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The Centre for Southern Hemisphere Oceans Research

Annual Report

Year 1 (July ’17 to June ’18)

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

UNSW SYDNEY

UNIVERSITY of TASMANIA

Foreword

I am pleased to present the first 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 ocean 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.

I am very pleased by the quality of the research being delivered by the six project teams and I am happy to report that, apart from a couple of delays due to extenuating circumstances, this year's project milestones were met. This accomplishment is particularly notable given that several of the projects were delayed by a longer than anticipated recruitment process. Project output included 20 journal publications, 8 of these in high impact journals, the *Nature* group and *Science Advances*.

I enjoyed meeting the new wave of early career researchers via video at the Centre's science seminar in early May 2018. Their research is providing new insights on the Southern Hemisphere and its connectivity to equatorial and Northern Hemisphere coupled ocean-atmosphere systems. I look forward to hearing more from our new Postdoctoral Fellows as they report on project findings over the next few years. I commend the Centre for its contribution to developing capability in the important field of climate science.

Our newly formed international Advisory Committee attended the science seminar and met with the Centre Steering Committee in early May. Advisory Committee members provided valuable feedback to our project leaders during the seminar project presentations. The Committee, with its depth of experience in climate research, made a worthwhile contribution to the joint Committee discussion of the Centre's draft science plan, due to be released in late September 2018.

I look forward to the next year of CSHOR.

Kind regards,

Dr Susan Avery

Steering Committee Chair

July 2018

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Acknowledgments

The Centre acknowledges the valuable assistance of the following individuals and organisations during the first year of CSHOR's scientific research program.

Partners

Qingdao National Laboratory for Marine Science and Technology (QNLM)

Commonwealth Scientific and Industrial Research Organisation (CSIRO)

University of New South Wales (UNSW)

University of Tasmania (UTAS)

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1 Executive summary

The first year of operations at the Centre demonstrated the importance of strategic partnerships in delivering outstanding new science and communicating that science to broader scientific and public audiences. A quick summary of highlights in research and communication as well as a summary of recognition of CSHOR work is presented in this executive summary.

1.1 Research achievements

Exciting findings emerged during the first year of CSHOR, resulting in 8 high profile research articles published by the *Nature* group (7) and Science Advances (1). In total, there were 20 publications.

During the very early days of the Centre, we published a *Nature Climate Change* paper on the increasing rate of global mean sea-level rise during 1993-2014 (Chen et al., 2017). The paper examined the contribution of thermal expansion, due to heat uptake, to global mean sea level based on various observation and data assimilation products.

In a paper published in *Nature Climate Change* (Wang et al., 2017a) it is demonstrated that extreme El Niño frequency increases linearly with the GMT towards a doubling at 1.5 °C warming. This increasing frequency of extreme El Niño events continues for up to a century after GMT has stabilized, underpinned by an oceanic thermocline deepening that sustains faster warming in the eastern equatorial Pacific than the off-equatorial region.

A *Nature Communication* paper shows that, the extreme pIOD frequency is projected to increase linearly with the GMT but approaches a maximum as the GMT stabilises (Cai et al., 2018a), in stark contrast to a continuous increase in the extreme El Niño frequency long after the GMT stabilisation.

A study based on previous Argo float deployments, published in *Nature Climate Change* (Gao et al., 2017) shows that wind-driven changes in formation and subduction of Subantarctic Mode Water in the Southern Ocean can explain the large increase in ocean heat content in the southern hemisphere oceans.

The results from a study published in *Science Advances* (Silvano et al., 2018) suggest that increased glacial meltwater input in a warming climate will both reduce Antarctic Bottom Water formation and trigger increased mass loss from the Antarctic Ice Sheet, with consequences for the global overturning circulation and sea level rise.

A study recently published in *Nature* (Rintoul, 2018) shows how the large-scale circulation of the Southern Ocean, which is of great importance to global climate, emerges from dynamics that play out on local and regional scales, catalysed by topography. Another paper in the same issue of *Nature* (Rintoul et al., 2018) assesses how Antarctica and the Southern Ocean will change over the next 50 years under high and low greenhouse gas emissions scenarios.

Earlier this year, 11 deep Argo floats supplied by collaborators from the USA, Japan and France were deployed from the RV *Investigator* and all are working successfully. This is the first deployment of deep Argo floats in the Southern Ocean.

A science plan, outlining the fundamental scientific research the Centre will carry out over the next 5 years, will be finalised by September 2018.

1.2 Communication Highlights

Communication is an important component of the CSHOR activities. The formation of the Centre and its official launch on 22 May 2017 was reported by the Australian Broadcasting Commission (ABC), Medianet, CISION PR Newswire, South Wind and Eco Voice. The CSHOR website went live in March, 2018. It is a valuable entry point to CSHOR and enables staff to share research highlights.

The Centre science was highlighted through a special session convened by three Centre scientists (Drs Santoso, Wang and Zhang) at the Australian Meteorological and Oceanographic Society 12th International Conference for Southern Hemisphere Meteorology and Oceanography (AMOS-ICSHMO 2018) held at UNSW Sydney in early February.

Also in February, the Sydney Morning Herald (SMH) interviewed Dr Steve Rintoul regarding new results from research conducted on the RV *Investigator* that demonstrated a shift in a decades-long trend towards fresher, less dense water off Antarctica. The SMH article by Peter Hannam can be found through this link.

The CSHOR Hobart office hosted the CSHOR Science Seminar and a joint CSHOR Steering and International Advisory Committee Meeting on 3 and 4 May, 2018. Over 40 guests attended the seminar, including the CSHOR Steering and Advisory Committees. Advisory Committee Members commented that, 'CSHOR is an excellent team and the science seminar is a great display. The presentations addressed important key questions and highlighted collaboration with other institutions'. Read more at this link.

CSHOR Science Seminar 3 May 2018

Additional communication highlights include:

- The Hobart Mercury Newspaper published a full page article on 7 May, 2018 introducing CSHOR's Postdoctoral Fellows.
- A *Nature* article published in June (Rintoul et al. 2018) was referred to in *The Conversation* report on the decline of the Antarctic Ice Sheet over the last 25 years. Rintoul et al. presented two narratives on the future of Antarctica and the Southern Ocean, from the perspective of an observer looking back from 2070.
- Coming up in early August, the Centre will host a booth highlighting CSHOR research at the Australian Antarctic Festival in Hobart. CSIRO Marine Laboratories will be open to the public over the 4 days' of the festival.

1.3 Awards and special mentions

The Centre won an award in the category of "Achievement in International Talents and Knowledge Introduction and International Collaboration" at China's 16th International Talents Exchange Meeting held in Shenzhen in April. CSHOR was the only winner for the category and the only winner from the Shandong province.

Prof TAN 15 April 2018

The award, established in celebration of the 40th Anniversary of China's Reform and Opening-Up Policy, was received on behalf of CSHOR by Prof Gongke TAN. Prof TAN is Director, Department of International Affairs at QNLM, China and Director of the Centre for International Cooperation at the First Institute of Oceanography, State Oceanic Administration, China (FIO), and a CSHOR Steering Committee Member. The Chinese government established 40 awards in total.

