modes such as the Madden Julian Oscillation (MJO) (De Mott et al., 2016). The development of warm shallow diurnal layers in the ocean during the light wind periods of the suppressed phase of the MJO is likely a key contributor to its eastward phase speed and strength, through moistening the lower atmosphere via enhanced latent heat fluxes, in turn modulating convection strength (Seo et al. 2014). This process is intrinsically non-linear and remains a challenging target for the current coupled climate models used for seasonal and medium range forecasts. In part, this is due to the fine upper ocean vertical resolution (~1 m) and fast coupling timescales (1-3 hours) required (De Mott et al. 2016).

Several recent intensive field programs have focussed on resolving these processes, such as the CINDY and DYNAMO in the central equatorial and northern tropical Indian Ocean (Yoneyama et al. 2013; Moum et al. 2014) campaigns. However, differences in flux balances and ocean responses are found across the MJO domain, with contrasting behaviour found between the equatorial Indian and western Pacific regimes. One region with recognised very large MJO (Vialard et al. 2013) and diurnal SST variability (Zhang et al. 2016) is off Australia’s northern North West Shelf. To date, this region has not been sampled at the high frequencies needed to resolve diurnal warming and responses in the near surface atmosphere. In addition, the role of salinity and rain in controlling the development of these diurnal layers remains poorly known, requiring further high-resolution ocean datasets across a larger set of regimes and events.

Objective 1: To obtain new insights into air-sea coupling in the east Indian Ocean warm pool region north-west of Australia in conjunction with the Year of Maritime Continent experiment, using fast ocean profiling platforms (resolving the very near surface temperature) to measure SST continuously as well as the key atmospheric variables such as humidity, air temperature, vector winds and radiation parameters. Such measurements in the region will be unprecedented.

b) How sensitive are coupled numerical models to the diurnal air-sea coupling?

The warm pool off Australia's North West shelf owes its existence to the Indonesian Throughflow, and the upper ocean structure is profoundly dependent on Pacific influences transmitted through the Maritime Continent. Large salinity and temperature anomalies are advected into the region and planetary waves over various timescales impact the stratification. Thus the ITF, plus local processes, set the context of the fast coupling we are targeting, and so upstream information will be critical in understanding how these are modulated from season to season.

Objective 2: To understand coupled model sensitivities in capturing the scale, strength and atmospheric responses to diurnal warming events, and improve our understanding of the impacts of ENSO and MJO on upper ocean thermal and salinity structures in the warm pool.

a) What are the key drivers of the interannual and decadal variations of heat and freshwater balances in the Indian Ocean? How important are the Pacific teleconnections through oceanic and atmospheric bridges?

Additionally, the roles of the ITF and ocean boundary currents on the upper ocean heat and salinity balance of the Indian Ocean are still not well understood due to lack of observations. Upper ocean warming has been observed in the Indian Ocean since 1960s (Alory et al. 2007). Decadal enhancement of the warming trend during the climate change hiatus period has been suggested to be closely associated with the La Niña-like condition in the Pacific and strengthened ITF transport (Lee et al. 2015; Vialard 2016). Still, the relative contributions from the heat advection and air-sea heat exchanges have not been quantified, to attribute multi-decadal changes of the Indo-Pacific Oceans. Excess air-sea heat flux and the Pacific warm water transport via the ITF help a large meridional heat flux exiting the Indian Ocean across 32°S, estimate to be as much as 1.5 PW (Lumpkin and Speer 2007; Ganachaud and Wunsch 2000), which plays the biggest role in balancing heat loss in both the Atlantic and Southern Oceans. Nevertheless, we have little knowledge on the pathways of the poleward heat transport in the Indian Ocean and their variability on interannual to decadal timescales.

Objective 3: To quantify the drivers of the decadal variations of the Indian Ocean heat storage and the poleward heat transport in the Indian Ocean using numerical model outputs, and engage in Indian Ocean Observing System review to design observation programs to monitor the key processes.

2.3.2 What will the project deliver over 3 to 5 years?

Year 1: Carry out first phase field program, including the acquisition and deployment of two pilot profilers, establish satellite communication and data handling system and testing of two-way communications for at-sea re-missioning. Explore, using remotely sensed data, diurnal SST variability in the region, particularly exploiting the data collected by the fast sampling Himawari-8 satellite; rerun the BoM's coupled forecast model for historical MJO events, archiving sub-daily ocean and air-sea flux output for analysis and benchmarking the model behaviour against satellite data.

Upper ocean temperature and salinity balances in the tropical Indian Ocean, including the eastern Indian Ocean warm pool, will be analysed based on data-assimilating model products. The impacts of ENSO, IOD and MJO on the temperature extremes off north-west Australia during the 2015–16 El Niño will be assessed, and journal papers submitted.

Year 2: Second phase field program, targeted for late 2018–early 2019 and comprising a swarm of five to eight profilers and the atmospheric flux platform, will be carried out, contributing to testing solutions for key tropical oceans and climate observational challenges as discussed in the recent TPOS2020 interim report (Cravatte et al. 2016); field data will be processed and QCd, and made available to the project team; rerun the BoM's coupled forecast model for the time period overlapping the field program, archiving sub-daily ocean output; begin detailed comparisons of model performance; submit journal paper on the pilot study.

Upper ocean heat and salt balances in the Indo-Pacific warm pool will be further explored based on observations and model simulations and journal papers submitted.

Year 3: Field program results disseminated and shared with partner researchers to improve coupled physics in the seasonal forecast models and carry out sensitivity tests. Journal paper on the second field program dataset and coupled model evaluations submitted.

Year 4: Journal publications on the field campaigns in the eastern Indian Ocean warm pool and associated modelling study finalised.

Report on assessment of the interannual to decadal variations of the meridional heat transport in the Indian Ocean and their association with the Indian Ocean overturning circulation, as well as the strategies for long-term monitoring.

Year 5: Further development of cost-effective observation strategies to monitor the air-sea coupling in other ocean systems.

Finalise project publications.

2.4 Southern Ocean dynamics, circulation and water mass formation

Project leader: Prof Matthew England

The Southern Ocean has recently undergone significant changes in ocean thermal structure, with recent observations indicating rapid surface warming in the Amundsen-Bellingshausen Seas (Jones et al. 2016), over the shelf around parts of the Antarctic margin (Schmidtke et al. 2014) and in the abyssal bottom water layers (Purkey and Johnson, 2010, 2012, 2013). Yet our understanding of the underlying mechanisms remains fragmented and incomplete. This project aims to further our understanding of the processes by which oceanic temperatures are changing around Antarctica, particularly the above patterns of warming, by exploiting cutting edge ocean-sea ice models guided by (and evaluated against) the most recent ocean observations, alongside theory. The project further aims to understand the associated changes in ocean carbon uptake in the region using ocean models including full biogeochemistry sub-modules.

