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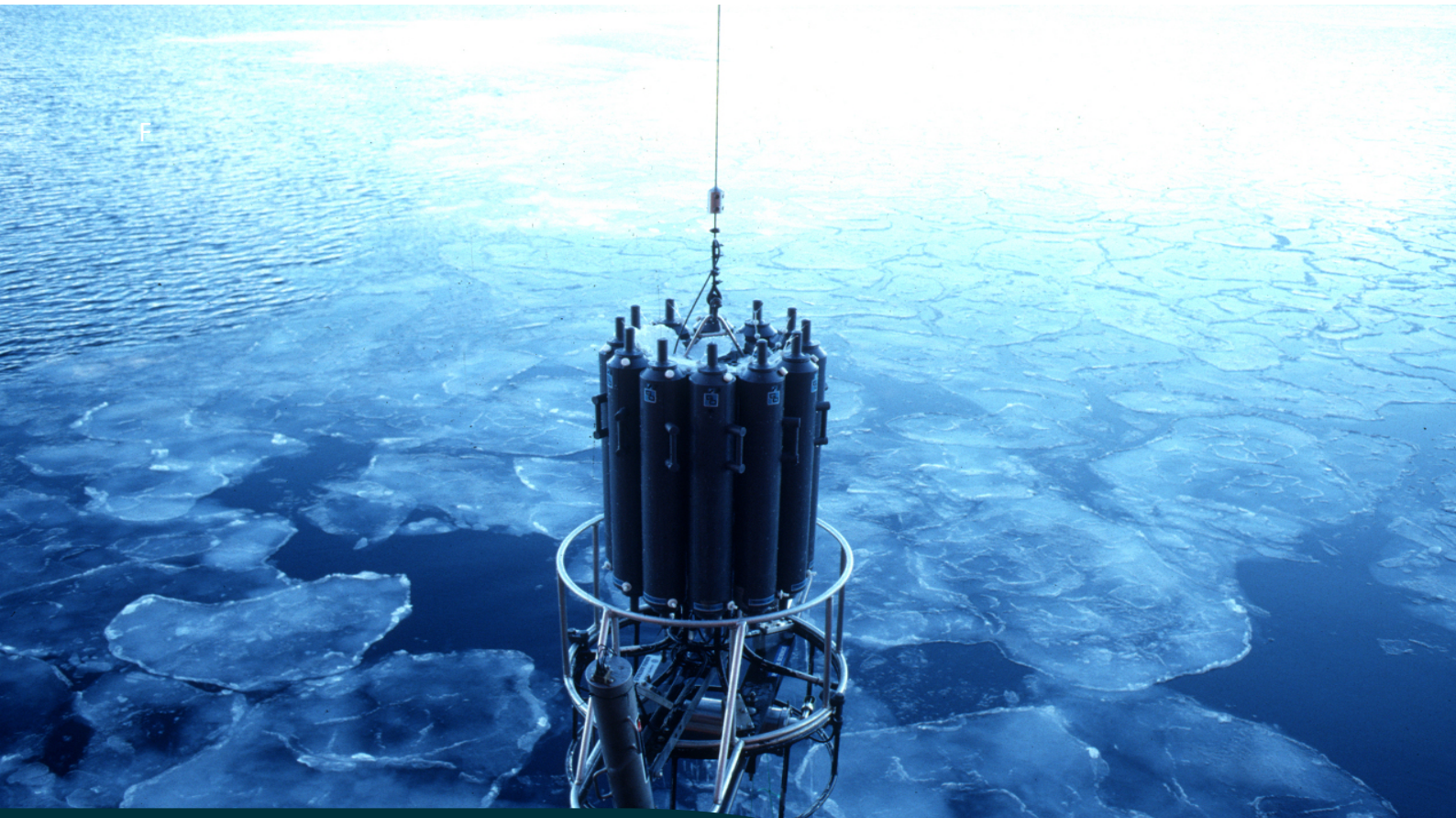
2018-19 Annual Report

Centre for Southern Hemisphere Oceans Research



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

CSIRO

UNSW SYDNEY

UNIVERSITY of TASMANIA

Published: September 2019.

Cover Image

Deploying a CTD, a sampling device which collects data on conductivity (salinity), temperature and depth in pancake ice, Antarctica, July 2012 (Courtesy CSIRO).

Foreword

I am pleased to present the second Centre for Southern Hemisphere Oceans Research Annual Report as required under Clause 13 of the Centre's Research Collaboration Umbrella Agreement.

The Centre was launched in May 2017 with the aim of conducting fundamental research into the role of the Southern Hemisphere oceans in regional and global climate systems. It is a collaborative research partnership between CSIRO, China's Qingdao National Laboratory for Marine Science and Technology (QNLM), the University of New South Wales and the University of Tasmania.

The high quality of the Centre's research is reflected in the achievements reported by the six project teams. I have been impressed with how much work is produced by a relatively small team of researchers. I believe CSHOR's emphasis on fostering international collaboration is a major contributor to this productivity along with dedicated formalized partnerships.

Centre staff were busy throughout the year organising and sponsoring international workshops and seminars. I enjoyed catching up with the postdoctoral fellows at the CSHOR Science Seminar in Hobart in May 2019. They presented an impressive body of work for the year.

I hope you enjoy reading about the many accomplishments described in this report – results that are providing scientific breakthroughs in the understanding of the Southern Ocean and its connectivity to Earth's climate and weather systems.

Kind regards,

Dr Susan Avery

Steering Committee Chair

August 2019

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Acknowledgments

The Centre for Southern Hemisphere Oceans Research (CSHOR) acknowledges the valuable assistance of the following individuals and organisations during the second year of CSHOR's scientific research program.

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1 Executive summary

The second year of operations at the Centre continue to demonstrate the importance of strategic partnerships in delivering outstanding new science. The significant research reported by our six project teams confirms that we are on our way to discovering more about the southern hemisphere oceans from the tropics to the Antarctic. The components of the earth system are more tightly connected and more complex than previously thought, whether it is between the three oceans, between the tropics and high latitudes, or between sea ice, land ice, the ocean, and the atmosphere. It is this very tight connection that further highlights the need for such international collaboration as CSHOR, as no single institution and nation can meet the challenge.

CSHOR research has begun to address some of the key challenges in climate science, such as El Niño-Southern Oscillation complexity, interactions between the three tropical oceans, and the role of Southern Ocean heat sequestration in the fate of the Antarctic sea ice, Antarctic land ice, and global sea level in a warming climate. While some of the research has been published, there is much work carried out during the second year that will be published early in 2019-20, including, the role of Southern Ocean in sequestering carbon, and the potential contribution of Antarctic land-ice melting to global sea level. The cutting-edge science that CSHOR undertakes is attested by a large increase in investment through significant programs within and outside Australia led by our CSHOR scientists.

CSHOR research, communication and outreach is summarised in this section. Detailed project reports are provided in Section 2. Section 3 charts the Centre's revenue and expenditure for the 2018-19 financial year. Internal management and co-ordination are outlined in Section 4.

1.1 Research achievements

Significant findings were reported by CSHOR projects throughout the year. The Centre produced four high profile research articles published by the *Nature* group (three) and *Science* (one). In total, there were 28 publications. A selection of research achievements is presented below.

1.1.1 ENSO and the IOD

A *Nature* review paper providing a synthesis of the current understanding of the spatio-temporal complexity of the El Niño-Southern Oscillation (ENSO) and its influence on the earth system generated considerable interest (e.g. Altmetric score of 169) (Timmermann et al., 2018).

In a *Nature* paper published in December 2018, Cai et al. show for the first time strong inter-model consensus over sea surface temperature variability of a type of El Niño, the eastern Pacific El Niño that is strong in both strength and impact, despite differences in the details of the simulated El Niño across models. This paper was highlighted in a *Nature* 'News and Views' piece and Drs Cai and Santoso were interviewed by various media outlets, including *The Los Angeles Times*, Fairfax media and the Australian Broadcasting Corporation (ABC). It has generated continued interest since publication (e.g. Altmetric score of 511).

In a *Science* paper published in March 2019 Cai et al. review what we know about pantropical interactions, discuss possible ways of improving predictions of current climate variability, and consider how projecting future climate under different anthropogenic forcing scenarios may be improved. They argue that making progress in this field will require sustained global climate observations, climate model improvements, and theoretical advances.

1.1.2 Antarctica and the Southern Ocean

Early in 2018, the first array of Deep Argo floats was established near Antarctica, in partnership with the United States, France and Japan. The floats are delivering measurements of full-depth ocean properties with unprecedented spatial and temporal detail.

In late 2018, CSHOR participated in the highly successful RV *Investigator* voyage to a standing meander in the Polar Front. CSHOR researchers will use voyage data to investigate air-sea fluxes, mixed layer depth variations, and velocity structure of the Polar Front.

Observations of Southern Ocean eddies collected on the RV *Investigator* were used to explore the meridional salt and heat transport across the Subantarctic Front, and the importance of the region south of Australia in this transport.

The Southern Ocean dynamics, circulation and water mass formation project team is forging ahead and many of the agreed project milestones have reached completion or near to completion sooner than expected. Activities during the past year have focused on the dynamics of the Antarctic Circumpolar Current (ACC), the mechanisms for exchange across the Antarctic continental slope, and the variability of bottom water properties. The project highlights the unique role the Southern Ocean biological and physical carbon pumps play in taking up and sequestering carbon, and the role that future changes in Southern Ocean productivity may have on the global carbon cycle.

CSHOR project scientists have demonstrated the value of Southern Ocean observations and have been able to secure funds for additional Argo floats from the Australian Science and Industry Endowment Fund ($2m). Project staff have also led the development of a successful proposal for the Australian Antarctic Program Partnership ($50m over 10 years) and contributed to the development of a $56m proposal for a Special Research Initiative for Excellence in Antarctic Science and additional investment by the Integrated Marine Observing System in ice-capable Argo floats.

1.1.3 Sea-level rise

CSHOR conducted a systematic comparison between sea-level projections from The Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC AR5) and sea-level observations based on tide gauges and satellite altimetry over their overlapping period. Good consistency between projections and observations in the recent decade was found, indicating the robustness and usefulness of IPCC AR5 sea-level projections for future adaptation planning.

1.1.4 Indo-Pacific inter-basin exchange and coupled warm pool dynamics

CSHOR has collaborated with scientists from China's First Institute of Oceanography (FIO) to carry out a 6-day chartered voyage in the southeast Indian Ocean warm pool, deploying one Meteorology and Ocean Profiling Buoy (MOPB) from the FIO and eight fast profiling floats from CSIRO.

CSHOR's Indo-Pacific inter-basin exchange project and the Integrated Marine Observing System (IMOS) will lead Australian involvement in an exciting new international collaborative study of the Indonesian Throughflow. The study named MINTIE (Measuring and Modelling the INdonesian Throughflow International Experiment) brings together many international partners, including Australia, the United States, China, and Indonesia.

1.2 Communication and outreach highlights

Communication is an important component of CSHOR activities. As well as publishing in scientific journals, CSHOR staff have been busy promoting southern hemisphere oceans research via media interviews, at international meetings, and by organising and supporting scientific workshops and seminars.

1.2.1 Media

Below is a summary of CSHOR's media activity throughout the 2018-19 financial year.

A July 2018 *CSIRO Blog* introducing the Timmermann et al. paper was promoted via social media. The blog was viewed by 1235 people with an average time on page of 4 mins 25 secs (1.5 mins more than average). It was the 11th most read blog for July. According to *Facebook* statistics there were 19687 reaches, 191 reactions, 30 shares, 16 comments, and a 4% engagement rate. *Twitter* statistics from two tweets resulted in 3278/4033 impressions, 16/50 total engagements. And the *LinkedIn* reach generated 1888 impressions and 50 clicks.

The Cai et al. *Nature* paper published in December 2018 was the subject of 11 media reports with an audience of 116,045.

CSHOR's visit to QNLM in January was posted on CSIRO's *Twitter* Account. Two posts were created, three retweets and 10 likes were received.

CSHOR scientists, Drs Cai and Santoso, were quoted in *The Age* newspaper highlighting the increased probability of a large El Niño by the end of 2019. The article by Peter Hannam discusses the findings from an international climate science conference held in Chile in March 2019.

The Cai et al. pantropical climate interactions paper was posted to the *SciMex* website in early March 2019. A CSIRO *ECOS* article published later in March received 250 views, the average time spent on the page was 4 mins 50 secs.

In May 2019, a *CSIRO Blog* titled, 'What we learnt from spending winter under Antarctic sea ice', was read by 492 people with an average time on page of 4 mins 24 secs (1.5 mins more than average). News articles were published in the *Hobart Mercury* and *Courier Mail* online. The associated tweet reached 7,498 people, and the *Facebook* post promoting the blog reached 11,633 people and generated 73 reactions.

1.2.2 Outreach

In July 2018 the Centre Director and staff helped to organise and promote the Global Ocean Summit 2018 (GOS2018). The Summit was held at QNLM in Qingdao, China and was hosted by *Science* and QNLM.

CSHOR staff attended the QNLM Academic Annual Meeting in Qingdao in mid-January 2019. Staff also toured the wonderful facility at QNLM and attended a banquet in honour of CSHOR's visit to Qingdao. CSHOR staff received a friendly and gracious reception.

Later in January CSHOR gathered over 50 ENSO experts and students in Hobart for a three-day symposium, with the aim of addressing important scientific questions regarding the reliability of current modelling and observational tools, and what advances are required to improve projections of ENSO in a changing climate. The symposium was followed by a two-day writing session for authors of an ENSO monograph commissioned by the American Geophysical Union (AGU), edited by Drs McPhaden, Santoso, and Cai. CSHOR staff, Drs Cai, Santoso, Wang and Zhang, are contributing authors.

CSHOR ENSO Science Symposium Hobart 29 – 31 January 2019

CSHOR research was presented to over 300 visitors at the CSIRO Aspendale Laboratory Open Day in March 2018.

CSHOR and CSIRO hosted the second Deep Argo Workshop at CSIRO Marine Laboratories Hobart in May 2019. Over 30 international and national scientists attended the workshop. A public seminar on the first day of the workshop was well attended by Hobart-based ocean scientists.

2nd Deep Argo Workshop, CSIRO Hobart, May 2019

CSIRO and the CSHOR office hosted the CSHOR Science Seminar on 16 May. Project leaders provided an overview of the year's research and presented their plans for next financial year. Over 40 guests attended the seminar. Guest presenter, Dr Ian Allison, delivered a talk titled, 'From Indulgence to Global Relevance: a fifty-year journey towards understanding the role of Antarctica in the climate system'.

CSHOR research was presented at a host of national and international meetings. Major conferences and workshop attended by CSHOR staff are listed in Appendix C.

1.3 Awards and special mentions

Dr Foppert won second prize for her presentation at the QNLM Academic Annual Meeting Young Scholars' Forum held in Qingdao, China in mid-January. Dr Foppert's talk was titled, 'Hot spots of eddy-driven transport across the East Antarctic slope'. QNLM invited many young scientists from partner organisations both in China and internationally to submit a presentation to the forum. The presentations were of a high calibre across a broad range of ocean science disciplines.