2 Project performance and highlights

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)

2.1.1 Research activities

It has been a fruitful year with 11 papers produced (9 published/in press), mostly led by members of this project, with 1 paper published in *Nature Climate Change* and 1 in *Nature Communication*. Another *Nature Climate Change* paper is under review. Also, a review paper on "ENSO Complexity" (Timmermann et al., 2018) by a large group of international ENSO researchers is due to appear this year in *Nature* (accepted during reporting period, and currently under embargo). Drs Wenju Cai, Agus Santoso, and Guojian Wang, as well as Dr Xuebin Zhang (project 6 leader) contributed to the paper. The participation of CSHOR members in this review paper signifies the significant contribution of CSHOR to ENSO research at an international level.

Our project members participated in various national and international workshops and conferences (Appendix C), either as presenters, session conveners, organisers, or combination of these. As an example of our contribution to enhancing international collaboration, Dr Wenju Cai held a "Tropical Interbasin Interactions: a review" workshop in Xiamen, China this January. The workshop was attended by many leading experts in this area (e.g., Tim Li from University of Hawaii, Dr Matthieu Lengaigne from IPSL in France, Dr Jong-Seong Kug from POSTECH in South Korea, Dr Shayne McGregor from Monash University in Australia, Prof Jin-Yi Yu from UC Irvine, and Prof Yan Du from South China Sea Institute of Oceanology). This workshop produced the first draft of a review on tropical interbasin climate interactions which will be submitted to either *Science* or *Nature*. Drs Agus Santoso, Guojian Wang, and Benjamin Ng will all be involved in this project. At a national level, Dr Santoso organised an ENSO Dynamics workshop in November 2017 at UNSW which was attended by 25 Australian ENSO researchers from Bureau of Meteorology, CSIRO, Monash University, and The University of Tasmania. The organising members include Dr Harry Hendon (Bureau of Meteorology), Prof Matthew England (UNSW, project 4 leader), and Assoc Prof Dietmar Dommenget (Monash University). The workshop report has been submitted as an article to the *Bulletin of the American Meteorological Society* (BAMS) and is currently under review.

2.1.2 Project performance against milestones

Most project milestones were met, apart from an outstanding staff appointment noted in milestone 1, and a deliverable specified in milestone 5 which is on track but slightly delayed due to new project opportunities requiring immediate attention (AGU monograph by M. McPhaden, A. Santoso, W. Cai; a review paper on ENSO-IOD by Santoso et al. commissioned by *Nature Communications*; paper

revision by Santoso et al. for the *Bulletin of the American Meteorological Society*; Cai et al. new submissions to *Nature* journals - all of which have not been included in the last quarterly report). Cai et al. (2018) perspective paper on the impact of model biases on future projections of extremes is also still under an unusually long review process in *Nature Climate Change* but is hoped to be returned for revision within the next few months.

Milestone 1: Recruit research scientists

The research scientist and 1 postdoctoral fellow have been appointed. A suitable candidate for the second postdoctoral position was not found in the last round of advertisements. The position will be re-advertised and hopefully filled by the beginning of October 2018.

Milestone 2: Understanding the ultimate risk of extreme El Niño associated with a 1.5˚C warming target

We discovered that the frequency of extreme El Niño events at 1.5 °C warming doubles that of the pre-industrial level, and continues to increase long after stabilization of the 1.5 °C warming. During the transient increase of CO2, the frequency of extreme El Niño events evolves linearly with the rising global mean temperature (GMT), conveying a simple but powerful message that any increase in CO2 directly leads to a higher risk of an increased frequency of extreme El Niño events. The continued increase in extreme El Niño frequency long after the GMT stabilization suggests a higher risk of extreme El Niño to future generations and highlights the need to take into account the greater risks beyond the transient period.

The dynamical processes responsible were explored. We have documented these findings and the associated mechanism in a paper published in *Nature Climate Change*. This piece of work leads to another study looking at the impacts of 1.5 °C warming ("peak and decline" emission scenario) on extreme positive Indian Ocean Dipole (pIOD) events. It is found that the frequency of extreme pIOD increases linearly with GMT during transient period and plateaus thereafter. The result is published in *Nature Communications*.

Wang, G. J., Cai, W. J., Gan, B. L., Wu, L. X., Santoso, A., Lin, X. P., Chen, Z. H., & McPhaden, M. J. (2017). Continued increase of extreme El Niño frequency long after 1.5 degrees C warming stabilization. *Nature Climate Change, 7*(8), 568-572.

Cai, W., Wang, G., Gan, B., Wu, L., Santoso, A., Lin, X., Chen, Z., Jia, F., & Yamagata, T. (2018). Stabilised frequency of extreme positive Indian Ocean Dipole under 1.5 °C warming. *Nature Communications, 9*(1), 1419.

Milestone 3: Assessing the impact of model biases on projected increase in frequency of extreme positive Indian Ocean Dipole and extreme ENSO events

A paper was published in *Journal of Climate* examining the impact of well-known biases in the CMIP5 models to the projected increase in frequency of extreme pIOD events. The study suggests that there are potentially a number of emergent constraints that may infer an overestimation (e.g., IOD amplitude) or an underestimation (e.g., thermocline depth over eastern equatorial Indian Ocean) for projected frequency of extreme PIOD.

An invited perspective piece on the impacts of systematic model biases on projected Indo-Pacific climate extremes has been submitted to *Nature Climate Change*. However, the review process has taken unusually longer than expected.

Toward a better understanding of the impact of model bias in ENSO and IOD simulation is the need to explore the processes that are not adequately resolved by current generation of models. A study that is recently published in *Climate Dynamics* uses a high resolution ocean model coupled to simple atmosphere model to examine the effect of tropical instability waves (TIWs), which are not well represented in climate models, on ENSO irregularity. It was found that TIWs show significant effect (20-70%) relative to the effect of atmospheric noise, indicating the need for a higher ocean model resolution for improved ENSO simulations.

Wang, G. J., Cai, W. J., & Santoso, A. (2017). Assessing the Impact of Model Biases on the Projected Increase in Frequency of Extreme Positive Indian Ocean Dipole Events. *Journal of Climate, 30*(8), 2757-2767.

Holmes, R. M., McGregor, S., Santoso, A., & England, M. H., (2018). Contribution of Tropical Instability Waves to ENSO Irregularity. *Climate Dynamics*, in press.

Milestone 4: Examination of the characteristics of ENSO extremes and the strong 2015/16 El Niño

The 2015/16 El Niño is an extreme event that is distinct to the previous extreme El Niño in 1982/83 and 1997/98. A review paper has been published in *Reviews of Geophysics* documenting the different characteristics of ENSO extremes. The paper establishes the 2015/16 El Niño as the first extreme El Niño in the 21st Century, discusses the state of understanding on ENSO extremes and provides a list of indices that can be used to characterise such events.

The new findings in this paper has inspired another study focusing on the definition of extreme El Niño event highlighting why a threshold of 5 mm per day of Niño3 rainfall can well represent extreme El Niño events. The paper also assesses the impact of extreme El Niño occurrences on long-term trend and its influence on projected frequency of extreme El Niño.