The project outcomes will include: (1) an advance in our knowledge of the processes driving Antarctic surface warming Amundsen-Bellingshausen Seas as well as in the south Indian sector; (2) new understanding of the processes and dynamics driving recent continental shelf warming, particularly in the region of the West Antarctic Ice Sheet and off the Totten Ice Shelf; (3) simulations that constrain the processes leading to abyssal water warming around the Southern Ocean; and (4) an improved understanding of the Southern Ocean carbon cycle. Other long-term benefits include better constraints on future predictions of ocean-ice interactions around the Antarctic coastline, and an improved understanding of the potential impact of Antarctic meltwater on global sea level and ocean circulation.

The Southern Ocean takes up more anthropogenic heat and carbon dioxide than any other basin (Khatiwala et al. 2014; Marshall et al. 2014; Armour et al. 2016). The sensitivity of Southern Ocean circulation to climate change is therefore a critical question, as weakening of the Southern Ocean 'sink' for heat and carbon would provide a positive feedback accelerating the rate of climate change. Present climate models suggest that the Southern Ocean is absorbing a vast amount of additional heat in response to rising greenhouse gases in the atmosphere. However, the processes regulating subduction and water mass formation in the Southern Ocean are poorly understood and poorly modelled in present-day climate simulations. This project will employ state-of-the-art global 0.1 degree ocean-ice simulations to improve our understanding of heat uptake processes around Antarctica, and where relevant, other limited domain sector simulations resolving the sub-mesoscale. These new tools will advance our understanding of the drivers of recent temperature change in the oceans around Antarctica, from the surface to the abyss.

Observations have revealed significant changes in recent decades in the Southern Ocean, extending throughout the water column (Böning et al. 2008; Purkey and Johnson 2010, 2012, 2013; van Wijk and Rintoul 2014). While some progress has been made in understanding the drivers of Southern Ocean change (e.g. Gille 2008; Böning et al. 2008; Meijers et al. 2012; van Wijk and Rintoul 2014; Spence et al. 2014, 2017; Jones et al. 2016), the dynamics responsible for the observed changes remain poorly understood.

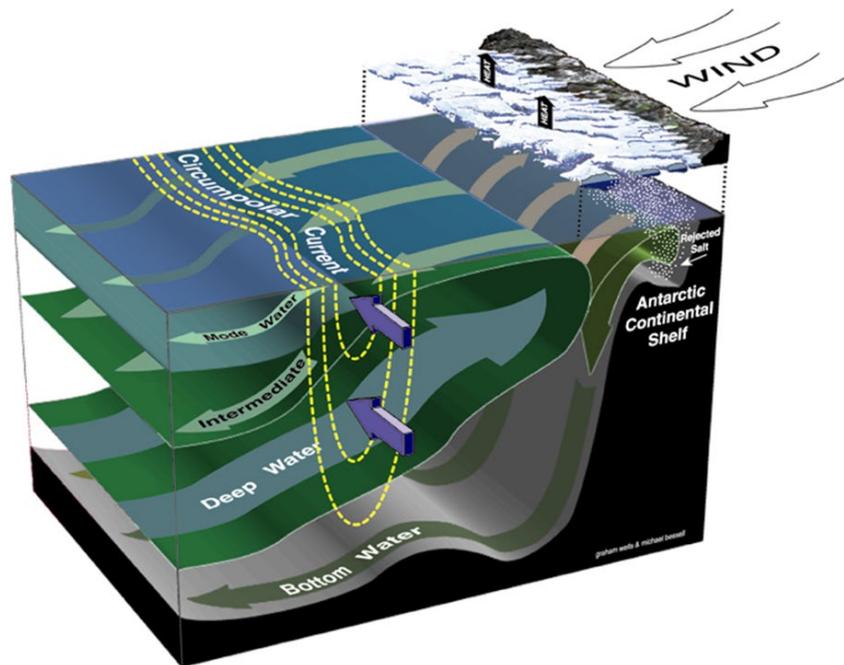


Figure 4 A highly schematic representation of the circulation of the Southern Ocean, including the strong eastward flow of the Antarctic Circumpolar Current (yellow dashed lines and purple arrows, showing flow into the page), and the overturning circulation consisting of poleward and upward motion of Circumpolar Deep Water, balanced by equatorward flow of mode, intermediate and bottom water. Sea ice and brine rejection is illustrated by white ice floes and white dots, respectively, in the upper right of the figure. (Rintoul 2000).

2.4.1 Project aims and objectives

The project will focus on the following specific and interconnected topics:

- a) **How large is the interannual variability in the different sectors and regions of the Southern Ocean? What are the mechanisms driving these changes in the observational period? How may these mechanisms change in the future?**
 - i) **Warming in the surface Southern Ocean**

Much progress has been made on the drivers of recent Southern Ocean surface cooling and regional sea-ice expansion (e.g. Purich et al. 2016a,b, 2018), yet relatively little work has addressed the mechanisms for significant surface warming in the Amundsen-Bellingshausen Seas. Ocean and coupled models of varying resolution will be used to explore the drivers of the Amundsen-Bellingshausen Sea warming, including warming driven by changes in the pathway/temperatures of the Antarctic Circumpolar Current (ACC), atmospheric teleconnections from the tropics, and coupled ice-ocean feedbacks (Figure 4).

Objective 1: To use a high-resolution ocean model to examine the role of westerly wind anomalies in driving changes in the upwelling and poleward transport of Circumpolar Deep Water. Observations will be used to test and improve the model simulations.

ii) Warming in the abyssal ocean

The most rapid changes observed in the deep ocean occur near Antarctica (Purkey and Johnson 2010, 2012). Antarctic Bottom Water has warmed, freshened and contracted, with the largest signals of change observed south of Australia (Rintoul 2007; van Wijk and Rintoul 2014). These deep ocean signals likely reflect a combination of changes in surface forcing, water mass formation, and ocean–ice interaction, but the physical mechanisms driving deep ocean change remain obscure.

Objective 2: To use observations of Antarctic Bottom Water change to guide a hierarchy of model experiments to investigate the sensitivity of the lower cell of the Southern Ocean overturning circulation to changes in forcing (wind, heat flux and freshwater flux from sea ice melt and melting ice shelves).

iii) Warming over the Antarctic continental shelf

One potential impact of Southern Ocean change is mass loss from the Antarctic ice sheet. Ocean warming or changes in ocean circulation that increase the ocean heat flux to the base of the floating ice shelves can drive enhanced melt and thinning; increased thinning can, in turn, reduce the buttressing provided by the ice shelf, leading to an increase in ice sheet discharge and sea-level rise (Dupont and Alley 2005). The response of the ice sheets to greenhouse warming remains the largest uncertainty in projections of sea-level change in future centuries (Church et al. 2013). The key scientific question is “What controls the delivery of ocean heat to Antarctic ice shelves?” Ocean heat flux into ice shelf cavities depends on both ocean temperature and circulation and is regulated by a number of processes, including exchange across the Antarctic Slope Front and shelf break, bathymetric control of the shelf circulation, air–sea interaction and polynya dynamics, and the dynamics of exchange with the ice shelf cavity itself.

Objective 3: To generate simulations using global coupled models, high resolution regional models, and idealised process models to assess the sensitivity of ocean–ice shelf interaction to changes in forcing. The model studies will be guided by recent and ongoing observations showing that the East Antarctic Ice Sheet is more vulnerable to ocean heat flux than previously believed (Rintoul et al. 2016; Silvano et al. 2016, 2017).

b) What are the implications for Southern Ocean carbon uptake and how may carbon-climate feedbacks modulate this response?