From the left, Prof Zhimeng ZHUANG, QNLM Deputy Director; Dr. Xu ZHANG, QNLM and Dr Annie Foppert, CSIRO CSHOR, both receiving 2nd prize; and Prof Jinming SONG, QNLM Deputy Director (photo courtesy of QNLM).

Dr Sloyan accepted an invitation to join the International Laboratory for High-Resolution Earth System Prediction (iHESP) Scientific Advisory Board (SAB). iHESP, located at Texas A&M University (TAMU), is a collaboration between National Center for Atmospheric Research (NCAR), Texas A&M University, and the Qingdao National Laboratory for Marine Science and Technology (QNLM).

Prof England accepted an invitation to join the Advisory Board of a major new European Project, SO-CHIC (Southern Ocean Carbon and Heat Impact on Climate). SO-CHIC is a partnership across 15 European and United Kingdom agencies, including Sorbonne University, Southampton, Reading, Alfred Wegener Institute (AWI), Eidgenössische Technische Hochschule Zürich (ETH), Oxford and Geomar).

Dr Cai has taken on a new role as Co-chair of the World Climate Research Programme (WCRP) Climate and Ocean - Variability, Predictability, and Change (CLIVAR) Scientific Steering Group. The four-year term commenced on 1 January 2019.

2 Project performance and highlights

In this section project leaders report on the progress of their research. CSHOR publications cited in the text are listed at the end of each project report, the 2018-19 publications are emphasised in bold text. Footnotes are used to reference the few citations which are not affiliated with CSHOR. Appendix E comprises a list of CSHOR manuscripts published in 2018-19. Datasets produced by several of the projects are recorded in Appendix D.

2.1 Project 1: Understanding present and future dynamics of ENSO, the IOD, and their interactions with the southern hemisphere oceans

Project leaders – Drs Agus Santoso (UNSW/CSIRO) & Guojian Wang (CSIRO)

The El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are the dominant modes of interannual climate variability over the tropical Pacific and Indian Oceans respectively. ENSO and IOD exert strong influence on regional and large-scale ocean and atmospheric circulations, altering weather patterns and occurrences of marine and climate extremes. This can lead to catastrophic natural disasters against the backdrop of a warming planet due to anthropogenic greenhouse effect. Given their major global impacts on society and environment, the complex mechanisms behind ENSO and IOD and how they may change under greenhouse warming are important scientific issues that demand focussed investigations.

This project is contributing to international and national efforts in understanding the complexity of these climate phenomena and their intricate interplay with the changes in background climate.

We highlight the importance of ENSO event diversity for understanding ENSO dynamics, teleconnection and impact, as to improve seasonal forecast and future projections (Santoso et al., 2019a). We also begin to appreciate that the tropics are a tightly interconnected system, rather than a one-way impact of ENSO onto the other ocean basins. Significant feedbacks from the Indian and Atlantic Oceans are also exerted onto the Pacific (Cai et al., 2019). These two-way interactions affect the character of ENSO and Pacific decadal variability and shed new light on the recent hiatus in global warming.

2.1.1 Research activities

One of the major tasks of our project this year was to further investigate how ENSO responds to climate change – an issue that has been plaguing climate scientists for decades with no clear consensus. Specifically, climate models have shown a lack of agreement in how ENSO sea surface temperature (SST) variability changes under greenhouse warming, given the complexity of the ENSO system (Timmermann et al., 2018). CSHOR research has furthered this understanding. Previously, we have constructed a conceptual nonlinear framework for extreme El Niño by examining the associated rainfall response and found that the frequency of extreme convective El Niño events is

projected to increase under greenhouse warming (Cai et al., 2014[1]). The increased frequency could persist up to about a century after greenhouse warming plateaus (Wang et al., 2017). We analysed outputs from models which most reasonably simulate a nonlinear relationship between two dominant patterns of SST anomalies associated with ENSO (Cai et al., 2018) to show for the first time that extreme warm El Niño events (events with positive SST anomaly centred in the equatorial eastern Pacific) will increase in amplitude and frequency. Our current work (Wang et al., 2019) reconciles the seemingly distinct types of extreme El Niño: the extreme convective El Niño (rainfall-based definition) and extreme warm El Niño events (SST-based definition), finding that the two types of events are linked; but the link can be weaker in certain models and under greenhouse warming. Recognising ENSO event diversity is important for understanding ENSO dynamics, teleconnection and impact, as to improve seasonal forecast and future projections (Santoso et al., 2019a).

ENSO and IOD, and their interactions, are influenced by air-sea processes outside their respective basins. We recently reviewed this inter-basin connectivity (Cai et al., 2019), and found that beside the strong influence of ENSO on other basins, there are significant feedbacks from the Indian Ocean and the Atlantic Ocean onto the Pacific. We found that reducing systematic biases in tropical variability provides a pathway forward for improving climate predictions and projections. We are also reviewing the connections between Pacific Ocean and Indian Ocean, and have found a linkage between ENSO and IOD event diversity with important ramifications for understanding impact and future projections (Santoso et al., 2019b).

2.1.2 Project performance against milestones

Apart from milestone 1, which the CSHOR Steering Committee agreed to postpone, all project milestones were met. An overview of performance against each milestone follows.

Milestone 1: Recruit one postdoctoral research fellow

Postponed until 2020 or 2021. Project objectives and deliverables will not be affected.

Milestone 2: Assess the impact of model biases on projected increase in frequency of extreme positive Indian Ocean Dipole and extreme ENSO event

An invited perspective piece on the impacts of systematic model biases on projected Indo-Pacific climate extremes (Cai et al., 2019) found that common biases in the Pacific Ocean and the Indian Ocean that plague CMIP3 and CMIP5 (phases 3 and 5 of the Coupled Model Intercomparison Project) models do not exert systematic impact on the projected occurrences of extreme El Niño and positive IOD events.

[1] Cai W., Borlace S., Lengaigne M., van Rensch P., Collins M., et al. (2014). Increasing frequency of extreme El Nino events due to greenhouse warming. *Nature Climate Change* 4, 111-116.

Milestone 3: Examine the robust increase in El Niño sea surface temperature variability under greenhouse warming

Using tropical Pacific SST anomaly patterns, Cai et al. (2018) diagnosed a robust future increase in Eastern Pacific (EP) El Niño variability. The EP El Niño pattern and its anomaly centre differ vastly from one model to another, and so cannot be represented by the spatially fixed Niño3 SST index which has otherwise been the conventional approach. The robust increase in EP El Niño SST variability occurs at the unique anomaly centre of each model. The paper was the subject of a *Nature* 'News and Views' article[2].The results are also discussed in a book chapter submitted for the AGU monograph (Cai et al., 2019).

Milestone 4: Submit a review paper on "Tropical Inter-basin Interactions"

Cai et al. (2019) reviewed advances in our understanding of the pantropical inter-basin climate interactions, and highlight the significant feedbacks from the Indian and Atlantic Oceans on the Pacific and vice versa. This has implications for understanding the recent global warming hiatus which featured a La Niña-like cooling over the tropical Pacific enhanced by Atlantic warming. The result implies that inter-basin interactions need to be properly simulated in models for better seasonal climate predictions and future projections.

Milestone 5: Using data collected and experiments conducted last financial year, examine the link between wind surges and extreme ENSO/IOD events, including the modulating effect of decadal variability

Westerly wind events (WWEs), abrupt abatements or reversals of the Trade Winds, are integral to the development of El Niño. WWEs cause an eastward displacement of the west Pacific warm pool, which in turn promotes more WWEs and an eastward shift of atmospheric convection. This WWE-El Niño coupling is crucial for development of strong El Niño events. However, factors influencing WWE generation are not fully understood.

Cai et al. (2019) show that decadal mean surface ocean temperatures in the tropical Pacific associated with a warm phase of the Pacific Decadal Oscillation (PDO) is one potential factor that boosts development of WWEs and the frequency of strong El Niño events. Given that the positive PDO itself is partially a consequence of the decadal modulation of El Niño, such linkage implies a positive feedback that operates between weather and decadal variability, influencing the frequency of strong El Niño from one decade to another.

Milestone 6: Investigate climate drivers of Indonesian Throughflow variability in observation and CMIP5 models

The Indonesian Throughflow (ITF) forms an important part of the global thermohaline circulation and acts as an oceanic pathway that connects the tropical Pacific and Indian Oceans. How it is simulated in climate models is not clear. An analysis of CMIP5 models by Santoso et al. (2019) reveals a clear linkage between ITF variability and ENSO and IOD in these models. ITF variability also occurs

[2] https://www.nature.com/articles/d41586-018-07638-w.

on decadal time scales. During the recent global warming hiatus, the ITF transport was enhanced, leading to freshening of the Indian Ocean (Makarim et al., 2019). The observation-based analysis by Makarim et al. reveals previously unnoticed ITF pathway in the Indian Ocean that became more apparent during the hiatus. Such results warrant modelling investigation.

Milestone 7: Submit a paper on understanding ENSO and IOD characteristics in climate models

Extreme El Niño events, defined by Niño3 rainfall exceeding 5 mm per day, double in the future under greenhouse warming and will continue to increase for another century even after global mean temperature stabilises (Cai et al., 2014; Wang et al., 2017). Cai et al. (2018) found that eastern Pacific El Niño variability defined by SST will be increased as well, in sharp contrast to previous conclusion by using Niño3 SST.

Wang et al. (2019) next examine whether there is any difference between strong convective El Niño events (rainfall-based definition) and strong EP El Niño events (SST-based definition). They found that climate models from the CMIP5 can simulate convective events which are not concurrent with warm events, unlike observed. The disassociation highlights the role of eastward migration of western Pacific convection and equatorward shift of the South Pacific Convergence Zone associated with the faster warming over the EP region as a result of greenhouse warming.

ENSO and IOD modelling are discussed in a review paper that has been commissioned by *Nature Communications* (Santoso et al., 2019b).

2.1.3 Project publications[3]

Cai, W., A. Santoso, G. Wang, L. Wu, M. Collins, M. Lengaigne, S. Power, and A. Timmermann (2019). Chapter 13: ENSO Response to Greenhouse Forcing. AGU Monograph: *ENSO in a Changing Climate*. McPhaden, M., A. Santoso, W. Cai (Eds.), Wiley, submitted.

Cai W., Wang G., Dewitte B., Wu L., Santoso A., Takahashi K., Yang Y., Carreric A., McPhaden M. J. (2018). Increased variability of eastern Pacific El Nino under greenhouse warming. *Nature*, 564, 201-206, doi: 10.1038/s41586-018-0776-9

Cai, W., G. Wang, X.-T. Zheng, W. Zhong, A. Santoso, H. Yan, T. Cowan, L. Wu, M. McPhaden (2019). Westerly wind events boosted by a Pacific Decadal Oscillation warm phase. *Science Advances*, to be submitted.

Cai, W., Wang G., Santoso A., Wu L., Lin X., Gan B., Chen Z., Jia F., and Collins M. (2019). In search for impacts of systematic model biases on projected Indo-Pacific climate extremes. *Nature Climate Change*, under review.

Cai, W., Wu, L., Lengaigne, M., Li, T., McGregor, S., Kug, J.-S., . . . Chang, P. (2019). Pantropical climate interactions. *Science*, 363, eaav4236, doi: 10.1126/science.aav4236.

[3] 2018-19 publications in bold text.

Holmes, R. M., McGregor, S., Santoso, A., & England, M. H. (2018). Contribution of Tropical Instability Waves to ENSO Irregularity. *Climate Dynamics*, doi.org/10.1007/s00382-018-4217-0.

Jo. H.-S., Yeh S.-W., Cai W., 2019: An Episodic Weakening in the Boreal Spring SST–Precipitation Relationship in the Western Tropical Pacific since the Late 1990s, *Journal of Climate*, 32, 3837-3845, doi.org/10.1175/JCLI-D-17-0737.1.

Makarim, S., J. Sprintall, Z. Liu, W. Yu, A. Santoso, X.-H. Yan, R. D. Susanto (2019). Previously unidentified Indonesian Throughflow pathways and freshening in the Indian Ocean during recent decades. *Scientific Reports*, 9:7364, doi: 10.1038/s41598-019-43841-z.

Santoso A., W. Cai, G. Wang, B. Ng, M. McPhaden, A. Timmermann (2019b). El Niño Southern Oscillation, the Indian Ocean Dipole, and their interactions. *Nature Communications*, to be submitted.

Santoso, A., M. England, J. Kajtar, W. Cai (2019). Characteristics and climate drivers of Indonesian Throughflow variability in a CMIP5 model ensemble. *Journal of Climate*, to be submitted.

Santoso, A., H. Hendon, A. Watkins, S. Power, D. Dommenget, M. England, L. Frankcombe, N. Holbrook, R. Holmes, P. Hope, E.-P. Lim, J.-J. Luo, S. McGregor, S. Neske, H. Nguyen, A. Pepler, H. Rashid, A. Sen Gupta, A. S. Taschetto, G. Wang, E. Abellan, A. Sullivan, M. Huguenin, F. Gamble, F. Delage (2019a). Dynamics and predictability of the El Niño-Southern Oscillation: An Australian perspective on progress and challenges. *Bulletin of the American Meteorological Society*, 100, 403-420, doi:10.1175/BAMS-D-18-0057.1.

Wang G., Cai W., Gan B., Wu L., Santoso A., Lin X., Chen Z., McPhaden M. J. (2017). Continued increase of extreme El Niño frequency long after 1.5°C warming stabilisation. *Nature Climate Change*, doi:10.1038/nclimate3351.

Wang G., Cai W., Santoso A. (2019). Stronger increase in the frequency of extreme convective El Niño than extreme warm El Nino under greenhouse warming. *Journal of Climate*, under review.

Timmermann, A., S.-I. An, J.-S. Kug, F.-F. Jin, W. Cai, A. Capotondi, K. M. Covv, M. Lengaigne, M. J. McPhaden, M. F. Stuecker, K. Stein, A. T. Wittenberg, K.-S. Yum, T. Bayr, H.-C., Chem, Y. Chikamoto, B. Dewitte, D. Dommerget, P. Grothe, E. Guilyardi, Y.-G. Ham, M. Hayashi, S. Ineson, D. Kang, S. Kim, W. Kim, J.-Y. Lee, T. Li, J.-J. Luo, S. McGregor, Y. Planton, S. Power, H. Rashid, H.-L. Ren, A. Santoso, K. Takahashi, A. Todd, G. Wang, G. Wang, R. Xie, W.-H. Yang, S.-W. Yeh, J. Yoon, E. Zeller, and X. Zhang. (2018). El Nino-Southern Oscillation complexity. *Nature*, 559, 535-534, doi.org/10.1038/s41586-018-0252-6.

2.2 Project 2: Indo-Pacific inter-basin exchange

Project leader – Dr Bernadette Sloyan (CSIRO)

As the only inter-basin exchange at low latitudes, the Indonesian Throughflow (ITF) connects two warm pools of global climate significance – the eastern Indian and western Pacific. The full drivers of ITF transport variability and its impacts on regional and global climate remain poorly understood. Regional ocean and climate models struggle to simulate the region due to complex bathymetry and processes. A dearth of observations, particularly of the flow itself and the internal seas, is impeding progress.