Other studies on this topic include a heat budget analysis of the Niño3.4 region for the extreme El Niño events which has been published in *Climate Dynamics*. Another study on the impact of strong El Niños on air temperature over Indian Ocean-rim countries has also been published in *Climate Dynamics*. Further, the peculiarity and the challenge in predicting the 2014-2016 El Niño evolution instigated an ENSO dynamics workshop that was organised by Dr Santoso and involved several colleagues at the Australian Bureau of Meteorology and universities, leading to a paper that has been submitted to the *Bulletin of the American Meteorological Society*.

Santoso, A., McPhaden, M. J., & Cai, W. (2017). The Defining Characteristics of ENSO Extremes and the Strong 2015/2016 El Niño. *Reviews of Geophysics, 55*(4), 1079-1129.

Cai, W., Wang, G., Santoso, A., Lin, X., & Wu, L. (2017). Definition of Extreme El Niño and Its Impact on Projected Increase in Extreme El Niño Frequency. *Geophysical Research Letters, 44*(21), 11,184-111,190.

Abellán, E., McGregor, S., England, M. H., & Santoso, A. (2017). Distinctive role of ocean advection anomalies in the development of the extreme 2015–16 El Niño. *Climate Dynamics*.

Herold, N., & Santoso, A. (2017). Indian Ocean warming during peak El Niño cools surrounding land masses. *Climate Dynamics*.

Milestone 5: Investigating climate drivers of Indonesian Throughflow variability in observation and CMIP5 models

Understanding the interactions between ENSO and IOD requires a better understanding of Indonesian Throughflow (ITF) variability, as the ITF connects the Indian and Pacific Oceans. There are multi-timescales in the variabilities in the transport of Indonesian Throughflow (ITF), including seasonal, interannual, decadal and multi-decadal signals associated with climate drivers. Dr Santoso is at present analysing a set of CMIP5 models to understand how ITF variability and its relationship with ENSO and IOD are represented in these models. In addition, a review paper on inter-basin tropical climate interactions led by Dr Wenju Cai is underway. The paper stems from a workshop in Xiamen, China early this calendar year that Dr Cai organised to initiate the review to address how modes of tropical climate variability such as ENSO and IOD interact and are influenced by air-sea processes outside their respective basins. Several studies have examined this issue in the last decade or so, and thus it is necessary to carry out a review given the complex processes involved and in light of recent development on the projections of extreme climate events. About 15 experts in the field were invited to present at the workshop and are currently working on a first draft of the review paper.

Milestone 6: Exploring possible modulation of decadal tropical Pacific condition on central Pacific and eastern Pacific El Niño

Given that central Pacific El Niño is occurring more often in recent decades, and the recent 2015/2016 extreme El Niño produces strong SST variability in central Pacific, it is necessary to explore possible modulation of decadal tropical Pacific condition on the two types of El Niño.

The dynamical processes responsible were explored. We have documented these findings and the associated mechanism in a paper published *in Geophysical Research Letters*.

Zhong, W. X., Zheng, X. T., & Cai, W. J. (2017). A decadal tropical Pacific condition unfavorable to central Pacific El Niño. *Geophysical Research Letters*, 44(15), 7919-7926.

Milestone 7: Collecting data and conducting experiments for Year 2 projects

Observational and model collections, as well as numerical experiments are progressively being conducted for future projects.

2.2 Project 2: Indo-Pacific interbasin exchange

Project leader – Dr Bernadette Sloyan (CSIRO)

2.2.1 Research activities

We successfully recruited a new research scientist and a postdoctoral fellow, Drs Beatriz Peña-Molino and Océane Richet, respectively, to the project. Dr Peña-Molino joined the project in November 2017 and Dr Richet in February 2018.

Our project members have participated in a number of national and international conferences and workshops (Appendix C); providing international exposure and recognition of the CSHOR Indo-Pacific interbasin exchange project. Drs Susan Wijffels and Bernadette Sloyan participated in the CLIVAR Indian Ocean Observation System review meeting. The Indian Ocean Observation System is undertaking a systematic review of the observing system for current and future science and application requirements. At the Northwestern Pacific Ocean Circulation and Climate Experiment (NPOCE) meeting, Dr Wijffels (represented by Dr Ming Feng) presented recent work on the analysis of the 7-year mooring time series data in the Ombai Strait that combines data from 2003-2006 and 2011-2015. Dr Océane Richet presented work on the application of tidal forcing in high resolution models and our plans to add tidal forcing to our high-resolution region model.

2.2.2 Project performance against milestones

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

Milestone 1: Understanding the response of the ITF and regional seas to intraseasonal - interannual forcing: collation of existing data

We used 25 years of Advanced Very High-Resolution Radiometer (AVHRR) data from NOAA Polar Orbiting Environmental Satellites, received by 6 Australian and 2 Antarctic reception stations, to construct a detailed climatology of sea surface temperature (SST) around Australasia. The data have been processed following international GHRSST protocols to help reduce instrument bias using in situ data, with only night-time nearly cloud-free data used to reduce diurnal bias and cloud contamination. A pixel-wise climatology (with four annual sinusoids) and linear trend are fit to the data using a robust technique and monthly non-seasonal percentiles derived. The resulting Atlas, known as the SST Atlas of Australian Regional Seas (SSTAARS), has a spatial resolution of ~2km and thus reveals unprecedented detail of regional oceanographic phenomena, including the footprint of the seasonal boundary current flows and standing mesoscale features in the Indonesian Seas. The Atlas (and associated statistics) will provide a benchmark for our high-resolution ocean models and spatial interpolation of the mooring data. A manuscript has been accepted subject to revision.

The Australian Integrated Marine Observing System (IMOS) Ombai Strait and Timor Passage mooring data (2011-2015), including the coastal shelf data have been processed and collated into a 4-year time-series. The International Nusantara Stratification and Transport (INSTANT) Ombai Strait and Timor Passage mooring data (2004-2006) have been reprocessed using the techniques applied to the Australian Integrated Marine Observing System (IMOS) mooring data. The combine INSTANT

and IMOS mooring data provide a 7-year time-series data set that will be used to investigate the interannual variability of the transport in these important Indonesian Throughflow passages.

The coastal satellite sea level anomaly (SLA) data from the AVSIO X-track (https://www.aviso.altimetry.fr/index.php?id=3047) along-track data has been downloaded for the Indonesian Seas region. This data combines numerous satellite altimetry products (TOPEX/Poseidon, Geodat Follow On, Jason-1,2,3, Envisat, and Saral/Altika) resulting in a 25-year (1993-2018) SLA time-series data set. We have undertaken additional processing of the time-series data to remove high frequency noise.

The XBT data set has been updated to new data along the Indian, Indonesian Sea and western Pacific sections. These data now include data to 2018.

We have also been active participants in international efforts to build and maintain the observational data records via chairing and attending international ocean observing science planning and advocacy meetings, including lead authorship on a number of supported OceanObs 19 whitepapers.