The Southern Ocean plays a critical role in mitigating the rate of climate change, through taking up more than 40% of the annual ocean uptake (Takahashi et al. 2009; Lenton et al. 2013). Recent studies have reported large multi-year changes in the strength of the Southern Ocean carbon uptake (de Vries et al. 2017; Landschützer et al. 2015; Lenton et al. 2012) and highlighted the strong link between carbon and heat uptake now and into the future (Fröhlicher et al. 2015). In recent decades the Southern Ocean has undergone significant changes in heat, freshwater and winds, however there remains limited consensus on what and how these physical mechanisms drive multi-year changes, particularly as the response does not appear to be the same in all sectors of the Southern

Ocean. This is further complicated by the limited carbon cycle observations in many areas of the Southern Ocean and the fact that many studies average or interpolate these observations in non-dynamically consistent frameworks (de Vries et al. 2017; Lanschützer et al. 2015).

In the future, the ocean is projected to undergo large changes in response to a changing climate that are likely to act as both positive and negative feedbacks on climate. Consequently, how the Southern Ocean responds to these changes will determine the role it plays in the global carbon cycle, in heat uptake and storage, and in providing the key ecosystem services it delivers. Therefore, understanding what drives the observed changes in the present day, and how these drivers will change into the future, is a critical question that needs to be addressed, and one that will have important links to future climate and policy e.g. IPCC upcoming report on the oceans and AR6.

Objective 4: To address questions about carbon uptake in the Southern Ocean and carbon–climate feedbacks. A series of model simulations – ocean only, coupled to ocean biogeochemistry, and Earth System Model simulations – will be used. These will be linked to surface and deep-ocean observations collected in the Southern Ocean to ensure that important processes are represented in the simulations.

If time permits, an additional question will also be pursued that will take advantage of the tools, methods and models developed for the topics discussed above. This relates to the dynamics of the Antarctic Circumpolar Current (ACC), and is described below as topic c).

c) Dynamics of the Antarctic Circumpolar Current

The overturning circulation is dynamically coupled to the ACC (Figure 4). Until recently, most theoretical work on the ACC has taken a zonal-mean view of the dynamics. This approach has been very useful, but recent work has made clear that localised dynamics play a key role in the momentum and vorticity budgets of the ACC, as well as cross-front exchange and subduction (Sallée et al. 2010, 2012; Thompson and Naveira Garabato 2014). We will use high-resolution models to explore ACC dynamics, with a focus on interaction across scales. The momentum and vorticity budgets of the ACC have long been known to depend on interaction of the current with sea floor bathymetry, but exactly how the large-scale balances are maintained is not understood. Internal waves, sub-mesoscale filaments and mesoscale eddies all likely play a role in determining the response of the current to changes in forcing.

Objective 5: To use high-resolution model studies to explore the impact of local dynamics on the response of the Antarctic Circumpolar Current to anomalies in forcing (time permitting).

2.4.2 What will the project deliver over 3 to 5 years?

Year 1: Model simulations explaining the dynamics and processes controlling the rate of surface warming in the Amundsen-Bellingshausen Seas. This includes coupled climate simulations and ocean–ice high-resolution models. Forcing via wind, heat and freshwater fluxes will be varied across simulations, as well as exploration of tropical drivers (e.g. ENSO, IPO).

Year 2: Model experiments explaining the processes responsible for abyssal ocean warming. This will include high-resolution ocean–ice models as well as limited domain ultra-high-resolution process-based experiments. Forcing via wind, heat and freshwater fluxes will be varied across simulations, with work exploring the resulting teleconnections to warming in the lower cell.

Year 3: Quantification of factors controlling ocean heat fluxes onto the Antarctic margin and its sensitivity to changes in forcing, assessed using idealised process models, regional studies, and comprehensive general circulation models.

Year 4: New estimates of anthropogenic carbon uptake over the Southern Ocean using a high-resolution biogeochemical model. Documentation of the primary physical mechanisms responsible for exchange of carbon between the atmosphere and the Southern Ocean.

Year 5: New high-resolution simulations of change in the Antarctic Circumpolar Current (pathways, properties, eddy heat fluxes, etc.) and impacts of these changes on the intrusion/steering of warm Circumpolar Deep Water toward the Antarctic shelf.

2.5 Southern Ocean observations and change

Project leader: Dr Steve Rintoul

Observations show that the Southern Ocean has undergone substantial change in recent decades. In the Antarctic Circumpolar Current, the upper ocean has warmed (Gille 2008) and freshened (Böning et al. 2008), in response to wind-forced changes in location of the current and changes in water mass formation (Meijers et al. 2012). At higher latitude, sea surface temperatures have cooled. The properties and stratification of the deep ocean are also evolving, with warming, freshening and contraction of the Antarctic Bottom Water (Purkey and Johnson 2010, 2012; van Wijk and Rintoul 2014) (Figure 5). However, the physical mechanisms driving water mass change in the Southern Ocean remain poorly understood and observations are sparse in space and time.

The project will collect new physical and biogeochemical observations in the Southern Ocean and use them with the historical record to develop a better physical understanding of the sensitivity of circulation and water mass formation to changes in forcing.