This project is using observational data to develop a high-resolution model to focus on: the response of the ITF and regional seas to intraseasonal–interannual forcing; dynamics of the Indonesian Seas; strength and spatial patterns of tidally driven mixing and internal wave generation; and modulation of the ITF by external ocean forcing.

2.2.1 Research activities

This year we provided significant input to a *Frontiers in Marine Science* community paper focusing on the need for sustained observations and modelling requirements to address key societal questions relating to the Indonesian Seas (Sprintall et al., 2019). We also provided input to a number of other community papers for a special volume of *Frontiers in Marine Science* in support of the September 'Ocean Obs'19' conference (Sloyan, et al., 2019; Palmer, et al., 2019; Hermes, et al., 2019).

Our team will lead the Australian component of the Measuring and Modelling the INdonesian Throughflow International Experiment (MINTIE) project. This three-year international collaborative study of the Indonesian Throughflow was funded this year to enhance understanding of the oceanic processes in the Indonesian region. The international MINTIE observational effort is a novel combination of a three-year deployment of a transport and water mass resolving mooring array within the major ITF passages, and simultaneous observations from profiling and mixing floats in the interior seas. The study will use observations and a series of high-resolution model simulations to investigate the drivers and dynamics of the Indonesian Throughflow. MINTIE international partners include Australia, the United States, China, and Indonesia. CSHOR and the Australian Integrated Marine Observing System (IMOS) will contribute floats, moorings and high-resolution modelling capability to this international study.

Project members participated in several national and international conferences and workshops (Appendix C), enhancing the international leadership of CSHOR. Dr Wijffels gave an invited talk at the AGU Fall Meeting in 2018. Drs Sloyan and Richet attended the QLMN Annual Academic Meeting and visited Dr Dongliang Yuan at the Institute of Oceanology, Chinese Academy of Sciences (IOCAS), in Qingdao in January 2019. Both team members presented a seminar and met with Dr Yuan's research group at IOCAS. Drs Wijffels and Peña Molino presented work at the Australian Meteorological and Oceanographic Society (AMOS) Annual Meeting in June 2019. Dr Richet was invited to visit Dr Ariane Koch-Larrouy at the Laboratoire d'Etudes et Geophysique et Océanographie Spatiales (LEGOS) in Toulouse, France. Dr Richet gained experience and insight into the inclusion of tides in our high-resolution model, she also obtained observations from previous mixing experiments conducted by Dr Koch-Larrouy for assessing the simulation of mixing in the model.

Dr Sloyan accepted an invitation to join International Laboratory for High-Resolution Earth System Prediction (iHESP) Scientific Advisory Board (SAB). iHESP, located at Texas A&M University (TAMU), is a collaboration between NCAR, Texas A&M University, and the Qingdao National Laboratory for Marine Science and Technology (QNLM).

2.2.2 Project performance against milestones

All project milestones were met. An overview of performance against each milestone follows.

Milestone 1: Prepare input for an ARC Linkage grant

We prepared an Australian Research Council (ARC) Linkage grant proposal and submitted it to the University of Tasmania for endorsement. This proposal aimed to increase the number of mixing observations in the Indonesian Seas. However, the University of Tasmania assessment of the budget found that the proposal did not meet ARC funding rules for partner organisations. Thus, the proposal was not submitted to the 2018 Linkage round.

Given the successful funding of the MINTIE initiative we will revise the ARC proposal and work with the University of Tasmania to investigate the potential of ARC funding for the project.

Milestone 2: Participate in the development of an ITF/Indonesian Seas international observation program

We contributed to a community paper (Sprintall et al., 2019) that puts forward the design of an observational system for the Indonesian Seas. Although substantial progress has been made over the past decade in measuring and modelling the Indonesian seas, there are still key knowledge gaps and large uncertainties in estimated property transports between the Pacific and Indian Oceans. This paper considers these knowledge gaps and suggests a comprehensive observational strategy required for measuring the temporal and spatial scales of variability that govern the various circulation pathways of the ITF, the connection between the circulation and heat and freshwater transports and associated air-sea fluxes of the regional and global oceans.

The MINTIE observations, described above, and a series of high-resolution model simulations will commence in 2020 to investigate ITF drivers and dynamics.

Milestone 3: Conduct an analysis of observation and model data investigating the interannual variability of the ITF transport and properties

We continued with our comprehensive analysis of the IMOS ITF mooring data in the Ombai Strait and Timor Passage and papers are now in preparation. The comparison of the Ombai Strait interannual transport variability and its relationship to the winds is quite different between the INSTANT (2004-2006) and IMOS ITF period (2011-2015). The seven-year time series shows that while some of the transport peaks align with the wind divergence (La Niña/negative IOD), others do not. In addition, the upper (0-150 m) and deeper (0-1250 m) transport anomalies are often out of phase. It is not yet clear what processes might drive these contrasting responses.

We have found that the net transport in the Timor Passage during the IMOS period (2011-2015) was smaller than that of the INSTANT (2004-2006) period. Understanding the reasons for this difference is complicated by the fact that the IMOS and INSTANT mooring arrays were located at difference ends of the Timor Passage, and that the IMOS period was during an active ENSO phase while INSTANT is during a neutral ENSO phase. We found that the flow in the Timor passage during 2011-2015 is broader that the strait-centred jet measured by INSTANT.

Manuscripts detailing these findings are currently in preparation.

Milestone 4: Develop targeted model studies investigating the influence of Pacific and Indian climate modes on the ITF variability

We analysed the COSIMA 10-degree global model and contributed to a paper describing the model results for the region of the Indonesian Sea (Kiss et al., 2019). This global model then provided the boundary conditions of our 10 km and 4 km models.

Our investigation of the response of the background state of the Indonesian Seas to seasonally variable forcing using a high-resolution regional model (Richet et al., 2019) suggests that the signal induced by the seasonality of the forcing is confined in the surface layer. The seasonality of the forcing, especially with the monsoonal winds, induces a deepening of the mixed layer depth in the Indonesian Seas due to Ekman pumping and mixing at the base of the mixed layer with water below, leading to colder surface water. The observed changes on the background SST induced by the seasonal variability of the forcing in our simulations have the same order of magnitude than the seasonal cycle of the SST itself. Understanding the mechanisms behind the SST and SSS is essential to predict the response of the ocean to changes in the forcing.

We have now begun to develop the implementation of tides into this model. To this end we collaborated with experts in France.

A research paper on the interannual variability of the meridional heat transport in the Indian Ocean and influences from the Pacific climate variability was published in the *Journal of Climate* (Ma et al., 2019).

2.2.3 Project publications[4]

Downes, S. M., Sloyan, B. M., Rintoul, S. R., & Lupton, J. E. (2019). Hydrothermal heat enhances abyssal mixing in the Antarctic Circumpolar Current. *Geophysical Research Letters*, 46, 812– 821, doi.org/10.1029/2018GL080410.

Hermes, J. C., Y. Masumoto, L. Beal, M. Roxy, J. Vialard, M. Andres, H. Annamalai, S. Behere, N. d'Adamo, T. Doi, M. Feng, W. Han, H. Hendon, R. Hood. S. Kido, C. Lee, T. Lee, M. Lengaigne, R. Lumpkin, K. Navaneeth, B. Milligan, M. McPhaden, M. Ravichandra, T. Shinoda, A. Singh, B. Sloyan, P. Strutto, A. Subramanian, S. Thurston, T. Tozuka, C. Ummenhofer, U. Alakkat, R. Venkatesan, D. Wang, J. Wiggert, L, Yu, W. Yu (2019). A sustained ocean observing system in the Indian Ocean for climate related scientific knowledge and societal need, *Frontiers in Marine Science*, 6 (355), doi.org/10.3389/fmars.2019.00355.

Kiss, A. E., Hogg, A. McC., Hannah, N., Boeira Dias, F., Brassington, G. B., Chamberlain, M. A., Chapman, C., Dobrohotoff, P., Domingues, C. M., Duran, E. R., England, M. H., Fiedler, R., Griffies, S. M., Heerdegen, A., Heil, P., Holmes, R. M., Klocker, A., Marsland, S. J., Morrison, A. K., Munroe, J., Oke, P. R., Nikurashin, M., Pilo, G. S., Richet, O., Savita, A., Spence, P., Stewart, K. D., Ward, M. L.,

[4] 2018-19 publications are shown in bold text.

Wu, F., and Zhang, X. (2019). ACCESS-OM2: A Global Ocean-Sea Ice Model at Three Resolutions. *Geoscientific Model Development: Discussion Papers*, under review

Ma, J., Feng, M. Sloyan, B.M., Lan, J. (2018). Pacific influences on the low-frequency meridional temperature transport of the Indian Ocean. *Journal of Climate*, 32(4), 1047-1061, doi.org/10.1175/JCLI-D-18-0349.1.

Palmer M.D., Durack P.J., Chidichimo M.P., Church J.A., Cravatte S., Hill K., Johannessen J.A., Karstensen J., Lee T., Legler D., Mazloff M., Oka E., Purkey S., Rabe B., Sallée J-B., Sloyan B.M., Speich S., von Schuckmann K., Willis J. and Wijffels S. (2019) Adequacy of the Ocean Observation System for Quantifying Regional Heat and Freshwater Storage and Change. *Frontiers in Marine Science*, under review.

Purkey, S. G., Johnson, G. C., Talley, L. D., Sloyan, B. M., Wijffels, S. E., Smethie, W., . . . Katsumata, K. (2019). Unabated bottom water warming and freshening in the South Pacific Ocean. *Journal of Geophysical Research: Oceans*, 124, 1778–1794, doi.org/10.1029/2018JC014775.

Richet, O., Nikurashin, M., Peña Molino, B., Sloyan, B. M., and Wijffels, S. E. (2019). The role of the seasonal variability on the background state of the Indonesian Seas. *Journal of Geophysical Research: Oceans*, submitted.

Sloyan B.M., Wilkin J., Hill K.L., Chidichimo M.P., Cronin M.F., Johannessen J.A., Karstensen J., Krug M., Lee T., Oka E., Palmer M.D., Rabe B., Speich S., von Schuckmann K., Weller R.A. and Yu W. (2019) Evolving the Physical Global Ocean Observing System for Research and Application Services Through International Coordination. *Frontiers in Marine Science,* under review.

Sprintall, J., A. Gordon, S. Wijffels, M. Feng, S. Hu, A Koch-Larrouy, H. Phillips, D. Nugroho, A. Napitu, K. Pujiana, R. Susanto, B. Sloyan, B. Peña Molino, D. Yuan, N. Riama, S. Siswanto, A. Kuswardani, Z. Arifin, A. Wahyudi, H. Zhou, T. Nagai, J. Ansong, r. Bourdalle-badie, J. Chanut, F. Lyard, B. Arbic, A. Ramdhani, A. Setiawan (2019). Detecting change in the Indonesian Seas, *Frontiers in Marine Science*, 6 (257), doi.org/10.3389/fmars.2019.00257.

2.3 Project 3: Coupled warm pool dynamics in the Indo-Pacific

Project leaders – Drs Ming Feng (CSIRO) and Susan Wijffels (WHOI/CSIRO)

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 El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden-Julian Oscillation (MJO). These climate modes are likely the most important sources of enhanced weather and climate prediction on the globe.

This project is advancing our knowledge of high-frequency air-sea coupling in the eastern Indian Ocean warm pool through new observations of MJO and diurnal variability at the air-sea interface and coupled model simulations. We have identified the key roles of the ITF to carry the Pacific ENSO/PDO signals into the Indian Ocean. The decadal strengthening of the ITF heat transport has been found to be crucial for the fast warming trend of the southern Indian Ocean during the climate change hiatus period, and we have identified the role of the ITF heat transport variability due to ENSO on the meridional heat transport of the Indian Ocean. Interannual and decadal variations of the ITF transport are also important for the upper ocean salinity balance in the Indian Ocean,

especially the southeast Indian Ocean. These would have great implications on regional and global climate research.

2.3.1 Research activities

This year we collaborated with scientists from China's First Institute of Oceanography (FIO) to carry out a six-day voyage in the southeast Indian Ocean warm pool on a chartered vessel, deploying a meteorology and ocean profiling buoy (MOPB) from the FIO and eight fast profiling floats from CSIRO. Both the buoy and float deployments were successful, providing the first co-ordinated air-sea flux and upper ocean measurement in the southeast Indian Ocean warm pool. The observation data from the buoy and the profiling floats have been used to improve our understanding of the upper ocean response to the MJO forcing and tropical cyclone influences. The data have also been incorporated with coupled ocean-atmosphere model experiments to pinpoint the roles of upper ocean variability to feedback to the MJO evolution.

This campaign has been filling a major gap in the Global Ocean Observing System identified by the Climate and Ocean - Variability, Predictability, and Change (CLIVAR) Indian Ocean Regional Panel, where roles of the air-sea coupling associated with the MJOs and warm pool evolution have not been fully explored, and there are large discrepancies of air-sea flux patterns among different atmospheric reanalysis products. Dr Feng was interviewed by ABC Radio to introduce the importance of this campaign on Australian monsoon predictions.

Ma et al. (2019) identified ENSO's key role in driving the interannual-decadal variations of the meridional heat transport in the Indian Ocean, through both the oceanic waveguide and atmospheric teleconnection. These influence the Indian Ocean boundary currents, the interior geostrophic and Ekman transport. A paper on the upper Indian Ocean heat balance during the climate change hiatus period has been published in *Geophysical Research Letters* (Zhang et al., 2018). The role of the ITF transport variability on the Indian Ocean upper ocean salinity balance has been assessed using Argo data and numerical models. This study identified the important role of the strengthened ITF volume and heat transports during the global surface warming hiatus period in warming up the southern Indian Ocean in the past two decades. It appears that the heat transport anomaly is the dominant factor that drives the southern Indian Ocean warming. A research paper has been accepted in the *Journal of Climate* (Hu et al., 2019, in press).

Two PhD students, Ying Zhang and Jie Ma, have defended their PhD theses successfully. Both have joined the Chinese Academy of Sciences as research scientists.

2.3.2 Project performance against milestones

All project milestones were met. An overview of project performance against each milestone follows.

Milestone 1: Acquire five to eight profilers, establish the satellite communication and data handling system, source a suitably configured platform for the atmospheric surface observations (FIO MOPB), and arrange vessels for deployment and (if needed) recovery

Six Alamo fast profiling floats and two EX APEX profiling floats were purchased through the CSHOR project for the joint field campaign. In late November 2018, a chartered vessel, *Limitless*, from

Offshore Unlimited, was used to carry out a six-day field campaign, which successfully deployed the MOPB system and the profiling floats. The field campaign site was chosen on the edge of the eastern Indian Ocean warm pool, just outside the Australian Exclusive Economic Zone off the northwest coast of Australia, so that the MOPB system can be retrieved by opportunistic vessels from China. A paper describing the details of the field experiment is being drafted.