A paper by Wijffels et al. entitled, 'A fine spatial scale sea surface temperature atlas of the Australian regional seas (SSTAARS): seasonal variability and trends around Australasia and New Zealand revisited', has been accepted by *J. Marine System*.

Milestone 2: Understanding the response of the ITF and regional seas to intraseasonal - interannual forcing: Assessment of interannual variability

The Ombia Strait is a key exit passage of the Indonesian Throughflow to the Indian Ocean. The combined INSTANT and IMOS moored observations extend our record of the Ombia Strait to 7.5 years. From the combined time-series we have found that the Ombai Strait continues to feature strong baroclinity over the 7.5-years with changing vertical structure across all time-scales due to wave dynamics; higher frequencies being more barotropic and lower frequencies more mode 1-like. This change in dominance between barotropic and baroclinic has a strong impact on the relationship between heat flux and volume transport. Thus at the intraseasonal to interannual timescales it appears that volume transport is a poor proxy for heat transport. A manuscript describing these finding is now in preparation.

The combination of the INSTANT and IMOS Timor Passage mooring data is more difficult than at the Ombai Strait site given the complexities in constructing transports where we have shelf records, site changes and eddy recirculations to deal with. Here we started to attempt to unravel these issues through an analysis of the along-track coastal altimetry data set. At the IMOS mooring site, which lie along a ground track, we have found that the weakest surface velocities are found during the northwest monsoon (December to March) and the strongest during the southeast monsoon (May to September). We are beginning to extend the analysis of the coastal altimetry to the west to the INSTANT mooring site. We are beginning to extend the analysis of the coastal altimetry to the west to the INSTANT mooring site.

We have also investigated the role of the Indonesian Throughflow on the heat transport of the Indian Ocean. The interannual-decadal variations of the meridional temperature transport in the Indian Ocean are examined using an eddy-resolving global ocean circulation model for the period 1979-2014. We found that the Indian Ocean meridional temperature transport is highly influenced by remote forcing from Pacific El Niño–Southern Oscillation (ENSO) through both oceanic and

atmospheric waveguides, with stronger southward temperature transport during La Niña and weaker transport during El Niño. A paper examining Pacific influences on the meridional temperature transport of the Indian Ocean has been submitted to the *Journal of Climate*.

Milestone 3: Regional dynamics including the gating of the ITF and impact of tidal mixing on water masses and local heat budget

High performance computational resources have been established at the Australian National Computing Infrastructure (NCI) for this project.

We have setup a high-resolution model of the Indonesian Seas at 10 km, 4 km, and 1 km horizontal grids. The 4 km model has been extensively run using mean 2003-2006 boundary conditions. The boundary conditions are taken from a global 10 km model. Using the 4 km model we have a long control run and 5 perturbation experiments, that were designed to investigate the ocean dynamics that partition the Indonesian Throughflow into the three major exit passages: Lombok, Ombai and Timor. We are currently analysing these model runs.

Building on the mean 4 km model we have now setup a model with a mean annual cycle forcing. This will be used, with the observation data sets, to investigate the annual cycle of the Indonesian Seas.

In addition, we are actively involved in the COSIMA effort and are now assessing the simulation of the Indonesian Seas in this model.

2.3 Project 3: Coupled Warm Pool Dynamics in the Indo-Pacific

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

2.3.1 Research activities

We have successfully recruited a postdoctoral fellow, Je-Yuan (Andy) Hsu, who joined the project in February 2018.

We have accomplished a pilot study of fast profiling floats off northwest Australia, with the assistance of the Royal Australian Navy, which have gained us valuable experience in float preparation and communication, as well as sampling strategy and profiling data quality control. We have signed a research agreement with the First Institute of Oceanography, SOA, to conduct joint field work in November 2018, to deploy a Bailong buoy and a cluster of profiling floats northwest of Australia, as an effort to contribute to the Year of Maritime Continent international program. The planning of the field campaign has been well progressed.

We have also started to run the Bureau of Meteorology version of the ACCESS-S1 seasonal forecast model to simulate intra-seasonal weather systems in the eastern Indian Ocean warm pool off northwest Australia. We have tested model sensitivity to different air-sea coupling frequencies and ocean background mixing coefficients, in terms of diurnal SST variations and air-sea fluxes. The model results are being assessed with the TRMM satellite precipitation data and MTSAT-1R satellite SST diurnal variations.

In other areas, we have reviewed recent research progresses on the interannual/decadal variations and centennial changes of the Indonesian Throughflow. We have devoted efforts in understanding

the role of the increased Indonesian Throughflow heat transport during the recent climate change hiatus period on the warming trend of the southern Indian Ocean, with 1 paper accepted for publication in *Geophysical Research Letters.* A paper examining Pacific influences on the meridional temperature transport of the Indian Ocean has been submitted to the *Journal of Climate*. We have also advanced our knowledge on sea surface salinity variations in the eastern Indian Ocean warm pool on different time scales. In addition, we have improved our understanding of the impact of the 2015/2016 El Niño on the northern Australia region, especially on the extreme marine heatwave events. We have also contributed the construction of a high-resolution SST climatology for the Australian region.

Publications from this project:

Zhang, Y., Du, Y., & Feng, M. (2017). Multiple Time Scale Variability of the Sea Surface Salinity Dipole Mode in the Tropical Indian Ocean. *Journal of Climate*, 31(1), 283-296.

Benthuysen, J. A., Oliver, E. C. J., Feng, M., & Marshall, A. G. (2018). Extreme Marine Warming Across Tropical Australia During Austral Summer 2015–2016. *Journal of Geophysical Research: Oceans*, 123(2), 1301-1326.

Feng, M., Zhang, N., Liu, Q., & Wijffels, S. (2018). The Indonesian throughflow, its variability and centennial change. *Geoscience Letters*, 5(1), 3.

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*, in press

2.3.2 Project performance against milestones

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

Milestone 1: Acquisition and deployment 2 pilot profilers, establish the satellite communication and data handling system and testing of two-way communications for at-sea remissioning

Two pilot profiling floats were purchased in April 2018, one equipped with RBR CTD sensors and the other with Seabird sensors. Both floats were deployed off northwest Australia from a Royal Australian Navy vessel, and delivered more than 60 and 35 days of temperature and salinity profiling data, respectively. We have evaluated two-way satellite communications by trying different vertical sampling strategies. It appears that the RBR sensors provided more reliable temperature and salinity measurement and RBR float has a longer battery life. Data quality control was performed and the floats have captured nice diurnal SST variations and associated mixed layer depth variability. The floats have also captured strong semidiurnal internal tidal signals off the northwest shelf of Australia, which may enhance vertical mixing and affect the upper ocean heat balances.