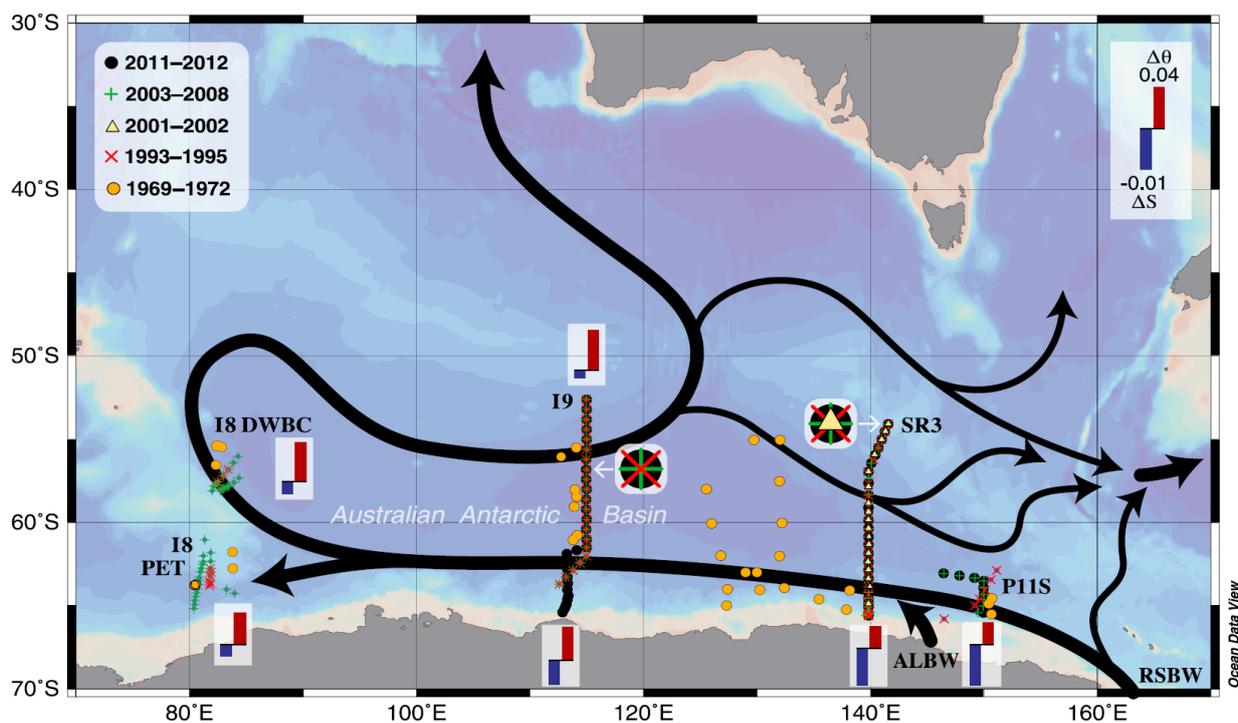


Figure 5 Schematic of the Antarctic Bottom Water export pathway (black arrows) through the Australian Antarctic Basin. Text labels indicate the sources of AABW (i.e. ALBW=Adélie Land Bottom Water and RSBW=Ross Sea Bottom Water) and the hydrographic sections used. Station locations are indicated by year (coloured symbols). Decadal rates of change in AABW core properties averaged over the bottom 300 m are shown by the insets at each section; salinity change (ΔS , blue bars) and potential temperature change ($\Delta\theta$, red bars). From van Wijk and Rintoul (2014).

2.5.1 Project aims and objectives

a) How and why is the Southern Ocean changing?

The overall aim of the project is to quantify variability and trends in ocean circulation and water mass formation in the Australian sector of the Southern Ocean, using a combination of shipboard data, float observations and satellite data, and to identify the physical mechanisms driving change.

The strongest signals of deep ocean change are seen near Antarctica (Rintoul 2007; Purkey and Johnson 2010, 2012, 2013; van Wijk and Rintoul 2014) but relatively few observations are available to define these trends. The deep ocean data that do exist are almost entirely limited to infrequent hydrographic sections. The project will analyse results from the 25-year time series of observations made south of Australia, including a new occupation planned for the 2017–18 austral summer, to quantify changes in physical and biogeochemical variables.

Objective 1: Quantify full-ocean depth changes along the SR3 repeat hydrographic section between Tasmania and Antarctica.

b) What processes are responsible for driving changes in the deep ocean near Antarctica?

Argo floats capable of profiling through the full ocean depth ('deep Argo') promise to revolutionise our ability to sample the deep ocean, much as regular Argo floats have done for the upper 2 km of the ocean. CSHOR will contribute to a pilot experiment using deep Argo floats in the Australian Antarctic Basin. This basin receives new bottom water formed in the Ross Sea and in the Mertz Polynya at 145°E. Measurements of chlorofluorocarbons (CFCs) show that inflow of newly-formed bottom water makes the Australian–Antarctic Basin the best ventilated of the deep basins around Antarctica (Orsi et al. 1999). Measurements from repeat hydrographic sections also show that the bottom waters in this basin are changing rapidly, becoming warmer, less salty, less dense, and contracting in volume (Aoki et al. 2013; van Wijk and Rintoul 2014; Katsumata et al. 2015). The drivers of bottom water change are not yet fully understood. Continuous, year-round measurements from the deep Argo array to be deployed by Australia, France, Japan and the USA (and possible investment from China) will provide critical observations needed to document and understand how and why bottom water is changing.

Objective 2: To use profiling floats to obtain the first comprehensive, year-round measurements of the Ross Gyre and quantify the circulation (as part of a collaborative project with NZ and the USA).

c) What is the nature of the poorly-observed ocean circulation between the Antarctic Circumpolar Current and the Antarctic coastline? How do the current systems of gyres, slope and coastal currents, and shelf-slope exchange found in this region regulate the transport of ocean heat to the Antarctic margin?

The high-latitude regions of the Southern Ocean are particularly poorly sampled, in part due to the presence of sea ice (Rintoul et al. 2014). New tools, including ice-capable profiling floats, provide new opportunities for sampling the region. Changes in water properties and circulation near the Antarctic margin are relevant to the stability of the Antarctic ice sheet and future sea-level rise, as well as for formation of Antarctic Bottom Water. For the Centre, two regions are of particularly high priority: Prydz Bay and neighbouring sectors of East Antarctica, and the Ross Gyre. The project will use a combination of ship-based measurements, moorings and ice-capable floats to explore these two regions. China and Australia have a long history of working in Prydz Bay, but have not yet combined forces in a joint experiment. In year 1, CSHOR scientists will explore opportunities for a joint field campaign to study ocean–ice shelf interaction, water mass formation and circulation in Prydz Bay. The Ross Gyre is the largest hole in the global Argo array and there is an opportunity for the China–Australia partnership to join forces to fill this hole, working alongside scientists from the USA and New Zealand.

Objective 3: To lead the design and implementation of the first international deep Argo pilot array in the Southern Ocean.

d) What are the physical mechanisms regulating ocean heat transport to Antarctic ice shelves? How vulnerable is the East Antarctic Ice Sheet to ocean heat transport?

One of the most serious potential consequences of Southern Ocean change would be an increase in basal melt of Antarctic ice shelves in response to increased ocean heat transport to the ice shelf cavities, leading to a retreat of the marine-based Antarctic ice sheet and more rapid sea-level rise (Dupont and Alley 2005). Recent work by CSIRO and the ACE CRC has shown that, counter to long-standing expectations, parts of East Antarctica are exposed to warm ocean waters that drive rapid basal melt of ice shelves (Rintoul et al. 2016; Silvano et al. 2016, 2017). These results suggest that East Antarctica may make a significant, but so far neglected, contribution to future sea-level rise.

We will use existing measurements to assess changes in Southern Ocean temperatures and circulation near the Antarctic margin. We will also explore the potential for joint fieldwork later in this term of CSHOR to investigate the factors regulating transport of warm ocean waters from offshore onto the continental shelf, and ultimately to ice shelf cavities. The Shackleton Ice Shelf is a potential target. Satellite measurements suggest the glaciers feeding the Shackleton Ice Shelf has been losing mass, but the cause is unknown as there are few ocean measurements near the Shackleton (Figure 6).

Objective 4: To assess the potential for warm ocean waters to reach ice shelf cavities in East Antarctica and drive enhanced basal melt, with potential focus areas including Prydz Bay and the Shackleton Ice Shelf.