The data stream obtained from the MOPB and the profiling floats has been evaluated to better understand the air-sea exchanges and upper ocean evolution under the influences of the MJO and the Australian monsoon. Strong diurnal warm layer variability was captured by the profiling float data. Data streams from the CSHOR field campaign have been assessed and compared with weather forecast models and the preliminary results have been presented at the ENSO, CSHOR, Australian Meteorological and Oceanographic Society (AMOS), and Year of the Maritime Continent (YMC) conferences and annual meetings.

Milestone 2: Run the BoM's coupled forecast model for the field work periods and analyse model outputs against observations

The project team has collaborated with the model team led by Dr Hendon, from the Australian Bureau of Meteorology, to use their global coupled model ACCESS-S1. Postdoctoral fellow, Dr Hsu, has explored the model performance on predicting the diurnal variation of SST (DV SST) and upper ocean structure off northwest Australia. The first part of model work focuses on the factors and effects of DV SST on the atmosphere environment during the suppressed phase of three MJO events from 2007 to 2009 (Hsu et al. 2019). The second part of model work is to study the DV SST and the air-sea interaction during the MJO period in December 2018. The model runs with six ensemble members and four different starting dates from 25 November to 9 December 2018 have been carried out. The model results have been compared to the CSHOR field measurements.

Milestone 3: Continue assessment of Indian Ocean heat balances associated with warm pool variability

The meridional heat transport of the Indian Ocean and the influences from the Pacific climate variability has been assessed (Ma et al., 2018), and a new manuscript on centennial changes of Indian Ocean heat balance under the influence of the greenhouse gas forcing is being prepared for journal submission.

In collaboration with scientists from QNLM, two papers on the Indian Ocean salinity balance and variability have been accepted for publication (Hsu et al., 2019 and Hu et al., 2019). Drs Wijffels and Feng have contributed two community white papers on the Indonesian Throughflow and Indian Ocean observing systems, which have been published in *Frontiers in Marine Science* (Sprintall et al., 2019 and Hermes et al., 2019).

Milestone 4: Assess models of diurnal upper ocean variations in the coastal regions off northwest Australia

Ms Maggiorano has made good progress with her PhD research. Hourly forcing from European Centre for Medium-Range Weather Forecasts Reanalysis (ECMWF ERA5) have been implemented in a numerical model on the North West Shelf of Australia based on Regional Ocean Modeling System (ROMS) and the model simulation for the period 2009-2016 has been carried out. The model currents have been validated against IMOS mooring stations current data and against Bluelink

Reanalysis (BRAN) ocean model data. The Sea Surface Temperature at 1 m depth has been validated against ESA Sea Surface Temperature Climate Change Initiative v.2 (CCI) and the bias on the surface temperature is significantly reduced compared with the previous runs with surface forcing from BRAN. The marine heatwave of February 2013 is well represented by the model, which captures a few degrees of SST anomalies and an increase of surface net flux the month before the peak of the marine heat wave, as reported in the literature.

Effort has been devoted to the closure of the upper ocean heat budget using the model output to understand the drivers of the marine heatwave, as well as analysing the magnitude of diurnal cycle of SST and its importance during the evolution of the marine heatwave. In the meantime, the ROMS model is being re-run with daily averaged forcing, which will allow an analysis of the model sensitivity to diurnal forcing. Some of the PhD work has been presented at the Australian Meteorological and Oceanographic Society (AMOS) Annual Meeting in June 2019. Appendix C lists major conferences and workshops attended by CSHOR staff.

2.3.3 Project publications[5]

Ma, J., Feng, M. Sloyan, B. M., Lan, J. (2018). Pacific influences on the low-frequency meridional temperature transport of the Indian Ocean. *Journal of Climate*, 32(4), 1047-1061, doi.org/10.1175/JCLI-D-18-0349.1.

Hermes, J. C., Y. Masumoto, L. Beal, M. Roxy, J. Vialard, M. Andres, H. Annamalai, S. Behere, N. d'Adamo, T. Doi, M. Feng, W. Han, H. Hendon, R. Hood. S. Kido, C. Lee, T. Lee, M. Lengaigne, R. Lumpkin, K. Navaneeth, B. Milligan, M. McPhaden, M. Ravichandra, T. Shinoda, A. Singh, B. Sloyan, P. Strutto, A. Subramanian, S. Thurston, T. Tozuka, C. Ummenhofer, U. Alakkat, R. Venkatesan, D. Wang, J. Wiggert, L, Yu, W. Yu (2019). A sustained ocean observing system in the Indian Ocean for climate related scientific knowledge and societal need, *Frontiers in Marine Science*, 6 (355), doi.org/10.3389/fmars.2019.00355.

Hu, S., Y. Zhang, M. Feng, Y. Du, J. Sprintall, F. Wang, D. Hu, Q. Xie (2019). Observed Interannual to Decadal Variability of Indian Ocean Salinity and the role of Indonesian Throughflow, *Journal of Climate*, in press.

Hsu, J.-Y., H. Hendon, M. Feng and X. Zhou (2019). Magnitude and Phase of Diurnal SST Variations in the ACCESS-S1 model during the Suppressed Phase of the MJOs. *Journal of Geophysical Research: Oceans,* submitted.

Sprintall, J., A. Gordon, S. Wijffels, M. Feng, S. Hu, A Koch-Larrouy, H. Phillips, D. Nugroho, A. Napitu, K. Pujiana, R. Susanto, B. Sloyan, B. Peña Molino, D. Yuan, N. Riama, S. Siswanto, A. Kuswardani, Z. Arifin, A. Wahyudi, H. Zhou, T. Nagai, J. Ansong, r. Bourdalle-badie, J. Chanut, F. Lyard, B. Arbic, A. Ramdhani, A. Setiawan (2019). Detecting change in the Indonesian Seas. *Frontiers in Marine Science,* 6 (257), doi.org/10.3389/fmars.2019.00257.

[5] 2018-19 publications are shown in bold text.

Sun, Q., Y. Du, Y. Zhang, M. Feng, J. Chowdary, S. Qiu, W. Yu. Interannual variability of sea surface salinity in the southwestern Tropical Indian Ocean. *Journal of Geophysical Research*, in press.

Zhang, Y., Feng, M., Du, Y., Phillips, H. E., Bindoff, N. L., & McPhaden, M. J. (2018). Strengthened Indonesian Throughflow Drives Decadal Warming in the Southern Indian Ocean. *Geophysical Research Letters*, 45(12), 6167-6175, doi.org/10.1029/2018GL078265.

2.4 Project 4: Southern Ocean dynamics, circulation and water-mass formation

Project leader – Prof Matthew England (UNSW)

Southern Ocean dynamics, circulation and water-mass formation fundamentally control our climate system by regulating the rate of ocean heat and carbon uptake, and via ice-melt at the Antarctic margin.

This project is exploring a range of unresolved questions regarding the dynamics, circulation and water-mass formation of the Southern Ocean. Focus areas include quantifying the drivers of Antarctic regional warming, including warming driven by changes in the pathway and temperatures of the Antarctic Circumpolar Current (ACC); understanding the impact of atmospheric teleconnections from the tropics, and the nature and time-scales of coupled ice-ocean feedbacks; examining what controls the delivery of ocean heat to Antarctic ice shelves; and exploring the sensitivity of ocean carbon uptake to changes in the upper cell over the Southern Ocean.

2.4.1 Research activities

Activities during the past year have focused on the dynamics of the ACC, the mechanisms for exchange across the Antarctic continental slope, and the variability of bottom water properties as well as estimating decadal trends in ocean carbon uptake from ocean biogeochemical models, exploring the fate of carbon and nutrients exported out of the Southern Ocean, and calculating the heat and salt transport from eddies based on novel *in situ* observations in the Australian sector of the Southern Ocean.

Drs Tamsitt and Foppert participated in the RV *Investigator* voyage to the Polar Front of the ACC. Dr Tamsitt will be co-supervising an honours student in the upcoming year to continue analysis of this voyage data.

Dr Tamsitt was invited to write a 'News and Views' article titled, "Moving windows to the deep ocean", for *Nature Climate Change* (Tamsitt, October 2018).

Other work within this project aims to quantify the subduction rates of Subantarctic Mode Water and Antarctic Intermediate Water using Argo data in combination with both Lagrangian and Eulerian approaches (led by CSHOR UNSW PhD student Mr Zhi Li in collaboration with Prof England and Dr Groeskamp). Prof England also collaborated with Dr Qian Li from UNSW to estimate the way mixed layer depth variations over the Southern Ocean can be linked to both ENSO variability as well as variations in the Southern Annular Mode.

Completed work includes a calculation of the magnitude of cross-shelf transport of heat around the Antarctic continental margin in the bottom boundary layer due to the passage of barotropic Kelvin

waves (Webb et al., 2019) and evaluation of the impact of meltwater due to Antarctic land-ice melt in CMIP5 model projections (Lago and England, 2019).

2.4.2 Project performance against milestones

All project milestones were met. Many of the agreed project milestones reached completion sooner than expected, allowing for three additional milestones which align with the project objectives and are a positive enhancement of the CSHOR research effort. An overview of performance against each milestone follows.

Milestone 1: Completion of a study of Antarctic Circumpolar Current dynamics in Drake Passage, including the first observation-based analysis of eddy-mean flow interaction using the concept of 'wave activity'.

Foppert (2019) investigates the dynamics of an oceanic storm track, where energy and enstrophy transfer between the mean flow and eddies, using observations from an eddy-rich region of the ACC. Results indicate the importance of barotropic processes and suggests the presence of mixed barotropic–baroclinic instability. The observed importance of barotropic processes in this work presents a challenge to the modelling community. The wave activity flux framework presented in the paper will help identify and quantify the relative importance of physical mechanisms controlling transfers of energy and enstrophy between eddies and the mean flow in the ocean.

Milestone 2: Participation on RV *Investigator* voyage to study dynamics, mixing and cross-front exchange in a standing meander of the Antarctic Circumpolar Current

In October and November 2018 Drs Foppert and Tamsitt participated in the highly successful RV *Investigator* voyage to a standing meander in the Polar Front. Dr Tamsitt aims to use voyage data to investigate air-sea fluxes and mixed layer depth variations across the Polar Front, to understand the influence of mesoscale ocean temperature anomalies in air-sea exchange. Dr Foppert has begun initial analysis on the full-depth CTD and LADCP data and aims to quantify the velocity structure of the Polar Front, with an interest in how the velocities evolve in an along-stream sense.

Observations of Southern Ocean eddies collected on the RV *Investigator* were used to explore the meridional salt and heat transport across the Subantarctic Front, and the importance of the region south of Australia in this transport. Patel et al. (2019) estimated that 21% of poleward heat transported across the Subantarctic Front was facilitated by long-lived cold core eddies. This work highlights the importance of observing, characterising and understanding the mesoscale in the Southern Ocean, and its response to climate variability and change.

Milestone 3: Develop and test a strategy for investigating exchange across the Antarctic continental slope and shelf break, using observations and models

Dr Tamsitt designed and executed multiple Lagrangian particle release experiments using output from a 1/10 degree ocean-sea ice model to investigate the spatial variation in pathways and residence time of warm Circumpolar Deep Water (CDW) crossing the Antarctic continental shelf break. The experiment output is continuing to be analysed and preliminary results were presented at the Australian Meteorological and Oceanographic Society (AMOS) Annual Meeting in June 2019. Results show complex spatial heterogeneity in residence times of CDW in the shelf, with generally shorter residence times in regions of rapid water mass transformation on the shelf and much longer

residence times elsewhere. These results emphasise that it is the residual of the heat transport of CDW onto the shelf and the transformation into denser waters on the shelf, rather than the heat transport of CDW onto the shelf alone, that is relevant for the reservoir of warm waters on the shelf available to melt the ice shelves. It is expected that the analysis with be completed by September 2019 and a manuscript will be prepared for submission in late 2019.

Analysing seal- and ship-based hydrography from the East Antarctic continental slope, Foppert et al. (2019) found that the along-slope variability in cross-slope eddy transport of Circumpolar Deep Water significantly alters the reservoirs of heat and salt at the shelf break such that it is warmer and saltier in 'eddying regions'.

Milestone 4: Estimate the magnitude of cross-shelf transport of heat around the Antarctic continental margin in the bottom boundary layer due to the passage of barotropic Kelvin waves, and develop new methods for quantifying heat transport in the oceans

The magnitude of cross-shelf transport of heat was estimated for flow onto the Antarctic continental shelf in the bottom boundary layer driven by coastal-trapped Kelvin waves (Webb et al., 2019). This was achieved by combining observations of cross shelf temperature gradients with 3D ocean general circulation models, ocean barotropic velocities and arrested Ekman layer theory. In addition, a new framework for quantifying the diathermal heat transport was proposed, enabling heat transport in temperature co-ordinates to be decomposed into that due to surface fluxes and all components of interior mixing (Holmes et al., 2019).

Milestone 5: Evaluate the impact of additional meltwater fluxes due to Antarctic land-ice melt in CMIP5 model projections

Lago and England (2019) used an ocean-sea ice model to investigate the potential long-term impact of Antarctic meltwater on ocean circulation and heat storage. The freshwater forcing was derived from present-day estimates of meltwater input from drifting icebergs and basal melt, combined with Representative Concentration Pathway (RCP) scenarios (RCP2.6, RCP4.5 and RCP8.5) of projected amplification of Antarctic meltwater. The additional freshwater was found to induce a substantial slowdown in the formation rate of Antarctic bottom water, reducing ventilation of the abyssal ocean. Under both the RCP4.5 and RCP8.5 meltwater scenarios, there is a near complete shutdown of Antarctic bottom water formation within just 50 years, something not captured by climate model projections.

Milestone 6: Analyse Subantarctic Mode Water formation and variability at two mooring sites in the southeast Indian and southeast Pacific oceans (Additional milestone)

Tamsitt et al. (2019a) compared air-sea heat fluxes and mixed layers from moorings in the southeast Indian and southeast Pacific Oceans, yielding insight into different heat loss regimes in the two regions and interannual variability in the region. This analysis showed that turbulent heat loss events in the Southeast Indian (SOFS) occur in two atmospheric regimes (cold air from the south or dry air circulating via the north), while heat loss events in the Southeast Pacific (OOI) occur in a single atmospheric regime (cold air from the south). On interannual timescales, wintertime anomalies in net heat flux and mixed layer depth are often correlated at the two sites, particularly when wintertime mixed layer depths are anomalously deep. This relationship is part of a larger basin-scale zonal dipole in heat flux and mixed layer depth anomalies present in both the Indian and Pacific basins, associated with anomalous meridional atmospheric circulation.

Milestone 7: Analyse the pathways and dynamics of upwelling in the Antarctic Circumpolar Current (Additional milestone)

Tamsitt et al. (2019b) analysed the pathway and variability of a pathway of upwelling Indian Ocean Deep Water in the Southern Ocean via the southern coast of Australia. The results show that deep water from the Indian Ocean flows along the southern coast of Australia until it reaches the ACC. The strength of the deep flow is highly variable and is related to variations in the overlying Flinders Current.