Milestone 2: Rerun the BoM's new coupled forecast model for several historical MJO events, archiving subdaily ocean and air-sea flux output for analysis and benchmarking the model behaviour against satellite data

The BoM ACCESS-S1 model is reconfigured at the NCI machine to simulate MJO related coupled processes in the eastern Indian Ocean warm pool. A large MJO event passed the Indo-Pacific warm pool from the end of December 2009 to January 2010. The precipitation rate can be more than 1.5 mm/hr, as measured by the TRMM satellites. One coupled model simulation was starting from Dec 9th 2009. Comparing to the measurements of SST taken by the MTSAT-1R satellites, the model overestimates the SST in the southeast Indian Ocean by ~ 1 °C, especially between 115—125 °E. The observed convective system occurring at 120 °E on Dec 13th 2009 can be captured in the model simulation. However, the simulated convective system has smaller spatial extent on Dec 13th 2009 than the satellite measurements. It also continuously propagates westward to 110 °E, unlike the observations. The overestimated SST may result in too much latent heat flux transferred from the ocean to atmosphere for the development and motion of convection in the model. Future work will continuously investigate the SST in the warm pool and the upper ocean response to the atmosphere convection.

Milestone 3: Further development and planning of the second phase field program, including acquisition and programming of 5-8 profilers, and sourcing a suitably configured platform for the atmospheric surface observations, and arrangements for vessels for deployment and (if needed) recovery

After the successful deployment of the pilot profiling floats, 4 more Alamo floats have been ordered. In addition, two EM-APEX profiling floats have also been ordered, which would provide information on the upper ocean mixing that are important for the diurnal SST and mixed layer evolution.

We have signed a research agreement with the First Institute of Oceanography to conduct joint field work in the eastern Indian Ocean warm pool and the FIO is going to provide the project with one Bailong buoy for the duration of the field program. The Bailong buoy is equipped with surface meteorology measurements required for the project.

A contract with an external contractor to supply a suitable vessel for the buoy and profiling float deployments is pending. The field program is planned for November 2018.

Milestone 4: Explore, using remotely sensed data, diurnal wind, cloudiness and SST variability in the region, particularly exploiting the data collected by the fast sampling Himawari-8 satellite

Working with research scientist, Dr Zhi Huang, from Geosciences Australia, we have archived the Himawari-8 satellite SST data onto the GA machine. We have started to assess diurnal SST variations observed from the Himawari satellite and their responses to the MJO cycle during the two austral summers, 2015-2016 and 2016-2017. Their relationship with wind and solar radiation variability have been assessed and results have been presented at the AMOS conference and CSHOR workshop.

Milestone 5: Assessing responses of upper ocean temperature and salinity balances in the tropical Indian Ocean, including the eastern Indian Ocean warm pool, to the impacts of ENSO, IOD, and MJO

Using ECCO model results, we have assessed the role of the increased Indonesian Throughflow heat transport during the recent climate change hiatus period on the warming trend of the southern Indian Ocean, with 1 paper accepted for publication in *Geophysical Research Letters.* We have also analysed the CSIRO OFAM model simulation during 1979-2014 to assess the contribution of the Indonesian Throughflow on the southward heat transport in the Indian Ocean and identified a concerted response to ENSO variability through both oceanic bridge and atmospheric teleconnection. The climate change impact on the Indian Ocean heat transport is also being assessed.

We have advanced our knowledge on sea surface salinity variations in the eastern Indian Ocean warm pool on different time scales, in the context of a sea surface salinity dipole mode. In addition, we have improved our understanding of the impact of the 2015/2016 El Niño on the northern Australia region when the deep convection is shifted to the central Pacific and the Australian monsoon is weakened, especially on the occurrences of extreme marine heatwave events that cause significant ecological damage. The contribution of the MJO events on the peak of the marine heatwaves have been assessed.

In other areas, we have reviewed recent research progresses on the interannual/decadal variations and centennial changes of the Indonesian Throughflow. We have also contributed the construction of a high-resolution SST climatology for the Australian region.

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

Project leader – Prof Matthew England (UNSW)

2.4.1 Research activities

Two main research activities were completed during the first year of CSHOR prior to the commencement of postdoctoral fellows, Drs Veronica Tamsitt and Annie Foppert. In the first, coupled model experiments were configured and evaluated using a global coupled climate model with additional freshwater and salinification applied to the Southern Ocean to assess the influence of recent regional trends in surface salinity on temperature and sea-ice extent. This work is described under the milestones listed below. In the second project, described here, future projections of Antarctic ice shelf melting were developed using the Finite Element Sea Ice/Ice-Shelf Ocean Model (FESOM), forced by atmospheric output from CMIP5 models. The CMIP5 forcing was carefully chosen based on agreement with historical atmospheric reanalyses over the Southern Ocean; the best performing models are ACCESS 1.0 and the CMIP5 multi-model mean. Their output is bias-corrected for the RCP4.5 and RCP8.5 scenarios, and used to force the model. During the 21st Century simulations, we find that total ice shelf basal mass loss increases by between 41% and 129%. Every sector of Antarctica shows increased basal melting in every scenario, with the largest increases occurring in the Amundsen Sea. The main mechanism driving this melting is an increase in warm Circumpolar Deep Water on the Antarctic continental shelf. A reduction in wintertime sea ice

formation simulated during the 21st Century stratifies the water column, allowing a warm bottom layer to develop and intrude into ice shelf cavities. This effect seems to be overestimated in the Amundsen Sea because of a cold bias in the present-day simulation. Other consequences of weakened sea ice formation include freshening of High Salinity Shelf Water and warming of Antarctic Bottom Water. Furthermore, freshening around the Antarctic coast in the simulations causes the Antarctic Circumpolar Current to weaken and the Antarctic Coastal Current to strengthen.

2.4.2 Project performance against milestones

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

Milestone 1: Recruit postdoctoral fellows

Two postdoctoral fellows have been hired under this project: Dr Annie Foppert from University of Rhode Island commenced in January 2018, and Dr Veronica Tamsitt from Scripps Institute of Oceanography / UCSD commenced in in April 2018.

Milestone 2: Configure model simulations to explore the dynamics and processes controlling the rate of surface warming in the Amundsen-Bellingshausen Seas

Experiments were configured using a global coupled climate model (ACCESS1.0) with additional freshwater and salinification applied to the Southern Ocean to assess the influence of recent regional trends in surface freshening, and increases in salinity. The simulations set out to explore the impact of multi-decadal salinity changes as a result of processes including precipitation minus evaporation, sea-ice variations and ice melt. The findings from these experiments are described below under milestones 3 and 4.

Global ocean-sea-ice simulations have also been configured across three different resolutions to explore this problem, at 1°, 0.25° and 0.1° horizontal resolutions. All simulations use the GFDL/NOAA MOM5 ocean model. The 1° version is based on the ocean-ice component of the coupled ACCESS-CM model. The 0.25° version is based on the Spence et al. (2014) model, and the 0.1° version is based on the model described in Spence et al. (2017) and Stewart et al. (2017). This high-resolution global 0.1° ocean-sea ice model is based on the GFDL CM2.6 coupled climate model (Griffies et al., 2015). The atmospheric forcing is derived from version 2 of the Coordinated Ocean-ice Reference Experiments (Large and Yeager, 2009) and includes full interannual variability over the historical era. The model does not include ice shelf cavities or tides. The 0.1° model horizontal resolution has 75 vertical levels chosen to maximise the resolution of the 1st mode baroclinic radius of deformation. Along the Antarctic continental slope, the model resolution in the zonal direction varies from 2.6-5.5 km. The meridional resolution is Mercator north of 65°S, but is capped at a minimum of 4.7 km south of this latitude. No mesoscale eddy parameterisations are employed, despite the fact that the first baroclinic Rossby radius of deformation in the model varies from 1.8-5.5 km along the Antarctic slope. The model's horizontal resolution is therefore insufficient to completely resolve the mesoscale eddy field in the region of interest.