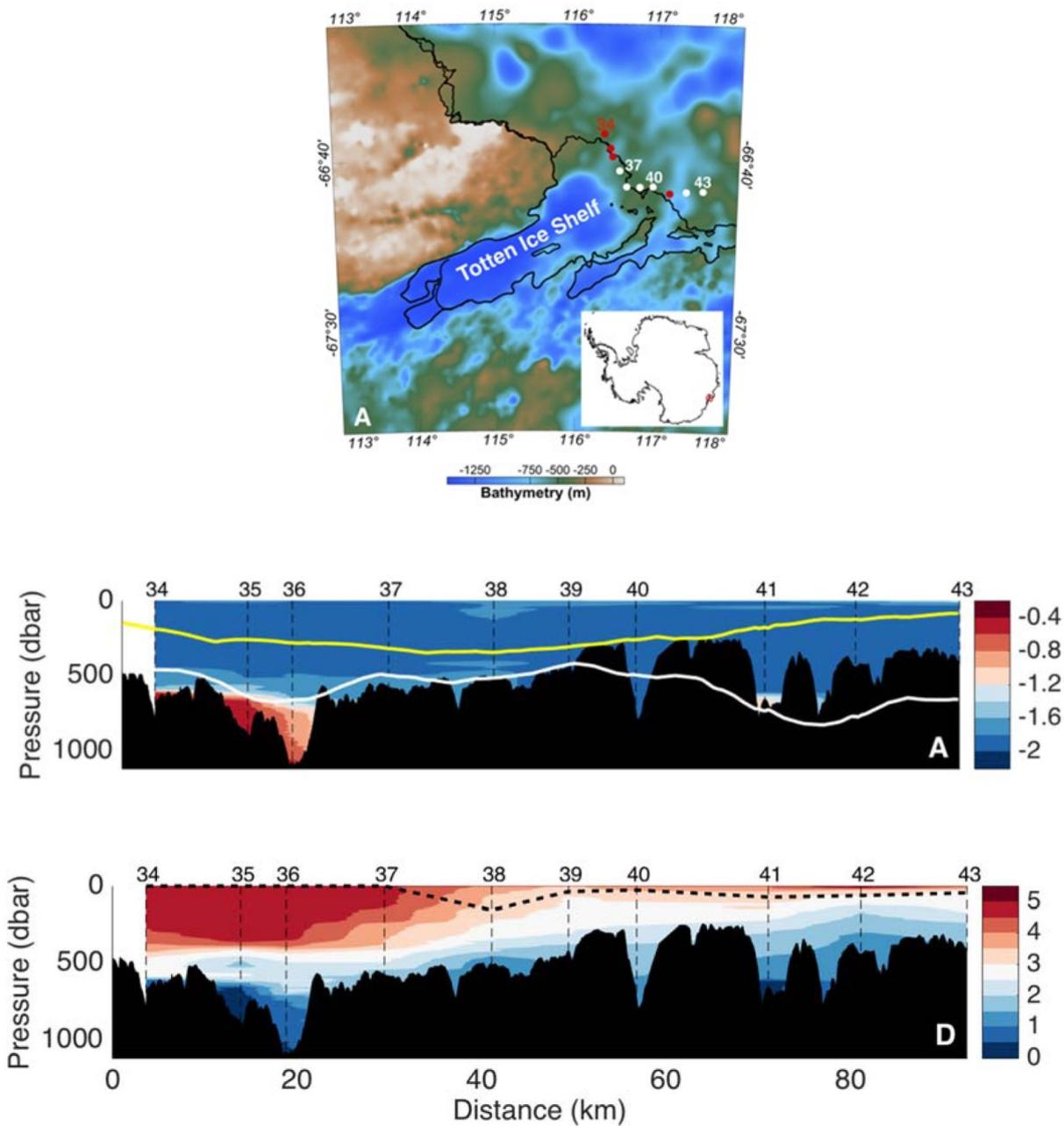


Figure 6 Location of stations occupied near the Totten Ice Shelf on *RSV Aurora Australis* in January 2015, the first ship to reach the front of the ice shelf. These measurements showed that surprisingly warm water reached the ice shelf (middle panel), carrying sufficient heat flux into the cavity to support high basal melt rates. The lower panel shows direct evidence of elevated melt-water fraction in the outflow from the cavity at depths shallower than 400 m. (From Rintoul 2016, Silvano et al. 2016 and Silvano et al. 2017).

2.5.2 What will the project deliver over 3 to 5 years?

Year 1:

- Occupy the SR3 repeat transect between Tasmania and Antarctica, extending a time series commenced in 1991.
- Deploy a pilot array of deep Argo floats in the Australian Antarctic Basin, in collaboration with French, US and Japanese scientists.
- Deploy ice-capable profiling floats in the Ross Gyre, in collaboration with US and NZ.
- Quantify the sensitivity of bottom water formation to changes in forcing, as assessed from observations before and after calving of the Mertz Glacier Tongue.

Year 2:

- Quantify changes in bottom water in the Australian–Antarctic Basin from repeat hydrography.
- Publish a review of Southern Ocean dynamics, highlighting the global influence of localised dynamics in the Southern Ocean.
- Develop plans for joint field programs in Prydz Bay, the Shackleton Ice Shelf, and/or the Antarctic continental slope in the Australian–Antarctic Basin.
- Carry out a study of frontal dynamics and cross-front exchange in a standing meander of the Polar Front south of Australia, exploring how interactions between the flow and topography contribute to the dynamical balances of the Antarctic Circumpolar Current.

Year 3:

- Publish an analysis of seasonal and high frequency variability in bottom water properties as measured by the pilot array of deep Argo floats, including implications for observing change in the deep ocean from infrequent hydrographic sections.
- Quantify the circulation of the poorly-observed Ross Gyre.

2.6 The role of the Southern Ocean in sea-level change

Project leader: Dr Xuebin Zhang

Sea-level rise is an important issue related to anthropogenic climate change. Global mean sea level (GMSL) has been rising according to historical observations and is projected to continue to rise in the coming centuries. Several processes can affect GMSL, including ocean thermal expansion (estimated to be the largest contribution during the 21st century), mass loss of glaciers and ice caps, the Antarctic ice sheet and the Greenland ice sheet, and changes in the land water storage (Figure 7). The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) gave a comprehensive summary of GMSL's historical change and future projection. However, there are still significant uncertainties about those projections, in particular associated with dynamical contribution of the Antarctic ice sheet (Church et al. 2013).

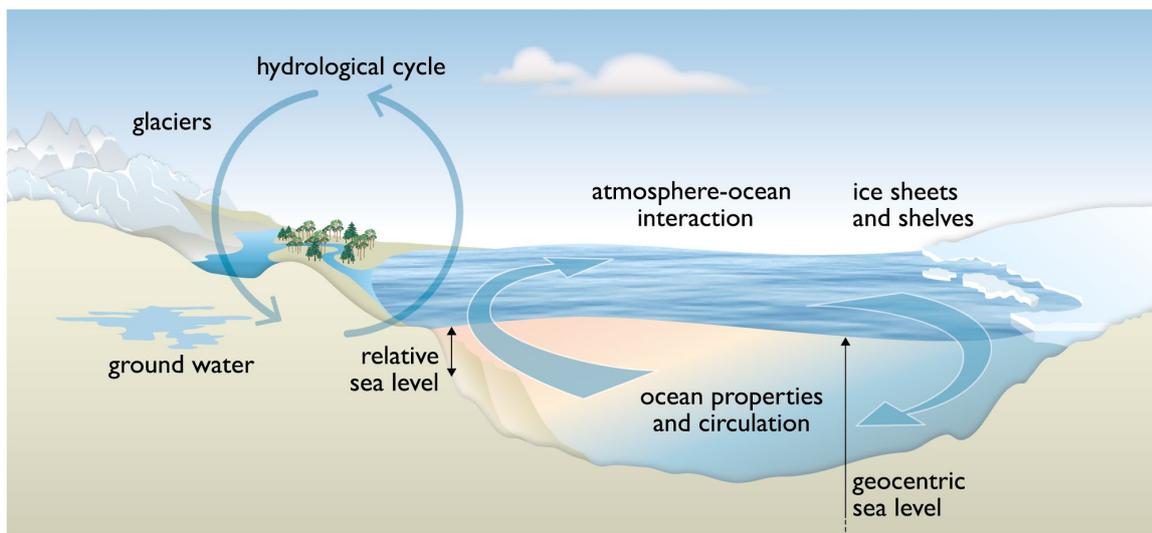


Figure 7 Climate-sensitive processes and components influencing global and regional sea level, which are considered in the Fifth Assessment Report (AR5) of Intergovernmental Panel on Climate Change (IPCC). (From Church et al. 2013)