Additionally, Dr Tamsitt and Dr Adele Morrison, at the Australian National University, developed an analysis of topographic upwelling hotspots in the Antarctic Circumpolar Current using a two-pronged approach in a 1/10 degree ocean-sea ice model. They successfully diagnosed energy budget terms in the model and conducted targeted Lagrangian particle release experiments in topographic upwelling hotspot regions. Analysis of experiment results is ongoing.

Devries et al. (2019) used simulations to explore the drivers of recent variability in ocean carbon uptake and its representation in ocean biogeochemical model. The study compared decadal variability of ocean CO_2 uptake using three independent methods and found that the ocean could be responsible for as much as 40% of the observed decadal variability of CO_2 accumulation in the atmosphere.

Hauck et al. (2019) used simulation over long timescales to explore and quantify the role of the Southern Ocean in the global carbon cycle, critical in understanding its response to variability and change.

Milestone 8: Analysis of changes in bottom water properties in conjunction with CSHOR project 5: Southern Ocean observations and change (Additional milestone)

Dr Foppert has commenced preliminary analysis of deep float data with one year of profiles south of Australia, to examine the spatial structure of bottom water properties and use that information to put the most recent observed changes in bottom water salinity along repeat hydrography section SR3 into a broader context. Additionally, Dr Foppert has assisted in piloting three deep floats that were recently deployed along the Antarctic slope.

Milestone 9: Present research findings at national and international conferences

Results were presented at multiple national and international meetings and conferences, including the AGU Fall Meeting in Washington D.C. (Dr Tamsitt and Prof England), EGU Annual Meeting in Vienna (Dr Foppert), CSHOR Annual Academic Meeting in Qingdao (Drs Foppert and Tamsitt) and Australian Meteorological and Oceanographic Society (AMOS) Annual Meeting in Darwin where Drs Foppert and Tamsitt convened a session on Antarctic and Southern Ocean science. Prof England gave an invited keynote lecture on Antarctic climate change at the Australian Marine Science Association (AMSA) Annual Conference in July 2018 and an invited talk at the Caltech workshop, The Future of Earth System Modeling: Polar Climates, in November 2018. Dr Lenton gave an invited key note presentation at the 4th Global Ocean Acidification Observing Network International Workshop in April 2019. Appendix C lists major conferences and workshops attended by CSHOR staff.

2.4.3 Project publications[6]

Devries, T., Le Quéré C., Andrews, O., Berthet, S, Hauck, J. Ilyina, T., Landschützer, P., Lenton, A., Lima. I., Nowicki, M. Schwinger, J., Séférian, R. (2019). Decadal trends in the ocean carbon sink. *Proceedings of the National Academy of Sciences*, 116(24), 11646-11651, doi.org/10.1073/pnas.1900371116.

Foppert, Annie (2019). Observed storm track dynamics in Drake Passage. *Journal of Physical Oceanography*, 3, 867-884, doi.org/10.1175/JPO-D-18-0150.1.

Foppert A., S. R. Rintoul and M. H. England (2019). Along-slope variability in cross-slope eddy transport in East Antarctica. *Geophysical Research Letters*, under review.

Hauck, J., Lenton, A., Langlais, C, Matear, R. J. (2018). The fate of carbon and nutrients exported out of the Southern Ocean. *Global Biogeochemical Cycles*, 32(10), 1556-1573, doi: 10.1029/2018GB005977.

Holmes, R. M., J. D. Zika, and M. H. England (2019). Diathermal Heat Transport in a Global Ocean Model. Journal of Physical Oceanography, 49, 141-161, doi.org/10.1175/JPO-D-18-0098.1.

Lago, V., and M. H. England (2019). Projected slowdown of Antarctic Bottom Water formation in response to amplified meltwater contributions, *Journal of Climate*, in press.

Patel, R. S., H. E. Phillips, P. G. Strutton, A. Lenton, Llort, J. (2019). Meridonal Heat and Salt Transport across the Subantarctic Front by Cold Core Eddies. *Journal of Geophysical Research: Oceans*, 124(2), 981-1004, doi:10.1029/2018JC014655.

Tamsitt, V (2018). Moving windows to the deep ocean (News and Views). *Nature Climate Change*, 8, 941-942, doi.org/10.1038/s41558-018-0324-5.

Tamsitt, V., I. Cerovečki, S. Gille, S. Josey and E. Schulz (2019a). A comparison of mooring air-sea heat flux and mixed layers in the Southeast Indian and Southeast Pacific Subantarctic Mode Water formation regions. *Journal of Climate*, submitted.

Tamsitt, V., L. D. Talley and M. R. Mazloff (2019b). A Deep Eastern Boundary Current carrying Indian Deep Water south of Australia. *Journal of Geophysical Research: Oceans*, doi.org/10.1029/2018JC014569.

Webb, D. J., R. M. Holmes, P. Spence, and M. H. England (2019). Barotropic Kelvin wave-induced bottom boundary layer warming along the West Antarctic Peninsula. *Journal of Geophysical Research: Oceans*, 124, 1595-1615.

[6] 2018-19 publications are shown in bold text.

2.5 Project 5: Southern Ocean observations and change

Project leader – Dr Steve Rintoul (CSIRO)

Linking the South Pacific, South Atlantic and Indian Ocean basins, the Southern Ocean has a considerable influence on global ocean currents, climate, biogeochemical cycles and sea-level rise. Changes in the Southern Ocean could have a far-reaching impact.

This project is collecting new physical and biogeochemical observations in the Southern Ocean and using them with the historical record to develop a better physical understanding of the sensitivity of circulation and water mass formation to changes in forcing. The overall objective 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.

2.5.1 Research activities

Research activities in 2018-2019 included deployment of the first Australian Deep Argo floats and a successful voyage on RV *Investigator* to investigate the dynamics of a standing meander in the Antarctic Circumpolar Current (ACC).

Downes et al. (2019) used helium data and estimates of ocean mixing in the deep ocean to show that buoyant hydrothermal plumes enhance abyssal mixing where the Antarctic Circumpolar Current interacts with sea floor topography.

Using observations from three coastal polynyas in East Antarctica, Moreau et al. (2019) showed that biological productivity was regulated by differences in supply of sea-ice meltwater and Circumpolar Deep Water.

Silvano et al. (2019) used profiling floats 'parked' on the sea floor between profiles to obtain the first measurements of the complete annual cycle underneath sea ice on the continental shelf near the Totten Glacier. The measurements showed that warm water was widespread and persistent on the continental shelf and capable of driving rapid rates of basal melt of the floating ice shelf. The inflow of warm water was shown to depend on seasonal variations in currents near the shelf break.

In work under review in *Nature*, Dr Herraiz-Borreguero has contributed to an investigation of how the dynamical barrier imposed by an ice shelf calving front ocean heat transport to the cavities of the Antarctic ice shelves, based on mooring observations and laboratories experiments in a rotating tank.

The work carried out by CSHOR in the Southern Ocean relies on several complementary programs that fund observations. CSHOR scientists have helped to secure new funding for a number of these initiatives, with benefits for CSHOR. Examples include a successful proposal for additional Argo floats from the Science and Industry Endowment Fund ($2m), leading development of the successful proposal for the Australian Antarctic Program Partnership ($50m over 10 years), contributing to the development of a $56m proposal for a Special Research Initiative for Excellence in Antarctic Science, and additional investment by the Integrated Marine Observing System in ice-capable Argo floats.

2.5.2 Project performance against milestones

An overview of performance against each milestone follows.

Milestone 1: Determine sensitivity of Antarctic Bottom Water formation to changes in forcing

A CSHOR voyage in January 2018 discovered that the salinity, density and volume of Antarctic Bottom Water had all increased, after nearly 50 years of freshening and contraction in volume. Over the past year we have been investigating the cause of the 'rebound'. Castagno et al. (2019) show that part of the answer is an increase in salinity of dense shelf water formed in the Ross Sea. Silvano et al. (to be submitted by September 2019) demonstrate that the increase in dense shelf water formation is mostly caused by an unusual increase in sea ice formation, in turn linked to wind anomalies connected to tropical variability. Foppert et al. (in preparation) are using Deep Argo data and repeat hydrography to quantify the 'rebound' of Antarctic Bottom Water. Lambelet et al. (2018) showed that bottom water formed along the Adélie coast has a unique geochemical signature that can be used to trace individual bottom water pathways. Papers published last year (e.g. Snow et al., 2018 and Silvano et al., 2018) also contribute to this milestone.

Milestone 2: Quantification of the strength of the Ross Gyre and its interactions with the Antarctic Circumpolar Current and Antarctic Slope regime

Good progress is being made on this milestone. Several voyages and float deployments will allow us to quantify the strength and structure of the Ross Gyre, one of the least well-observed parts of the Southern Ocean circulation. Another set of floats will be deployed this coming austral summer.

Milestone 3: Voyage on RV *Investigator* to explore dynamics of the Antarctic Circumpolar Current, cross-front exchange and mixing in a standing meander downstream of topography

The voyage was a great success, with all objectives achieved. A variety of observational approaches were used in the experiment: including CTDs, measuring conductivity, temperature, and depth, from the ship, a towed CTD system for high resolution measurements of the upper ocean, a turbulence profiler, underway measurements of velocity from two acoustic Doppler current profilers working at different frequencies, and EM-APEX floats that provide vertical profiles of temperature, salinity and horizontal velocity. A heavily-instrumented tall mooring was deployed and is scheduled for recovery in March 2020.

Milestone 4: Deep Argo pilot experiment to investigate changes in the deep Southern Ocean

This milestone is on track. We deployed the first Australian Deep Argo floats in January 2019, from a Japanese vessel. This brings the total number of active floats to 12, each profiling every 10-14 days. The floats are working well, and the floats deployed one year earlier all survived a winter under sea ice – the first time this has been demonstrated for Deep Argo floats. Work is in progress to use the deep float data along with repeat hydrography to provide insights into the nature and causes of change in the abyssal ocean. We expect to publish the first paper using Deep Argo data from the array in early 2020. CSHOR also hosted an international workshop on Deep Argo in May 2019. Participants at the workshop endorsed the experiment we are leading in the Australian Antarctic Basin and several countries promised additional float deployments.

Milestone 5: Publication of a holistic (physical, chemical, biological, social) assessment of the future of Antarctica

This assessment (Rintoul et al., 2018) attracted a lot of attention, including invitations to present the results in plenary talks at the Scientific Community on Antarctic Research (SCAR) Open Science Conference in Davos and the American Geophysical Union meeting in Washington D.C.

Milestone 6: Publication of a study showing how movement of ACC fronts influences heat delivery to the Antarctica Ice Sheet

Dr Herraiz-Borreguero built a Southern Ocean data base covering the period from 1900 to the present, using observations from ships, Argo floats, and oceanographic sensors mounted on seals. She has analysed the data to look at changes in Circumpolar Deep Water properties and location around the Antarctic shelf break. This analysis has shown a higher heat reservoir in the East Antarctic sector in the last 10 years compared to the last century. Assessment of the drivers, including movement of ACC fronts, revealed strong link between ACC frontal position and ice shelf thinning in specific regions of East Antarctica. Dr Herraiz-Borreguero was on parental leave for most of the year, which has delayed publication of the paper.

Milestone 7: Develop plan for future observations in CSHOR, in collaboration with other groups in Australia and overseas

In addition to the major proposals summarised in the project synopsis, we have also been developing proposals for new experiments. A proposal for ship time on RV *Investigator* to carry out a multi-disciplinary transect between Antarctica and southwest Australia will be submitted in August. This work will include new Deep Argo float deployments. Another proposal is under development for an international effort to exploit the unprecedented spatial and temporal coverage to be provided by the new Surface Water Ocean Topography (SWOT) satellite, to be launched in 2022. We have started scoping new experiments to look at ocean-ice shelf interaction in Prydz Bay, near the Shackleton and Cook Ice Shelves.

Milestone 8: Present research findings at international meetings

Results have been presented at numerous national and international meetings, including invited talks at the SCAR Open Science Conference, the AGU fall meeting, and the Australian Meteorological and Oceanographic Society. Appendix C lists major conferences and workshops attended by CSHOR staff.

2.5.3 Project publications[7]

Castagno, P. V. Capozzi, G. R. DiTullio, P. Falco, G. Fusco, S. R. Rintoul, and G. Budillon (2019). Rebound of shelf water salinity in the Ross Sea. *Nature Communications*, under review.

Downes, S. M., Sloyan, B. M., Rintoul, S. R., & Lupton, J. E. (2019). Hydrothermal heat enhances abyssal mixing in the Antarctic Circumpolar Current. *Geophysical Research Letters*, 46, 812–821, doi.org/10.1029/2018GL080410.

Lambelet, M., Tina van de Flierdt, Edward C V Butler, Andrew R Bowie, Steve R Rintoul, Ros J Watson, Tom Remenyi, Delphine Lannuzel, Mark Warner, Laura F Robinson, Helen C Bostock and Louisa I Bradtmiller (2018). The Neodynium isotope fingerprint of Adélie Coast Bottom Water. *Geophysical Research Letters*, 45(20), 11,247-211,256, doi.org/10.1029/2018GL080074.

Moreau, S., D. Lannuzel, J. Janssens, M. Arroyo, M. Corkill, E. Cougnon, C. Genovese, B. Legresy, A. Lenton, V. Puigcorbe, L. Ratnarajah, S. Rintoul, M. Rocca-Marti, M. Rosenberg, E. Shadwick, A. Silvano, P.G. Strutton, B. Tilbrook (2019). Sea Ice Meltwater and Circumpolar Deep Water Drive Contrasting Productivity in Three Antarctic Polynyas. *Journal of Geophysical Research: Oceans*, 124(5), 2943-2968, doi:10.1029/2019jc015071.

Rintoul, S. R., Chown, S. L., DeConto, R. M., England, M. H., Fricker, H. A., Masson-Delmotte, V., Naish, T. R., Siegert, M. J., & Xavier, J. C. (2018). Choosing the future of Antarctica. Nature, 558(7709), 233-241, doi.org/10.1038/s41586-018-0173-4.

Schlitzer, R., Anderson, R. F., Dodas, E. M., Lohan, M., Geibert, W., Tagliabue, A., . . . Zurbrick, C. (2018). The GEOTRACES Intermediate Data Product 2017. Chemical Geology, 493, 210-223 (Rintoul one of 238 authors), doi.org/10.1016/j.chemgeo.2018.05.040.

Silvano, A., Rintoul, S. R., Kusahara, K., Peña-Molino, B., van Wijk, E., Gwyther, D. E., & Williams, G. D. (2019). Seasonality of Warm Water Intrusions Onto the Continental Shelf Near the Totten Glacier. *Journal of Geophysical Research: Oceans*, 124(6), 4272-4289, doi:10.1029/2018jc014634.

Silvano, A., Rintoul, S. R., Peña-Molino, B., Hobbs, W. R., van Wijk, E., Aoki, S., Tamura, T., & Williams, G. D. (2018). Freshening by glacial meltwater enhances melting of ice shelves and reduces formation of Antarctic Bottom Water. *Science Advances*, 4(4), doi:10.1126/sciadv.aap9467.