In addition to these global models, a circumpolar version of the FESOM model was set up and integrated to explore the projected trends in ocean-ice shelf interactions around the Antarctic

margin; these experiments are also available to examine the surface warming in the Amundsen-Bellingshausen Seas.

Milestone 3: Select and refine the suite of models for latter components of project

In terms of the experiments configured with additional freshwater and salinification applied to the Southern Ocean, these simulations were attempted with zonal average forcing, and then later refined to include full spatial patterns of observed sea surface salinity trends, to explore the impact of multi-decadal salinity changes as a result of regional variations precipitation minus evaporation, sea-ice variations and ice melt. The findings from these experiments are described below under milestone 4.

Milestone 4: Analysis of the experiments regarding surface warming in the Amundsen-Bellingshausen Seas

We found that imposing regional surface salinity trends in a coupled climate model enables recent temperature and sea-ice trends to be captured, including warming in the Amundsen-Bellingshausen Seas. In sectors of freshening, there is a surface cooling and sea ice increase because of a reduction in ocean convection and weakened entrainment of warm subsurface waters into the surface ocean. In regions of increased salinity, such as the Amundsen-Bellingshausen Seas, the opposite occurs, with deeper mixed layers, and increased entrainment of warm subsurface waters into the surface. Remarkably, without any mechanical wind trend forcing, these simulations accurately represent the spatial pattern of observed surface temperature and sea ice trends around Antarctica. This highlights the importance of accurately simulating changes in Southern Ocean salinity to capture changes in ocean circulation, sea surface temperature, and sea ice. This work was published in the *Journal of Climate*.

Purich, A., England, M. H., Cai, W., Sullivan, A., & Durack, P. J. (2018). Impacts of Broad-Scale Surface Freshening of the Southern Ocean in a Coupled Climate Model. *Journal of Climate, 31*(7), 2613-2632.

Report on the early start of the 2018/19 milestones

Dr Tamsitt has completed analyses diagnosing Indian Deep Water pathways south of Australia. She has also coordinated and conducted analyses comparing air-sea heat fluxes and mixed layer depths from two moorings in key Subantarctic Mode Water formation regions of the Indian and Pacific. Dr Tamsitt has also begun a modeling project to understand the dynamics of Lagrangian upwelling hotspots in the ACC that will continue into the second half of 2018.

Dr Foppert has completed an analysis of observed storm track dynamics in the Drake Passage. This work looks at eddy-mean flow interactions in a wave activity flux framework and suggests mixed barotropic-baroclinic instability is occurring in the lee of a major submarine ridge; responsible for setting the observed regional eddy energetics pattern. Dr Foppert has also designed a research project and completed the initial analysis of hydrographic data to investigate mechanisms of cross-slope exchange and the spatial variability of eddy transport on the Antarctic continental slope. Dr Foppert has also begun to design a study to explore the ACC's time-dependent response to changes in wind forcing using numerical models.

2.5 Project 5: Southern Ocean observations and change

Project leader – Dr Steve Rintoul (CSIRO)

2.5.1 Research activities

A major highlight of the past year was the completion of a series of repeat hydrographic lines in the Southern Ocean. The voyage, carried out on the RV *Investigator,* collected full-depth measurements of a wide variety of physical, chemical and biological parameters. We re-occupied the complete SR3 line, as well as portions of three other repeat hydrographic sections. The data set will allow changes in temperature, salinity, oxygen, chlorofluorocarbons, carbon dioxide and trace elements and isotopes to be assessed throughout the full ocean depth.

During the voyage we also deployed a pilot array of Deep Argo floats, the first to be deployed in the Southern Ocean. Floats were contributed by the USA, France and Japan. The deep profiling floats will provide the first quasi-continuous measurements of full-depth profiles of temperature and salinity from the Southern Ocean. The floats therefore complement the longer but less complete time series of ocean change collected from ships.

Seven papers were published by the project in 2017-2018. Highlights include two papers published in the June issue of *Nature*. The first is a review of recent advances in understanding the dynamics of the Southern Ocean circulation. The study shows how the large-scale circulation of the Southern Ocean that is of great importance to global climate emerges from dynamics that play out on local and regional scales, catalysed by topography. The second paper uses the latest science to provide a holistic assessment of how Antarctica and the Southern Ocean will change over the next 50 years, considering 'high emissions' and 'low emissions' scenarios from the perspective of an observer in the year 2070. The paper has received worldwide media attention and was presented at a plenary panel event at the POLAR2018 conference in Switzerland.

Other research highlights from the past year include a study published in *Nature Climate Change* showing that wind-driven fluctuations in the thickness of the Subantarctic Mode Water layer dominate the recent increase in southern hemisphere ocean heat content; research published in *Science Advances* demonstrating that input of glacial meltwater can produce a positive feedback that enhances further basal melt of ice shelves, while also reducing formation of Antarctic Bottom Water; and two studies that provided new insights into the uptake and changing inventory of anthropogenic carbon dioxide in the Southern Ocean.

Rintoul, S. R. (2018). Global influence of localised dynamics in the Southern Ocean. *Nature* 558, 209-218.

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.

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).

Gao, L., Rintoul, S. R., & Yu, W. (2017). Recent wind-driven change in Subantarctic Mode Water and its impact on ocean heat storage. *Nature Climate Change*, 8, 58-63.

Langlais, C. E., Lenton, A., Matear, R., Monselesan, D., Legrésy, B., Cougnon, E., & Rintoul, S. (2017). Stationary Rossby waves dominate subduction of anthropogenic carbon in the Southern Ocean. *Scientific Reports*, 7(1), 17076.

2.5.2 Project performance against milestones

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

Milestone 1: Recruit CSOF5 Research Scientist

Dr Laura Herraiz-Borreguero arrived in June 2018 to take up the research scientist position. She returns to Hobart after completing a Marie Curie Fellowship in Denmark and the UK. Her expertise is in Southern Ocean observations, water mass formation, Southern Ocean circulation, and ocean – ice shelf interaction.

Milestone 2: Ice-capable profiling floats deployed in the Ross Gyre, in collaboration with the US and NZ

Ten floats were deployed successfully to study the circulation of the Ross Gyre, one of the most poorly-sampled regions of the Southern Ocean. The Ross Gyre study is a collaboration between CSHOR, Kevin Speer in the USA, and Mike Williams in NZ. The US and NZ partners also carried out research voyages that will contribute to quantifying the structure and strength of the gyre.