Sea-level changes are not expected to be spatially uniform, since several physical processes such as ocean density and circulation changes, loss of land ice mass and glacial isostatic adjustment, all cause regional variations. The mean sea-level rise will likely be felt through extreme sea level events, which lead to coastal flooding, inundation and erosion (McInnes et al. 2015). Over 100 million people live within a metre of current high tide mark, thus are highly possible to be affected by sea-level rise. Society needs reliable global and regional sea-level projections so that appropriate adaptation and mitigation planning can be adopted.

The Southern Ocean is a key area for improving understanding and projections of ocean heat content and sea-level change because:

1. it is one of the key areas where heat enters the ocean, resulting in heat storage in the upper ocean and in the abyssal layers, and contributing to sea-level rise via ocean thermal expansion (Purkey and Johnson 2010; Roemmich et al. 2015; Wijffels et al. 2016)
2. a warming ocean is critical to the dynamic response of the Antarctic ice sheet (Church et al. 2013; DeConto and Pollard 2016).

The purpose of this project is to study the role of Southern Ocean in sea-level change, based on which more reliable and detailed global and regional sea-level projection can be derived.

2.6.1 Project aims and objectives

a) Can we quantify the amount of heat entering the Southern Ocean?

The Southern Ocean is the largest heat sink based on both historical observation and future projection. However, the Southern Ocean is much less observed than the other regions, and the situation is ameliorated in the past decade due to the Argo program (Riser et al. 2016). The Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models, with coarse grid resolution, still have difficulty representing all related heat processes in the ocean (Griffies et al. 2015). As a result, how the heat is absorbed and redistributed in the Southern Ocean, and related underlying processes, are still not very clear to us. Therefore, better understanding of heat uptake and redistribution in the Southern Ocean through ocean and climate modelling (including high-

resolution modelling) guided by available observations is critical for us to give a robust estimate of heat uptake and its contribution to sea-level rise.

Objective 1: To use observations, ocean and climate modelling to examine the amount of heat entering the Southern Ocean.

b) To what degree does the Antarctic ice sheet contribute to regional sea-level change?

The Southern Ocean also plays a critical role in the contribution of the Antarctic ice sheet to sea-level rise, through ocean–ice shelf interaction, as well as complex interactions among the ocean–atmosphere–ice sheet system (Figure 8). Our understanding of those interactions is still in the early stage, partially due to very limited observations. For example, recent estimates of Antarctic ice mass flow into the Southern Ocean, based on several observing techniques, indicates that uncertainties are still large. There is still disagreement on the sign of change in East Antarctica (Allison et al. 2018). Similarly, the future projections of Antarctic ice sheet contribution also vary considerably, even over the 21st century, depending on model physics. For example, DeConto and Pollard (2016) implemented somewhat uncertain physics (in particular surface-meltwater-enhanced calving via hydrofracturing) and got much larger changes than the IPCC AR5 (>1 m possible by 2100). So far, there is no complete ensemble available considering different forcing and uncertainty in physics.

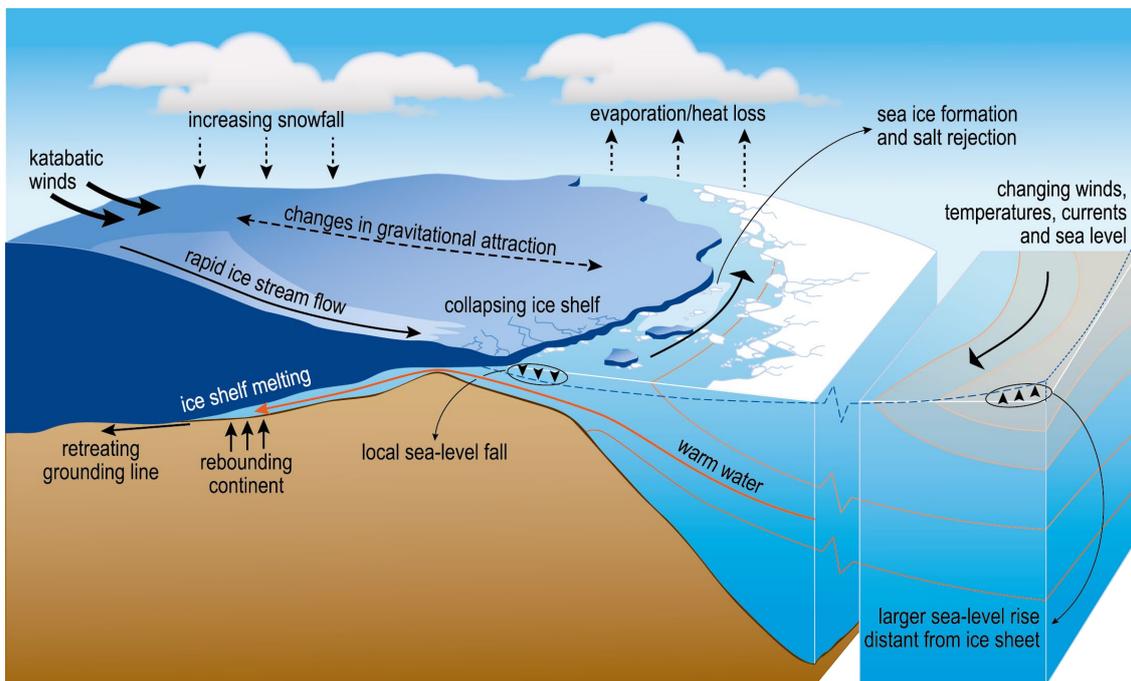


Figure 8 Interactions between ice sheets, ocean, and atmosphere affect the mass balance of Antarctic ice sheet. (From Willis and Church 2012)

Objective 2: To use updates of observations and projections of the Antarctic ice sheet contribution, together with other contributions, to better understand the regional sea-level change distribution and thus to refine sea-level projections.

c) Can we explain the regional distribution of sea level in the Southern Ocean and make connection to various forcings (such as wind and heat flux)?