Snow, K., Rintoul, S. R., Sloyan, B. M., & Hogg, A. M. (2018). Change in Dense Shelf Water and Adélie Land Bottom Water Precipitated by Iceberg Calving. *Geophysical Research Letters*, 45(5), 2380-2387, doi.org/10.1002/2017GL076195.

[7] 2018-19 publications are shown in bold text.

2.6 Project 6: The role of the Southern Ocean in sea-level change

Project leader – Dr Xuebin Zhang (CSIRO)

Global mean sea level (GMSL) has been rising according to tide gauge and satellite altimetry observations, and is projected to continue to rise, with a likely increase between 0.28 m and 0.98 m by 2100. A larger rise could occur if there is a significantly larger contribution from changes in Antarctic dynamics. Several processes can affect GMSL, including ocean thermal expansion, mass loss of glaciers and ice caps, the Antarctic Ice Sheet and the Greenland Ice Sheet, and changes in the land water storage. The Southern Ocean is a key area for improving projections of ocean heat content and sea-level change. It is one of the significant areas where heat enters the ocean, resulting in heat storage in the upper ocean and abyssal layers, and contributing to ocean thermal expansion. A warming ocean is critical to the dynamic response of the Antarctic Ice Sheet.

This project aims to produce new regional sea-level projections, based on improved understanding of ocean heat uptake and redistribution, dynamic sea-level distribution from new CMIP6 models, and new projections of Antarctic Ice Sheet mass loss.

In the past two years, this project has focused on: examining ocean heat uptake and redistribution in the Southern Ocean through analysing available observations CMIP5) models and carrying out numerical perturbation experiments; tuning up a suite of ocean models and carrying out carefully-designed numerical experiments with certain forcing being turned on or off; and quantifying uncertainty in Antarctic surface mass balance and carrying ice sheet modelling to project future contribution of Antarctic Ice Sheet to sea-level rise. Now the project team will work to bring all components together with the aim to produce a new version of regional sea-level projection, based on improved understanding of ocean heat uptake and redistribution, dynamic sea-level distribution from new CMIP6 models, and new projections of Antarctic Ice Sheet mass loss.

2.6.1 Research activities

Lyu et al. (2019) examined ocean heat uptake and redistribution in the southern hemisphere oceans and decomposed both analytically based on a theoretical framework, and numerically based on perturbation modelling experiments. They discovered that enhanced southern hemisphere mid-latitude warming is related to isopycnal deepening, due to both the wind-driven heat convergence and also the accumulation of extra surface heat uptake by the background ocean circulation. The equatorward and downward subductions of the surface heat and freshwater input in the high-latitude Southern Ocean result in cooling and freshening spiciness changes on density surfaces within the Subantarctic Mode Water.

Wang et al. (2019) conducted a systematic comparison between sea-level projections from the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC AR5) and sea-level observations based on tide gauges and satellite altimetry over their overlapping period. They found good consistency between projections and observations in the recent decade, indicating the robustness and usefulness of IPCC AR5 sea-level projections for future adaptation planning.

Wu et al. (2019b) identified two distinct dynamic sea-level modes responding very differently to changing greenhouse gas emissions in the future based on CMIP5 model simulations. Underlying

processes responsible for two modes and the implication for future mitigation and adaptation planning were also discussed. The results presented have implications for monitoring the planetary energy budget and evaluating ENSO's global imprints on ocean heat content in different estimates.

King et al. (2019) examined natural variability in Antarctic surface mass balance (net snow accumulation), focusing on testing the sensitivity to different noise models. This work will be presented at the 27th General Assembly of the International Union of Geodesy and Geophysics (IUGG) in July 2019.

Parallel Ice Sheet Model (PISM) was set up to simulate Antarctic Ice Sheet. A large ensemble comprising 100 different configurations of PISM (sampling the range of uncertainty in 10 key physical parameters) is run, and 'best' ensemble members that accurately replicate present-day state of Antarctic Ice Sheet was chosen to run into the future under a $4xCO_2$ stabilisation scenario. This work was reported at the Australian Meteorological and Oceanographic Society (AMOS) Annual Meeting in June 2019 and will be published next financial year.

Gregory et al. (2019) defines concepts and terminology associated with sea level and sea-level changes in order to facilitate progress in sea-level science, in which communication is sometimes hindered by inconsistent and unclear language.

Drs Zhang, Rintoul and Cai were invited to join the University of Tasmania (UTAS) bid to the ARC Antarctic Special Research Initiative (SRI), led by CSHOR collaborator, Matt King at UTAS. This is an exciting opportunity for both CSHOR and the Antarctic SRI to enhance scientific collaboration.

2.6.2 Project performance against milestones

Most project milestones were met. Milestone 2 was deferred to include recently completed modelling experiments in the manuscript. Milestone 3 was delayed due to the late arrival of mapping software and because of the need to resolve unexpected technical issues in implementing complex algorithms. An overview of performance against each milestone follows.

Milestone 1: Estimates of contribution of wind vs melting, natural vs anthropogenic in the historical sea level in the Southern Ocean over the past several decades

In addition to work presented in Lyu et al. (2019), Wang et al. (2019) and Wu et al. (2019b), we analysed sea-level change in the South Pacific during the late 20th Century and early 21st Century based on observations and climate models (Albrecht et al., 2019). We also examined the ENSO-related interannual variations of global ocean heat content and underlying processes (Wu et al., 2019a).

Milestone 2: Estimates of impacts of meso-scale eddies in regional sea-level distribution in the Southern Ocean, especially for the meridional dipolar structure

We tuned up a suite of ocean models and carried out perturbation numerical experiments were to estimate the impact of meso-scale eddies in ocean heat content and sea-level distributions in the Southern Ocean. The results of the analysis will be published next financial year.

In a closely-related analysis examining ocean gyre circulation and its connection to sea levels in the Southern Ocean, we compared coarse-resolution and high-resolution (eddy-resolving) model

results (Zhang et al., 2019). This study will be presented at the 27th IUGG General Assembly in July 2019.

Milestone 3: Sensitivity of multi-decadal Southern Ocean heat uptake estimates to vertical interpolation schemes

Good progress has been made even though there were technical difficulties in processing the large amounts of data to produce vertically interpolated profiles using more complex algorithms. A preliminary report on evaluating the various interpolation schemes has been drafted but more detailed analysis is required prior to publication.

Milestone 4: Compilation of state-of-the-art of Antarctic Ice Sheet mass flux rates from early 1990s to 2019, with robust error range (UTAS)

King and Watson (2019) analysed outputs from the RACMO2.3p2 numerical model and composite ice core records, to consider the most appropriate noise models when determining trends such as those used in quantifying recent ice sheet contribution to sea level. This analysis has been performed at the ice-sheet scale and for individual drainage basins.

In contrast to previous analysis which suggested that natural variability possessed an AR[1]-like noise, the new analysis, across both numerical models and ice cores, shows that AR[1] under-predicts noise at the lowest frequencies. Of a range of noise models tested, Generalised Gauss Markov is found to be most appropriate, resulting in increases in trend uncertainties over decades of factors two-five. For the period most relevant to ice sheet contribution to sea-level change, we find ice-sheet-wide trend uncertainties of 50 Gigatonnes -per-year (or 0.14mm/yr of global sea-level equivalent).

The work will be presented at the 27th IUGG General Assembly in July 2019.

Milestone 5: Estimates of the contribution of the Antarctic Ice Sheet to global sea level over the next 5,000 years, using a large ensemble ice sheet modelling approach to explore uncertainty due to model physics (UTAS)

The Parallel Ice Sheet Model (PISM) has been configured to simulate the entire Antarctic Ice Sheet. Specifically, it has been configured to explore the values of key physical parameters using a large ensemble modelling approach. Realistic atmospheric and oceanic boundary conditions have also been generated by using the CSIRO Mk3L climate system model to simulate the period from 41,000 years before present until 5,000 years into the future.

Preliminary work has used known bounds on the volume of the Antarctic Ice Sheet at the Last Glacial Maximum (~21,000 years ago) to identify the most realistic configurations of PISM. This constraint on the model physics leads to a projected Antarctic contribution to global sea level, under the RCP8.5 climate scenario, of 3.70±0.80m by the year 2500. Such values are notably lower than the range of 15.65±2.00m derived by DeConto and Pollard (2016[8]), suggesting that their estimates may

[8] DeConto, R. M., & Pollard, D. (2016). Contribution of Antarctica to past and future sea-level rise. *Nature*, 531(7596), 591-597, doi.org/10.1038/nature17145.

not be consistent with known changes in the Antarctic Ice Sheet during the last deglaciation. These results were presented at Australian Meteorological and Oceanographic Society (AMOS) Annual Meeting in June 2019. Appendix C lists major conferences and workshops attended by CSHOR staff.

Ongoing work is developing novel techniques to constrain ice sheet model physics using data from Antarctic ice cores. Updated results will be presented at the 20th INQUA Congress in Dublin, Ireland in July 2019. A manuscript is also in preparation for *The Cryosphere*.

2.6.3 Project publications[9]

Albrecht, F., O. Pizarro, A. Montecinos and X. Zhang (2019). Understanding Sea Level Change in the South Pacific during the late 20th and early 21st Century. *Journal of Geophysical Research: Oceans*, 124, doi:10.1029/2018JC014828.

Carson, M., K. Lyu, K. Richter, M. Becker, C. M. Domingues, W. Han, C. M. Little, L. Zanna (2019). Climate model uncertainty and trend detection of future regional sea level projections in the open ocean and coastal zone. *Surveys in Geophysics*, in press.

Gregory, J. M., Griffies, S. M., Hughes, C. W., Lowe, J. A., Church, J. A., Fukimori, I., . . . van de Wal, R. S. W. (2019). Concepts and Terminology for Sea Level: Mean, Variability and Change, Both Local and Global. *Surveys in Geophysics,* doi.org/10.1007/s10712-019-09525-z.

Han, W., D. Stammer, P. Thompson, T. Ezer, H. Palanisamy, X. Zhang, C. Domingues, L. Zhang and D. Yuan (2019). Impacts of natural internal climate modes on coastal sea level: a review, *Surveys in Geophysics*, in press.

Holbrook, N.J., D.C. Claar, A.J. Hobday, K.L. McInnes, E.C. Oliver, A. Sen Gupta, M.J. Widlansky, and X. Zhang (2019). AGU Monograph: *ENSO in a Changing Climate, Chapter 18: Ocean Extremes and Habitat Impacts*, under 2nd review.

King, M.A. and Watson C.S. (2019) Noise, variability and the emergence of trends in Antarctic Surface Mass Balance. *Geophysical Research Letters*, in preparation.

Lyu, K., X. Zhang, J.A. Church, and Q. Wu (2019). Processes responsible for the Southern Hemisphere ocean heat uptake and redistribution under anthropogenic warming. *Journal of Climate*, submitted.

Ponte, R. and co-authors (2019). Towards comprehensive observing and modeling systems for monitoring and predicting regional to coastal sea level, *Frontiers in Marine Science*, in press.

Van de Wal, R.S.W., X. Zhang, S. Minobe, S. Jevrejeva, R.E.M. Riva, C. Little, K. Richter and M. Palmer. Uncertainties in long-term processes-based coastal sea-level projections (2019). *Surveys in Geophysics*, under 2nd revision.

Wang, J., J.A. Church, X. Zhang and X. Chen (2019) Comparing global and regional sea level changes between observations and IPCC projections. *Nature*, submitted.

[9] 2018-19 publications are shown in bold text.

Wu, Q., X. Zhang, J. A. Church, and J. Hu (2019a). ENSO-related Global Ocean Heat Content Variations. *Journal of Climate*, 32, 45-68, doi: 10.1175/JCLI-D-17-0861.1.

Wu, Q., X. Zhang, J.A. Church, J. Hu, and W. Cai (2019b). Two sea level modes responding distinctively to changing greenhouse gas emissions. *Nature Climate Change*, in preparation.

Zhang, X., K. Lyu and J. Church (2019). Projected changes of ocean gyre circulation and associated sea level changes based on CMIP5 models. *Geophysical Research Letters*, in preparation.

3 Financial management

The Centre's revenue over a 5-year period to 2021-22 is AU$20m. An overview of the Centre's finances in 2018-19 is provided below.

3.1 Revenue

Total Revenue was $3,708m comprising contributions of $2m from QNLM funds and $1,708m from CSIRO funds (Figure 1).

Since the Centre's inception, CSIRO has contributed $2,792m (34% of Agreement funds) and QNLM $6m (60% of Agreement funds) (Figure 2). CSIRO currently holds $2,385m funds in trust to be rolled over to 2019-20 operations.

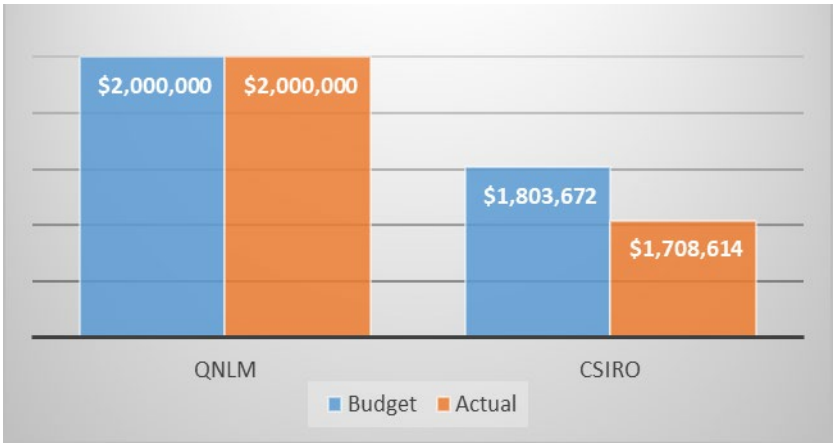

Figure 1 Revenue 2018-19: budget vs actual $

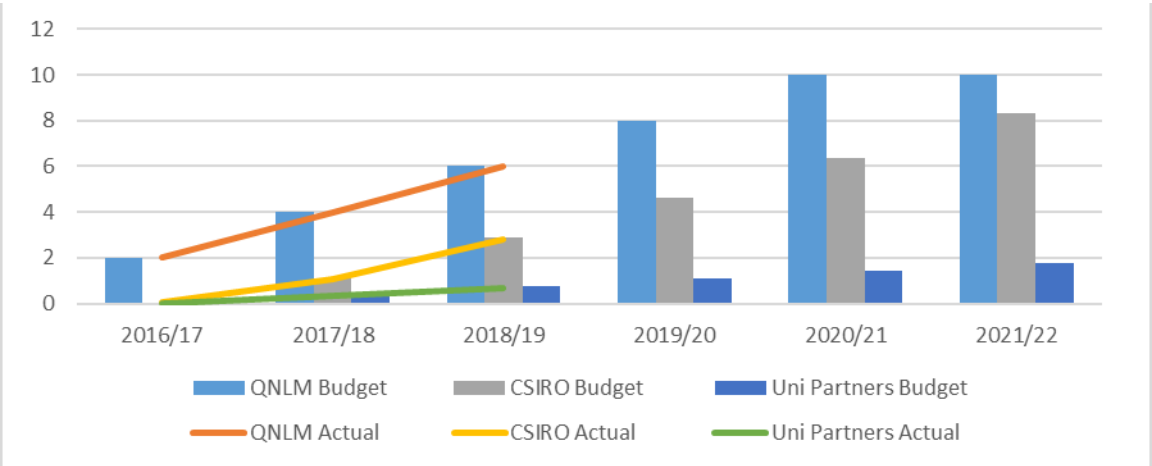

Figure 2 Revenue: cumulative budgets to 2021-22 ($m)

3.2 Expenditure

The total 2018-19 expenditure incurred was $4,247,042 acquitted to each partner as follows:

Fund source	2018-19 Budget	2018-19 Actuals	Variance
QNLM	$2,575,156	$2,194,289	-$380,867
CSIRO	$1,803,672	$1,708,614	-$95,058
UNSW (In-kind)	$300,000	$260,915	-$39,085
UTAS (In-kind)	$150,000	$83,224	-$66,776

The underspent variance on QNLM/CSIRO funds was -$475,925 which reflects a movement of $292,146 QNLM funded capital deferred to 2019-20 and $183,779 underspent in normal operations, with labour expenditure slightly down on the budget due to staff taking leave, less travel than anticipated and lower publication costs (Figure 3).These funds will be carried forward to 2019-20.