Milestone 3: Complete repeat hydrographic line south of Tasmania and deploy deep Argo pilot array to assess deep ocean change, in collaboration with ACE CRC

A highly successful multidisciplinary voyage on RV *Investigator* was carried out in January – February 2018. All voyage goals were achieved and a large number of additional stations were completed. We re-occupied the GO_SHIP SR3 line and portions of three other repeat lines at 150°E (P11), 62°S (S4) and 132°E. The voyage collected a wide variety of chemical measurements, including carbon parameters, chlorofluorocarbons, and trace elements and isotopes. We deployed 11 Deep Argo floats, the first floats deployed in the Southern Ocean that are capable of profiling the full ocean depth. We also deployed 4 surface carbon drifters for Japanese collaborators and 12 biogeochemical Argo floats for the US SOCCOM project. The combined data set will be used to detect and interpret changes of physical, chemical and biological variables throughout the full ocean depth.

Milestone 4: Voyage data quality controlled and ready for analysis; first deep Argo profiles assessed

Quality control of the data collected on the voyage is nearly complete and the data sets will be submitted to data centres soon. Preliminary assessment of the deep Argo profiles collected to date suggests that the floats are performing well.

Milestone 5: Publication of study investigating the sensitivity of bottom water formation to changes in forcing, as assessed from observations before and after calving of the Mertz Glacier Tongue

A study published in *Geophysical Research Letters* exploited the "natural experiment" that occurred following calving of the Mertz Glacier Tongue to assess the sensitivity of bottom water formation to changes in forcing. The regional icescape changed dramatically after the glacier tongue calved in February 2010. The size and ice formation rate in the Mertz Polynya decreased by about 50% after calving and a large volume of sea ice drifted into the area and melted, supplying fresh water to the surface ocean. Mooring records show that the density of shelf water formed in winter decreased sharply following the calving event, but the dense water leaving the shelf was still sufficiently dense to reach the sea floor in the deep ocean. A second, model-based, study showed that calving of the Mertz Glacier Tongue resulted in changes in ocean circulation that drove enhanced basal melt of nearby ice shelves.

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.

Cougnon, E. A., Galton-Fenzi, B. K., Rintoul, S. R., Legrésy, B., Williams, G. D., Fraser, A. D., & Hunter, J. R. (2017). Regional Changes in Icescape Impact Shelf Circulation and Basal Melting. *Geophysical Research Letters*, 44(22), 11,519-11,527.

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

Project leader - Dr Xuebin Zhang (CSIRO)

2.6.1 Research activities

It has been a successful year for the sea level project, with all project members on board and several manuscripts either finished or published, including one published in *Nature Climate Change*. Project collaborators include a team from UNSW led by Prof John Church, a UTAS team led by Prof Matt King, and Prof Xianyao Chen from QNLM/Ocean University of China. Several postdoctoral fellows and PhD students have been supervised jointly or are being recruited to join the project (e.g., 2 PhD students from Ocean University of China recommended by Prof Chen are scheduled to start their 2-year visiting study with us in August 2019, sponsored by the China Scholarship Council).

Over the past year our project members attended several national and international conferences and workshops, often chairing sessions or giving invited/keynote talks. For example, Dr Zhang gave a plenary talk on his high-resolution sea level projection work at the WCRP/IOC sea level conference in New York in July 2017. He was then invited to give a keynote talk on regional sea level projection at an international workshop organized by National Marine Data and Information Service (NMDIS), State Oceanic Administration of China in November 2017. In March 2018, Dr Zhang was invited to attend an "Understanding the relationship between coastal sea level and large-scale ocean circulation" workshop at the International Space Science Institute (ISSI), Switzerland. He give a talk on quantification of open ocean versus coastal sea level variance related to different climate modes. With a few international co-chairs, Dr Zhang convened a session on ocean heat content and sea

level at the 2018 AOGS Annual Conference in Honolulu in June 2018. He also presented a talk on projected changes of ocean gyre circulation and sea levels. With Drs Santoso and Wang (project 1), Dr Zhang also chaired the first CSHOR session at an international conference, the February 2018 AMOS/ICSHMO conference. He also presented a talk on the *Nature Climate Change* publication listed below.

Chen, X. Y., Zhang, X. B., Church, J. A., Watson, C. S., King, M. A., Monselesan, D., Legrésy, B., & Harig, C. (2017). The increasing rate of global mean sea-level rise during 1993-2014. *Nature Climate Change, 7*(7), 492-497.

2.6.2 Project performance against milestones

Most project milestones were met, with the exception of some delays to delivering milestones 4 and 5. Milestone 4 was held up because the postdoctoral fellow commenced his appointment later than planned and he has been mainly focused on delivering milestone 2. Proposed modelling experiments associated with milestone 4 will be completed by September 2018. Milestone 5 is delayed by 1 ½ months due to major flooding of UTAS offices during severe storm event in Hobart.

Milestone 1: Recruiting postdoctoral fellow

We recruited postdoctoral fellow, Dr Kewei Lyu, from the University of California, Irvine, he commenced his appointment in February 2018.

Milestone 2: Improved estimates of heat uptake and redistribution in the SO and associated sea level change, based on observations and models

We published a *Nature Climate Change* paper on the increasing rate of global mean sea-level rise during 1993-2014. This paper examined the contribution of thermal expansion, due to heat uptake, to global mean sea level based on various observation and data assimilation products, along with other contributions such as melting of Greenland and Antarctic Ice sheets. This paper drew great attention from both research community and the general public, which was widely reported via traditional and new social medias. It is ranked as the 95% percentile of the 72 tracked articles of a similar age in *Nature Climate Change*.

A *Journal of Climate* manuscript looking at ENSO-related interannual variations of global ocean heat content and underlying oceanic processes is currently under the 2nd review. The article provides novel insight on how ENSO events modulate global ocean heat content on interannual time scales.

We analysed multi-decadal oscillation in sea level and individual components, and presented the results at the 2018 AMOS/ICSHMO conference. A manuscript has been finished and is under internal review.

We analysed ocean heat uptake and redistribution in the Southern Ocean mainly based on CMIP5 models and available observations. We examined the relationship between projected future changes and present-day mean state biases, decomposing subsurface ocean temperature changes into heave and spiciness components, and relating them to surface atmospheric forcing (wind stress, heat and freshwater fluxes). The analysis is close to completion and is included in a draft manuscript targeting the *Journal of Climate*.

Milestone 3: Select and tune-up a suite of models (e.g., coarse- and high-resolution ocean models) for this project

Many numerical experiments have been proposed for this project, with the aim to separate the impacts of various forcing (e.g., wind vs freshwater; natural vs anthropogenic) on sea level and ocean dynamics in the Southern Ocean. Considering available computation resources and feasibility to finish all proposed numerical experiments, we selected to use: 1) a global ocean model (1/10 ^{o} and 1/4 ^{o}) based on our previous experience (1/10 ^{o} model has been used before in the CSIRO Ocean Downscaling Strategic Project led by Dr Zhang) and possible new development from the Consortium for Ocean-Sea Ice Modelling in Australia (COSIMA) led by Andy Hogg of ANU; 2) a Southern Ocean regional ocean sea ice model with different horizontal resolution (1^{o}, $1/3^{o}$, $1/6^{o}$, $1/12^{o}$) by collaborating with Drs Matt Mazloff and Bruce Cornuelle from Scripps Institution of Oceanography, UCSD, who have extensive expertise in Southern Ocean modelling and data assimilation.