Significant regional differences of sea level exist in the Southern Ocean, controlled by complex Southern Ocean dynamics and driven by various atmospheric and land forcings. It's hard to tell apart influences of various forcings in regional sea levels by examining available observations alone. However, numerical perturbation experiments, with some forcing turned on or off, can be very useful for us to separate influences from various forcings, and enable us to examine underlying processes better. In particular, we are interested in separating impacts of wind and buoyancy forcings, natural and anthropogenic forcings by designing and running perturbation experiments.

Objective 3: To separate the impact of wind-induced from Antarctic freshwater-induced ocean responses, and natural versus anthropogenic forcing in sea level and ocean dynamics in the Southern Ocean using carefully designed perturbation experiments (with some forcing turned on or off).

d) Is the dipole structure of sea-level change in the Southern Ocean derived from coarse resolution models robust?

For the regional distribution of sea-level change in response to anthropogenic warming, one of the key features based on CMIP5 climate models is a clear meridional dipolar structure of dynamic sea level in the Southern Ocean, with higher (lower) regional sea levels north (south) of $\sim 50^{\circ}\text{S}$ (Lyu et al. 2014; Bilbao et al. 2015), which is associated with the poleward expansion of the Hadley Cell and poleward strengthening and shifting of westerlies (Zhang et al. 2014). However, CMIP-type climate models usually have coarse resolution (typical nominal resolution of 1° in the ocean), therefore cannot represent mesoscale features well (Griffies et al. 2015). But, mesoscale eddies may play a significant role in the Southern Ocean circulation through eddy compensation and saturation (e.g. Farneti and Delworth 2010), as well in ocean heat uptake and redistribution (Griffies et al. 2015). Moreover, the ocean may respond differently to shifting vs strengthening of westerlies as found by Francombe et al. (2013) with an eddy-permitting ($1/4^{\circ}$) ocean general circulation model (OGCM). Thus it is critical to examine some regional sea-level distribution and related dynamical processes in the Southern Ocean between coarse-resolution and high-resolution (eddy-resolving) models, to identify similarities and differences between their representations, guided by available observations.

Objective 4: To examine whether the dipole structure of sea-level change derived from coarse resolution models is robust, whether the eddy-resolving model gives a similar dipolar structure, and whether there are distinct responses to strengthening vs shifting of westerlies.

We are going to address the above issues mainly based on available in-situ (such as Argo array) and satellite observations (such as altimetry), CMIP5/6 climate models, our eddy-resolving global OGCM (Oke et al. 2013; Zhang et al. 2016, 2017). For ice sheet contribution, we will use updated observations (e.g. from the Gravity Recovery and Climate Experiment (GRACE) satellite), state-of-

the-art analysis of ice mass flux estimates, as well as future projections based on either stand-alone ice-sheet modelling or coupled ocean–atmosphere–land–ice modelling, which will be available from our own ice sheet modelling, as well as from the Ice Sheet Model Intercomparison for CMIP6 (ISMIP6, Nowicki 2016).

2.6.2 What will the project deliver over 3 to 5 years?

Year 1:

- Estimates of heat uptake and redistribution in the Southern Ocean based on observations and models.
- Examination of sea-level response to poleward shifting vs strengthening of westerlies.
- Analysis of technique-specific uncertainties of Antarctic ice sheet mass flux time series.

Year 2:

- Estimates contribution of wind vs melting, natural vs anthropogenic in the historical sea level in the Southern Ocean over the past several decades.
- Estimates of impacts of mesoscale eddies in regional sea-level distribution in the Southern Ocean, especially for the meridional dipolar structure.
- Compilation of state-of-the-art of Antarctic ice sheet mass flux rates from early 1990s to 2019, with robust error range.

Year 3:

- Updated fingerprint of Antarctica ice sheet mass change in the Southern Ocean based on latest mass flux information.
- Refined projection of regional and global sea level associated with Antarctic ice sheet melting, based on stand-alone ice-sheet modelling and/or coupled ocean–atmosphere–land–ice modelling.

3 Communication

Communicating the results of CSHOR's research is integral to its success. The CSHOR audience includes QNLM, CSIRO, UTAS, UNSW, other project collaborators, CSHOR Steering and Advisory Committees, marine and atmospheric science organisations, government stakeholders, media organisations and the general public.

3.1 Key messages

- The goal of CSHOR is to improve our understanding of how the southern hemisphere oceans influence global and regional climate. Both Australia and China are strongly influenced by climate variability and change. Australia and China therefore have a strong common interest in better understanding how the southern hemisphere oceans influence the climate of our region and the rest of the globe. By tackling the most fundamental questions in southern hemisphere ocean climate research, CSHOR will help to inform an effective response to the challenges of climate change and variability.
- Leading the research is CSIRO and China's Qingdao National Laboratory for Marine Science and Technology, with the support of the University of New South Wales and the University of Tasmania.
- The Centre for Southern Hemisphere Oceans Research will tackle fundamental research into ocean processes that affect the climate of Australia, China and the rest of the globe – now and into the future.
- The Centre will promote scientific collaboration and the exchange of the ideas by attending, and where appropriate, organising workshops, conferences and public events.
- CSHOR is in a position to drive the grand challenges and engagement at a global level.
- The southern hemisphere oceans have a significant influence on Australian and global climate, but remain poorly observed and understood.
- The Centre will tackle important questions about the southern hemisphere oceans, their role in climate variability and change, their interaction with Antarctic ice shelves and their contribution to sea-level rise.
- It will also look at the interaction between the oceans and climate of China and Australia, including the way this affects the likelihood and severity of future flood and drought events.
- The Centre will be a proven model of collaboration to fund international science.

3.2 Communication goals

The overall communication goals are to inform the CSHOR audience of important research findings and to position CSHOR as a world-class climate research centre.

3.3 Objectives

- Ensure communication activities are aligned with and support information disseminated by our stakeholders and research partners, including QNLM, CSIRO, UTAS and UNSW.
- Coordinate and participate in communication activities with our research partners to increase science impact in southern hemisphere ocean climate research.
- Minimise misinformation about CSHOR through delivery of a clear communication campaign across the project life.
- Deliver consistent, timely and up-to-date tailored communication messages about CSHOR projects to key stakeholders and the general public on a yearly basis for the life of the projects.
- Position CSHOR science leaders as respected spokespeople on southern hemisphere ocean climate research.
- Grow traffic to our website at <https://cshor.csiro.au/>.

3.4 Tools

The following list of communication tools can be used to promote and enhance the reputation of CSHOR:

- Research partner publications – internal and external
- Media release/media pitching
- Brochures/fact sheets (technical and promotional)
- Written Q&As – in particular for issues management
- Website
- Stakeholder engagement events – presentations, face to face discussions, community forums
- Membership of international committees, such as the CLIVAR Pacific Panel and the Indian Ocean Panel.
- Engagement with international programs, such as the WCRP grand challenge and the UN Decade of Ocean Science for Sustainable Development (2021–2030).
- Ministerial or parliamentary briefings
- Articles for owned-channels – e.g. ECOS or CSIROscope
- Social media: Twitter, Facebook, LinkedIn, Instagram (CSIRO accounts only)
- Multimedia – videos, photography, animations
- Industry events, conferences, workshops or other scientific showcases
- Conferences
- Delegations
- Stakeholder events
- Workshops

3.5 Communication action plan and timeline 2018

The communication action plan and timeline will be updated at least annually.