Total expenditure since the Centre commenced is $6,407m, which is approximately one-third of the Centre's budget (Figure 4).

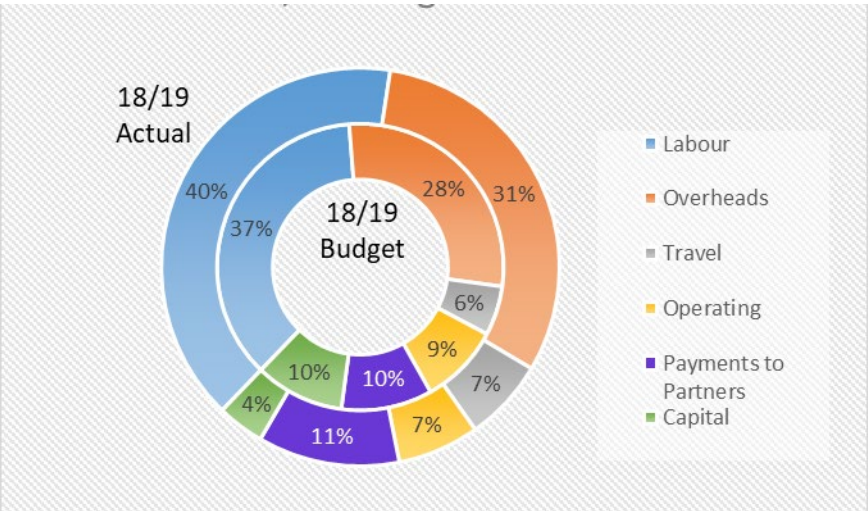

Figure 3 Expenditure breakdown by category: 2018-19 budget vs actual

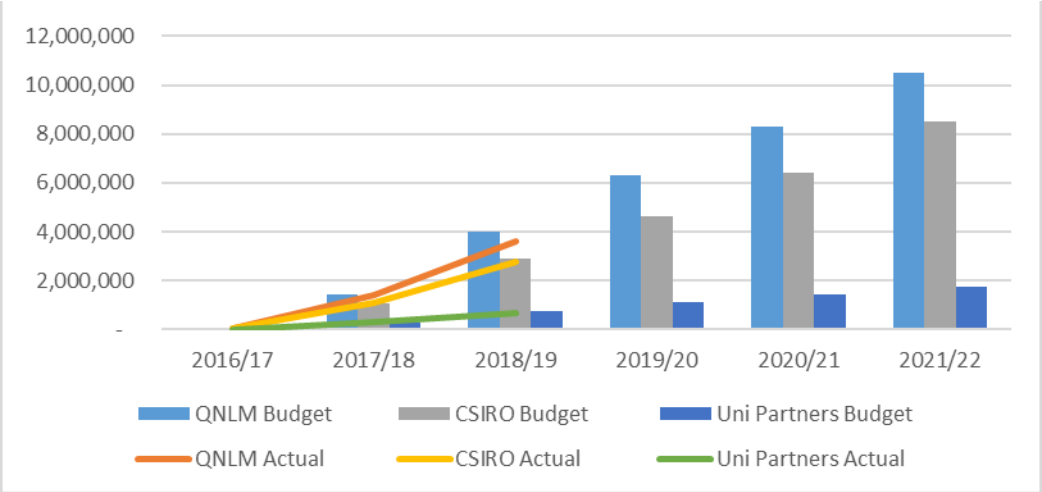

Figure 4 Expenditure: cumulative budgets to 2021-22 ($m)

3.3 Partner in-kind contribution

UNSW 2018-19 in-kind contribution was $260,000, -$39,000 under budget. UTAS 2018-19 in-kind contribution was $83,000, approximately -$66,700 under budget. The shortfall will be obtained in 2019-20 (Figure 5).

In-kind contributions since the Centre commenced are UNSW 42% at $521,830 and UTAS 28% at $141,810.

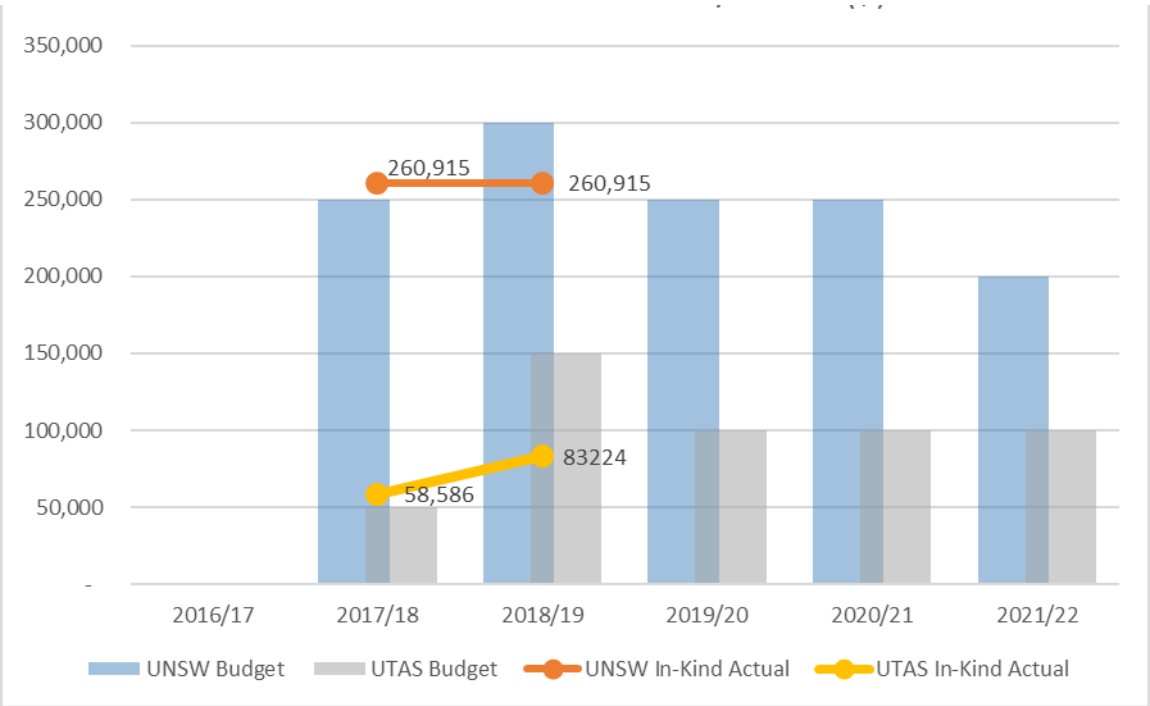

Figure 5 University partners in-kind contribution: 2018-19 year-to-date ($)

4 Management and co-ordination

The Centre was established via a five-year Research Collaboration Agreement between Qingdao National Laboratory for Marine Science and Technology Development Center (QNLM) and CSIRO. It is managed through a governance structure comprising a:

- Steering Committee (an independent Chair and two representatives each from QNLM and CSIRO).
- Advisory Committee (six independent science leaders and representatives of QNLM and CSIRO).
- Director, employed by or seconded to CSIRO.
- Research Leadership Team.

Steering and Advisory Committee Members are listed in the Acknowledgement Section (page 7).

The Research Leadership Team consists of the Director and the Project Leaders (See Appendix A).

The **CSHOR Steering Committee** convened via teleconference on 5 December 2018 and face-to-face on 16 and 17 May 2019.

The **CSHOR Research Leadership Team** met on 6 September 2018, 30 April 2019 and with the Steering Committee on 16 and 17 May 2019.

The **CSHOR Management Team**, comprising the Director, Project Support Officer and representatives from CSIRO Finance, Contracts, Communications and Business Development, joined the Leadership Team Meeting on the dates listed above and met separately on 23 July 2018, 29 October 2018, 4 February 2019, 18 March 2019 and 24 June 2019. Several members attended the CSHOR Science Seminar and Steering Committee Meeting on 16 and 17 May 2019.

The Director also attended various meetings at QNLM in Qingdao including internal budget planning meetings in November and December 2018, the QNLM Annual Meeting in January 2019 and contract agreement meetings in May 2019. CSHOR staff also travelled to Qingdao for the QNLM Annual Meeting.

Appendix A Project and support staff

Wenju Cai	Director
Ryan Crossing	Technical Services Officer - project 3 Coupled warm pool dynamics in the Indo-Pacific
Matthew England[10]	Project Leader - project 4 Southern Ocean dynamics
Ming Feng	Project Co-leader - project 3 Coupled warm pool dynamics in the Indo-Pacific
Annie Foppert	Postdoctoral Fellow - project 4 Southern Ocean dynamics
Craig Hanstein	Senior Technical Officer - project 3 Coupled warm pool dynamics in the Indo-Pacific
Laura Herraiz-Borreguero	Research Scientist – project 5 Southern Ocean observations
Je-Yuan (Andy) Hsu	Postdoctoral Fellow - project 3 Coupled warm pool dynamics in the Indo-Pacific
Andrew Lenton	Principal Research Scientist - project 4 Southern Ocean dynamics
Yuehua (Veronica) Li[11]	Research Associate - project 6 Southern Ocean sea-level change
Kewei Lyu	Postdoctoral Fellow - project 6 Southern Ocean sea-level change
Ben Ng	Postdoctoral Fellow – project 1 Understanding ENSO/IOD dynamics
Beatriz Peña-Molino	Research Scientist – project 2 Indo-Pacific inter-basin exchange
Océane Richet	Postdoctoral Fellow - project 2 Indo-Pacific inter-basin exchange
Steve Rintoul	Project Leader - project 5 Southern Ocean observations
Agus Santoso[12]	Project Co-leader - project 1 Understanding ENSO/IOD dynamics
Dirk Slawinski	Senior Experimental Scientist - project 3 Coupled warm pool dynamics in the Indo-Pacific
Bernadette Sloyan	Project Leader - project 2 Indo-Pacific inter-basin exchange
Veronica Tamsitt[13]	Postdoctoral Fellow - project 4 Southern Ocean dynamics
Bronte Tilbrook	Senior Principal Research Scientist - project 5 Southern Ocean observations
Guojian Wang	Project Co-leader - project 1 Understanding ENSO/IOD dynamics
Susan Wijffels	Project Co-leader - project 3 Coupled warm pool dynamics in the Indo-Pacific
Leonie Wyld	Project Support Officer
Xuebin Zhang	Project Leader - project 6 Southern Ocean sea-level change

[10] UNSW Scientia Professor of Climate Dynamics

[11] UNSW Research Associate

[12] UNSW Senior Research Associate and CSIRO Adjunct Science Leader

[13] UNSW staff based at CSHOR Hobart

SUPPORT STAFF[14]	
Fiona Brown	Communication Advisor, CSIRO Oceans and Atmosphere
Sandy Farnworth	Legal and Contracts Advisor, CSIRO Oceans and Atmosphere
Chris Gerbing	Communication Manager, CSIRO Oceans and Atmosphere
Hugh Kater	Business Development Manager, CSIRO Oceans and Atmosphere
Jane Sellenger	Contracts Manager, CSIRO Oceans and Atmosphere
Brenda Tuckwood	Finance and Projects Advisor, CSIRO Oceans and Atmosphere

[14] Provided by CSIRO

Appendix B PhD Students

Gauthier Gacoin	Ecole Normale Superieure of Lyon (ENS Lyon), France Project 5 Southern Ocean observations and change team member
Saisai Hou[15]	Ocean University of China Project 5 Southern Ocean observations and change team member
Zhi Li[16]	UNSW, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Jie Ma	Ocean University of China Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
Anna Maggiorano	UNSW Canberra, Australia Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
Jinping Wang[17]	Ocean University of China Project 6 Southern Ocean sea-level change project team
Ying Zhang	University of Chinese Academy of Sciences Project 3 Coupled warm pool dynamics in the Indo-Pacific team member

[15] Sponsored by the China Scholarship Council.

[16] Sponsored by the China Scholarship Council.

[17] Sponsored by the China Scholarship Council.

Appendix C Conference and workshop participation

C.1 First Quarter (July to September)

Australian Marine Science Association annual conference. Adelaide, Australia, 1-5 July 2018: Dr Feng and Prof England. Prof England gave an invited keynote lecture on Antarctic climate change.

NESP annual workshop, Australia, 2-5 July 2018: Drs Cai, Ng, Rintoul and Santoso.

Observed storm track dynamics in Drake Passage, UTas-IMAS Physical Oceanography meeting at IMAS Hobart, Australia, 18 July 2018: Drs Foppert and Tamsitt.

A second workshop on Tropical Interbasin Interactions, Jeju, South Korea, 22-25 August 2018: Drs Cai, Santoso, Wang and Ng.

C.2 Second Quarter (October to December)

EUMETSAT Science Conference, Tallinn, Estonia, 18-22 September 2018: Dr Sloyan.

ACOMO 2018, Canberra, Australia, 9-11 October 2018: Dr Feng.

CLIVAR Pacific Panel meeting and CLIVAR IV International Conference on ENSO, Ecuador, 13-18 October 2018: Drs Cai, Zhang and Wang.

GCOS Science Steering Committee, Helsinki, Finland, 22-27 October 2018: Dr Sloyan.

Third Western Pacific Ocean Circulation-ITF International Symposium on Western Boundary Currents and ENSO, Climate Dynamics, QNLM, Qingdao, China, October 30-31, 2018: Dr Feng.

CARe2018 - Climate Adaptation & Resilience Conference, HKUST, Hong Kong, 27-29 October 2018: Dr Zhang was invited (with all expenses covered) to travel to Hong Kong to give an invited talk and to provide insights as an expert panellist about sea-level rise at CARe2018. He also gave a summary report on behalf of the sea level working group to many Hong Kong stakeholders (including government agencies) about sea-level rise and storm surges.

The Future of Earth System Modeling: Polar Climates, Caltech workshop, USA, November 2018: Prof England was invited to present.

AGU Fall, Washington D. C. USA, 9-14 December 2018: Prof England and Drs Wijffels, Santoso and Tamsitt.

C.3 Third Quarter (January to March)

60th Anniversary celebration of the South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China, 7-11 January 2019: Dr Feng.

QNLM Academic Annual Meeting, QNLM, Qingdao, China, 10-11 January 2019: Drs Cai, Santoso, Wang, Ng, Sloyan, Zhang, Richet, Foppert, Tamsitt, Hsu and Ms Wyld.

CSHOR ENSO Science Symposium, UTAS/IMAS Hobart, Australia, 29-31 January 2019: Drs Cai, Santoso, Feng, Wang, Ng, Sloyan, Zhang, Richet, Foppert and Ms Wyld.

UNSW Water-Mass Transformation Workshop, Sydney, Australia, February 2019: Dr Tamsitt and Prof England.

4th International Years of Maritime Continent Workshop, Quezon City, the Philippines, 26-28 February 2019: Dr Feng

ENSO Impact on South America Workshop, University of Chile, Santiago, 4-6 March 2019: Dr Cai and Ng.

CMIP6 Model Analysis Workshop, Barcelona, Spain, 25-28 March 2019: Dr Cai.

C.4 Fourth Quarter (April to June)

The 2nd Tropical Pacific Decadal Variability Workshop, Paris, France, 1-5 April 2019: Dr Cai.

FAFMIP 2nd workshop, University of Reading, UK, 3-5 April 2019: Dr Zhang. He also visited Prof Jonathan Gregory of University of Reading (UK) in late March and early April to discuss regional sea level distribution and ocean-climate model perturbation experiments closely related to the CSHOR sea level project.

EGU General Assembly, Vienna, Austria, 7-12 April 2019: Dr Foppert.

4th Global Ocean Acidification Observing Network (GOA-ON) International Workshop, Hangzhou, China, 14-17 April 2019: Dr Lenton.

Centre launch ceremony of the International Laboratory for High-Resolution Earth System Prediction, Texas A & M University, USA, 24th April 2019: Dr Cai.

Visiting NOAA and AGU headquarter in Washington, USA, 26th April 2019: Dr Cai.

Building an International Transparent Ocean Community, Qingdao, China, 15-17 April 2019: Drs Cai and Wang.

WCRP JSC-40 meeting, Geneva, Switzerland, 6th-10th May 2019: Dr Cai.

The 2nd Deep Argo Workshop, Hobart, Australia, 13-15th May 2019: Drs Cai, Zhang, Wang.

CSHOR Science Seminar 2019, Hobart, Australia, 16th May 2019: Drs Cai, Rintoul, Wang, Santoso, Ng, Zhang, Sloyan, Feng, Foppert, Tamsitt, Hsu, Lyu and Ms Wyld.

CSHOR Steering Committee Meeting 2019, Hobart, Australia, 17-18th May 2019: Drs Cai, Rintoul, Zhang, Sloyan, Wang, Feng, Santoso and Ms Wyld.

AMOS-ICTMO 2019, Darwin, Australia, 11-14 June 2019: Drs Cai, Zhang, Wang, Wijffels, Peña Molino, Santoso, Feng, Foppert, Tamsitt, Hsu, Lyu and Ms Maggiorano. Drs Santoso, Wang and Zhang chaired the CSHOR session. Drs Foppert and Tamsitt convened a session on Antarctic and Southern Ocean science.

The 2nd workshop for ENSO impacts on South America, Sydney, Australia, 24-28th June 2019: Drs: Cai, Santoso, and Wang.

Appendix D Datasets

Datasets produced and made publicly available in 2018-19 are listed below.

Project 3: Coupled warm pool dynamics in the Indo-Pacific

8 high-frequency profiling float data off northwest Australia will be publicly available at Australian Ocean Data Network (AODN) 3 years after data validation (Two of these floats were listed in the CSHOR 2017-18 Annual Report).

ACCESS model outputs for the 2018-19 MJO experiment. The model data is being evaluated and will be made publicly available through AODN before the end of the project.

Project 5: Southern Ocean observations and change

Repeat hydrography from GO-SHIP line SR3, January – February 2018. Reported in the CSHOR 2017-18 Annual Report and now available from AODN and CLIVAR & Carbon Hydrographic Data Office (CCHDO).

Appendix E Publications

Albrecht, F., O. Pizarro, A. Montecinos and X. Zhang (2019). Understanding Sea Level Change in the South Pacific during the late 20th and early 21st Century. *Journal of Geophysical Research: Oceans*, 124, doi:10.1029/2018JC014828.

Cai W., Wang G., Dewitte B., Wu L., Santoso A., Takahashi K., Yang Y., Carreric A., McPhaden M. J. (2018). Increased variability of eastern Pacific El Niño under greenhouse warming. *Nature*, 564, 201-206, doi: 10.1038/s41586-018-0776-9.

Cai, W., Wu, L., Lengaigne, M., Li, T., McGregor, S., Kug, J.-S., . . . Chang, P. (2019). Pantropical climate interactions. *Science*, 363, eaav4236, doi: 10.1126/science.aav4236.

Downes, S. M., Sloyan, B. M., Rintoul, S. R., & Lupton, J. E. (2019). Hydrothermal heat enhances abyssal mixing in the Antarctic Circumpolar Current. *Geophysical Research Letters*, 46, 812–821, doi.org/10.1029/2018GL080410.

Devries, T., Le Quéré C., Andrews, O., Berthet, S, Hauck, J. Ilyina, T., Landschützer, P., Lenton, A., Lima. I., Nowicki, M. Schwinger, J., Séférian, R. (2019). Decadal trends in the ocean carbon sink. *Proceedings of the National Academy of Sciences,* 116(24), 11646-11651, doi.org/10.1073/pnas.1900371116.

Foppert, Annie (2019). Observed storm track dynamics in Drake Passage. *Journal of Physical Oceanography,* 3, 867-884, doi.org/10.1175/JPO-D-18-0150.1.

Gregory, J. M., Griffies, S. M., Hughes, C. W., Lowe, J. A., Church, J. A., Fukimori, I., . . . van de Wal, R. S. W. (2019). Concepts and Terminology for Sea Level: Mean, Variability and Change, Both Local and Global. Surveys in Geophysics, doi.org/10.1007/s10712-019-09525-z.Hauck, J., Lenton, A., Langlais, C, Matear, R. J. (2018). The fate of carbon and nutrients exported out of the Southern Ocean. *Global Biogeochemical Cycles*, 32(10), 1556-1573, doi: 10.1029/2018GB005977.

Hauck, J., Lenton, A., Langlais, C, Matear, R. J. (2018). The fate of carbon and nutrients exported out of the Southern Ocean. *Global Biogeochemical Cycles*, 32(10), 1556-1573, doi: 10.1029/2018GB005977.

Hermes, J. C., Y. Masumoto, L. Beal, M. Roxy, J. Vialard, M. Andres, H. Annamalai, S. Behere, N. d'Adamo, T. Doi, M. Feng, W. Han, H. Hendon, R. Hood. S. Kido, C. Lee, T. Lee, M. Lengaigne, R. Lumpkin, K. Navaneeth, B. Milligan, M. McPhaden, M. Ravichandra, T. Shinoda, A. Singh, B. Sloyan, P. Strutto, A. Subramanian, S. Thurston, T. Tozuka, C. Ummenhofer, U. Alakkat, R. Venkatesan, D. Wang, J. Wiggert, L, Yu, W. Yu (2019). A sustained ocean observing system in the Indian Ocean for climate related scientific knowledge and societal need, *Frontiers in Marine Science*, 6 (355), doi.org/10.3389/fmars.2019.00355.

Holmes, R. M., McGregor, S., Santoso, A., & England, M. H. (2018). Contribution of Tropical Instability Waves to ENSO Irregularity. *Climate Dynamics*, doi.org/10.1007/s00382-018-4217-0.

Holmes, R. M., J. D. Zika, and M. H. England (2019). Diathermal Heat Transport in a Global Ocean Model. *Journal of Physical Oceanography*, 49, 141-161, doi.org/10.1175/JPO-D-18-0098.1.

Jo. H.-S., Yeh S.-W., Cai W., 2019: An Episodic Weakening in the Boreal Spring SST–Precipitation Relationship in the Western Tropical Pacific since the Late 1990s, *Journal of Climate*, 32, 3837-3845, doi.org/10.1175/JCLI-D-17-0737.1.

Lambelet, M., Tina van de Flierdt, Edward C V Butler, Andrew R Bowie, Steve R Rintoul, Ros J Watson, Tom Remenyi, Delphine Lannuzel, Mark Warner, Laura F Robinson, Helen C Bostock and Louisa I Bradtmiller (2018). The Neodynium isotope fingerprint of Adélie Coast Bottom Water. *Geophysical Research Letters*, 45(20), 11,247-211,256, doi.org/10.1029/2018GL080074.

Ma, J., Feng, M. Sloyan, B.M., Lan, J. (2018). Pacific influences on the low-frequency meridional temperature transport of the Indian Ocean. *Journal of Climate*, 32(4), 1047-1061, doi.org/10.1175/JCLI-D-18-0349.1.

Makarim, S., J. Sprintall, Z. Liu, W. Yu, A. Santoso, X.-H. Yan, R. D. Susanto (2019). Previously unidentified Indonesian Throughflow pathways and freshening in the Indian Ocean during recent decades. *Scientific Reports*, 9:7364, doi: 10.1038/s41598-019-43841-z.

Moreau, S., D. Lannuzel, J. Janssens, M. Arroyo, M. Corkill, E. Cougnon, C. Genovese, B. Legresy, A. Lenton, V. Puigcorbe, L. Ratnarajah, S. Rintoul, M. Rocca-Marti, M. Rosenberg, E. Shadwick, A. Silvano, P.G. Strutton, B. Tilbrook (2019). Sea Ice Meltwater and Circumpolar Deep Water Drive Contrasting Productivity in Three Antarctic Polynyas. Journal of Geophysical Research: Oceans, 124(5), 2943-2968, doi:10.1029/2019jc015071.

Patel, R.S., H. E. Phillips, P.G. Strutton, A. Lenton, Llort, J. (2019). Meridonal Heat and Salt Transport across the Subantarctic Front by Cold Core Eddies. *Journal of Geophysical Research: Oceans*, 124(2), 981-1004, doi:10.1029/2018JC014655.

Purkey, S. G., Johnson, G. C., Talley, L. D., Sloyan, B. M., Wijffels, S. E., Smethie, W., . . . Katsumata, K. (2019). Unabated bottom water warming and freshening in the South Pacific Ocean. *Journal of Geophysical Research: Oceans*, 124, 1778–1794, doi.org/10.1029/2018JC014775.

Santoso, A., H. Hendon, A. Watkins, S. Power, D. Dommenget, M. England, L. Frankcombe, N. Holbrook, R. Holmes, P. Hope, E.-P. Lim, J.-J. Luo, S. McGregor, S. Neske, H. Nguyen, A. Pepler, H. Rashid, A. Sen Gupta, A. S. Taschetto, G. Wang, E. Abellan, A. Sullivan, M. Huguenin, F. Gamble, F. Delage (2019a). Dynamics and predictability of the El Niño-Southern Oscillation: An Australian perspective on progress and challenges. *Bulletin of the American Meteorological Society*, 100, 403-420, doi:10.1175/BAMS-D-18-0057.1.

Schlitzer, R. et al. (2018). The GEOTRACES Intermediate Data Product 2017. *Chemical Geology*, 493, 210-223 (Rintoul one of 238 authors), doi.org/10.1016/j.chemgeo.2018.05.040.

Silvano, A., Rintoul, S. R., Kusahara, K., Peña-Molino, B., van Wijk, E., Gwyther, D. E., & Williams, G. D. (2019). Seasonality of Warm Water Intrusions Onto the Continental Shelf Near the Totten Glacier. Journal of Geophysical Research: Oceans, 124(6), 4272-4289, doi:10.1029/2018jc014634.

Sprintall, J., A. Gordon, S. Wijffels, M. Feng, S. Hu, A Koch-Larrouy, H. Phillips, D. Nugroho, A. Napitu, K. Pujiana, R. Susanto, B. Sloyan, B. Peña Molino, D. Yuan, N. Riama, S. Siswanto, A. Kuswardani, Z. Arifin, A. Wahyudi, H. Zhou, T. Nagai, J. Ansong, r. Bourdalle-badie, J. Chanut, F. Lyard, B. Arbic, A. Ramdhani, A. Setiawan (2019). Detecting change in the Indonesian Seas, *Frontiers in Marine Science*, 6 (257), doi.org/10.3389/fmars.2019.00257.

Timmermann, A., S.-I. An, J.-S. Kug, F.-F. Jin, W. Cai, A. Capotondi, K. M. Covv, M. Lengaigne, M. J. McPhaden, M. F. Stuecker, K. Stein, A. T. Wittenberg, K.-S. Yum, T. Bayr, H.-C., Chem, Y. Chikamoto, B. Dewitte, D. Dommerget, P. Grothe, E. Guilyardi, Y.-G. Ham, M. Hayashi, S. Ineson, D. Kang, S. Kim, W. Kim, J.-Y. Lee, T. Li, J.-J. Luo, S. McGregor, Y. Planton, S. Power, H. Rashid, H.-L. Ren, A. Santoso, K. Takahashi, A. Todd, G. Wang, G. Wang, R. Xie, W.-H. Yang, S.-W. Yeh, J. Yoon, E. Zeller, and X. Zhang. (2018). El Nino-Southern Oscillation complexity. *Nature*, 559, 535-534, doi.org/10.1038/s41586-018-0252-6.

Tamsitt, V (2018). Moving windows to the deep ocean (News and Views). *Nature Climate Change*, 8, 941-942, doi.org/10.1038/s41558-018-0324-5.

Tamsitt, V., L. D. Talley and M. R. Mazloff (2019). A Deep Eastern Boundary Current carrying Indian Deep Water south of Australia. *Journal of Geophysical Research: Oceans*, doi.org/10.1029/2018JC014569.

Webb, D. J., R. M. Holmes, P. Spence, and M. H. England (2019). Barotropic Kelvin wave-induced bottom boundary layer warming along the West Antarctic Peninsula. *Journal of Geophysical Research: Oceans*, 124, 1595-1615, doi.org/10.1029/2018JC014227.

Wu, Q., X. Zhang, J. A. Church, and J. Hu (2019). ENSO-related Global Ocean Heat Content Variations. *Journal of Climate*, 32, 45-68, doi: 10.1175/JCLI-D-17-0861.1.

Zhang, Y., Feng, M., Du, Y., Phillips, H. E., Bindoff, N. L., & McPhaden, M. J. (2018). Strengthened Indonesian Throughflow Drives Decadal Warming in the Southern Indian Ocean. *Geophysical Research Letters,* 45(12), 6167-6175, doi.org/10.1029/2018GL078265.

Glossary [style = Heading 1 not numbered]

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WE DO THE EXTRAORDINARY EVERY DAY

We innovate for tomorrow and help improve today – for our customers, all Australians and the world.

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WE COLLABORATE
WE INNOVATE

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