Action	Audience	Responsibility	Date
Publish manuscripts in scientific research journals (manuscripts funded in full or part by CSHOR should be affiliated with and acknowledge CSHOR)	Stakeholders, researchers, general public	Project leaders and staff	ongoing
Present CSHOR research and promote CSHOR at Australian Meteorological and Oceanographic Society (AMOS) - International Conference for Southern Hemisphere Meteorology and Oceanography (ICSHMO)	Researchers	Director, staff and Comms Manager	February
Present CSHOR research and promote CSHOR at Ocean Sciences Meeting (OSM)	Researchers	Director and staff	February
Communication activity highlighting Rintoul voyage	General public, stakeholders, researchers	Comms Manager and Steve Rintoul	February
Launch CSHOR website	General public, stakeholders, researchers	Project support officer and staff	March
Present CSHOR research and promote CSHOR at the following meetings in Perth, Australia: Indian Ocean Global Observing System (IOGOOS)-14/Indian Ocean Regional Panel (IORP)-14/Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER)-8/ Indian Ocean Observing System Resources Forum (IRF)-8/The International Indian Ocean Expedition (IIOE)-2 SC2	Researchers	Staff	March
Present CSHOR research and promote CSHOR at the "Understanding the relationship between coastal sea level and large-scale ocean circulation" workshop, International Space Science Institute (ISSI), Bern, Switzerland	Researchers	Staff	March
Internal and external profile of new staff members	General public, stakeholders, researchers	Comms Manager	April
CSHOR Science Seminar	Researchers, stakeholders, general public	Director and staff	May
Communication activity highlighting Sloyan voyage	General public, stakeholders, researchers	Comms Manager and Bernadette Sloyan	May
Present CSHOR research and promote CSHOR at the Asia Oceania Geosciences Society (AOGS) Conference	Researchers	Director and staff	June
Present CSHOR research and promote CSHOR at The Climate and Ocean: Variability, Predictability, and Change (CLIVAR) - First	Researchers	Early Career Researchers (tbc)	June

Action	Audience	Responsibility	Date
Institute of Oceanography (FIO) Summer School on “Past, present and Future Sea Level changes”			
Present CSHOR research, promote CSHOR and assist QNLM by organising a session at the Global Ocean Summit	Researchers	Director	July
Present CSHOR research and promote CSHOR at Mawson’s Huts Foundation 2018 Australian Antarctic Festival	General public	Project support officer, Comms Manager, Director and staff	August
Communication activity highlighting water mass formation project (England/Rintoul)	General public, stakeholders, researchers	Comms Manager and project leaders	August
Communication activity highlighting sea-level change project (Zhang)	General public, stakeholders, researchers	Comms Manager and project leaders	September
Present CSHOR research and promote CSHOR at CLIVAR IV International Conference on El Niño–Southern Oscillation: ENSO in a warmer climate	Researchers	Director and staff	October
Communication activity highlighting ENSO/IOD project (Santoso and Wang)	General public, stakeholders, researchers	Comms Manager and project leaders	November
Communication activity highlighting coupled warm pool project (Feng and Wijffels)	General public, stakeholders, researchers	Comms Manager and project leaders	November-December
Present CSHOR research and promote CSHOR at AGU Fall Meeting	Researchers	Staff	December

3.6 Evaluation

The effectiveness of this communication plan will be measured by:

- production of regular CSHOR communication activities, which are accessible to the academic and broader community
- industry and government awareness and engagement with the projects
- research partner feedback, support and dissemination of information

Communication opportunities that involved a proactive campaign will be measured using standard CSIRO Corporate Affairs media and communication evaluation measures. These include:

- Media reports
- Coverage statistics
- Blog and social media reach
- Web hits
- Enquiries
- Evaluation of impact of the communication activity (e.g. further research)

4 Future directions and opportunities

CSHOR was established to advance challenging fundamental science that will help identify the risks and opportunities of climate variability and change. Some of the issues that are being addressed – such as the response of ENSO and the IOD greenhouse warming, and the interaction between the ocean and ice sheet at decadal timescales and beyond – have been long-standing. While CSHOR will make substantial progress on these issues, it is expected that a significant subset of associated scientific questions will be identified as CSHOR progresses, which will provide opportunities to broaden the scope of the CSHOR endeavour.

The close of the first phase of CSHOR coincides with the beginning of the United Nations Decade of Ocean Science for Sustainable Development (2021–2030), established to mobilise the scientific community, policy-makers, business and society around a program of joint research and technological innovation. This decade will consolidate efforts by the Intergovernmental Oceanographic Commission to boost international cooperation in ocean sciences. It will enable better coordination of research programs, observation systems, capacity development, maritime space planning and the reduction of maritime risks to improve the management of ocean and coastal zones resources. This global context provides an important impetus for CSHOR, having tested a feasible protocol for international science collaboration, to continue into a second phase, in accord with intentions of the UN.

To this end, there are several priority areas for CSHOR. One is to increase our observational effort in key regions by taking advantage of the ongoing rapid development of observational technologies, such as under-ice Argo and deep Argo. These technologies will facilitate observations of transport of warm ocean waters across the continental shelf break for studies of ocean–ice shelf interactions, the dynamics of variability and change near Prydz Bay, and deep ocean heat uptake by the Southern Ocean, enabling advances in one of the core science areas that CSHOR was established to tackle.

Another priority is to use data collected from moorings, float and ship-based observations to assess models and improve physical parameterisation, which in a high-resolution setting will guide future observation needs. This is applicable in the Indo-Pacific warm pool region, where complex air–sea interactions at various timescales (from diurnal and intra-seasonal to interannual) occur, but our understanding of the processes is poor, and there are virtually no observations available thus far. This is also applicable to the development of limited domain, ultra-high-resolution regional models, key for understanding the dynamics of warm-water intrusions onto the Antarctic continental shelf, and for investigation of the impact of Antarctic melt on the overturning circulation and potential for feedbacks. This knowledge is essential for assessing uncertainty in the upcoming CMIP6 and ISMIP6 model outputs, to estimate ice sheets' contribution to sea-level rise, and the associated global and regional sea-level projections.

Further, one of the fundamental characteristics of the Southern Ocean in a warming climate is that the surface warming is slower than other oceans but is spatially non-homogenous. Recent studies have suggested that these features could have a profound influence in the interhemisphere warming contrast and equatorial zonal temperature gradients, affecting the Asian monsoon and

extreme tropical climate. However, the extent and processes of the impact from the Southern Ocean remain inconclusive, and this offers another research priority.

Finally, at the close of the first phase of CSHOR, it will be appropriate to consider expansion into another field of associated research, such as marine biodiversity. This would be a natural progression from the science of the physical environment to inclusion of an impact-oriented focus. The potential for this expansion will become clearer as CSHOR evolves. Of course, other organisations may also be well-placed to address the science challenges, and should be entrained into CSHOR.

Looking ahead, by tackling the most fundamental questions in southern hemisphere ocean climate research, CSHOR is well-positioned to make a long-lasting contribution to the advancement of international climate science.

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