Milestone 4: Numerical experiments to test sea level response to poleward shifting vs strengthening of westerlies

Some testing for the wind perturbation experiments with 1/10 o model has been done, and we are working on setting up similar experiments with the 1/6 o regional Southern Ocean model. It is hoped we will finish all wind perturbation experiments in coming months (subject to computation resources at NCI), and we will then analyse model output and draft a manuscript.

In the meanwhile, we carried out some closely-related analysis on this subject looking at horizontal ocean gyre circulation and its connection to sea level in the future climate based on CMIP5 climate models. It has been reported at the 2018 AOGS conference, and is currently being wrapped up into a *Journal of Climate* manuscript.

Milestone 5: Analysis of technique-specific uncertainties of Antarctic Ice Sheet mass flux time series

The UTAS team lead by Dr King has been working on examining basin-scale noise properties to determine appropriate noise models and trend uncertainties for improved basin-scale mass flux estimates. This milestone is delayed due to severe storms and associated flooding of UTAS and the researchers' offices in May. UTAS team is catching up on this and will deliver by mid-August.

3 Financial Management

3.1 Revenue

The Centre's revenue over a 5 year period is AU$20m. QNLM contribution is on track, while CSIRO's contribution at $1,049,911 is 64% of the 2017/18 annual budget (Figure 1). The -36% variance is the result of reduced labour and overheads expenditure in year 1 due progressive lag on new staff start dates. All appointments commenced by the 3rd quarter.

Life to date revenue is 27% at $5,395,269 with contributions from QNLM $4,000,000, CSIRO $1,084,354, University Partners $310,915 (Figure 2).

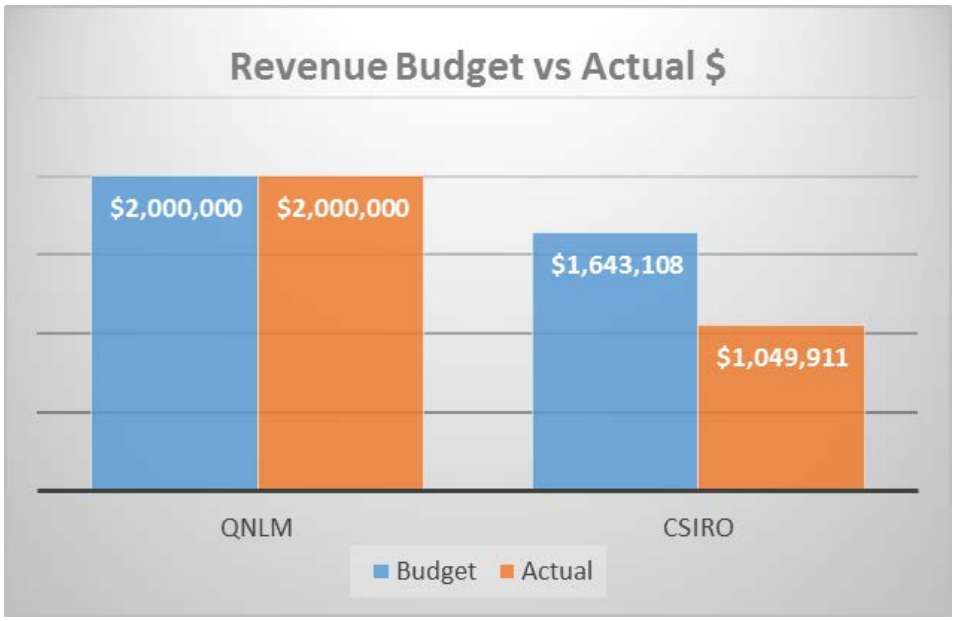

Figure 1 Revenue 2017/18: budget vs actual

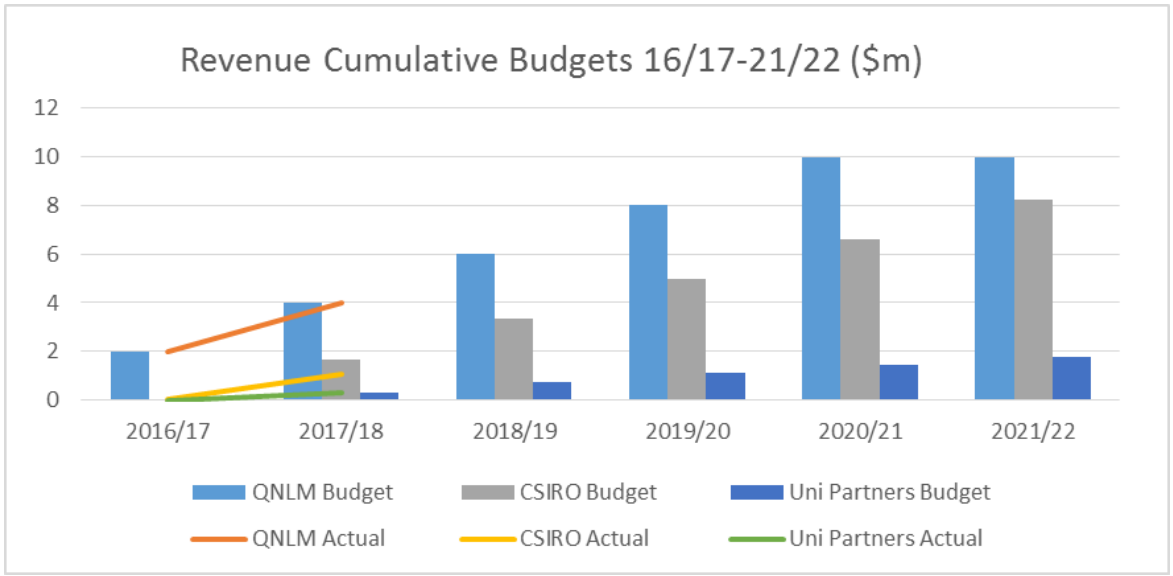

Figure 2 Revenue: cumulative budgets to 2021/22

3.2 Expenditure

Even though there was a delay as staff were recruited, the percentage range across the various parameters this financial year, such as labour, travel etc. (Figure 3), is still the same as the percentage range for the whole of the project life.

Total expenditure in 2017/18 was $2,757,601, approximately 72% of annual budget, split: QNLM $1,388,189; CSIRO $1,049,911; and Partner In-kind $319,501 (Figure 3). This returned a financial year underspent variance of $1,099,440 (-28%) in comparison of Actual vs Budget expenditure. The breakdown across each expenditure category as follows:

Labour & Overheads	-$1,040,686	underspent – due to recruitment delays
Operating Exp.	-$62,025	underspent – will be carried forward
Capital	+$53,271	overspent by $53,815 prepayment on 2018/19 floats
Partner In-kind	+$29,501	overspent

Partner Payments: CSIRO paid $300,000 to Partners in 2017/18 with $50,000 UTAS deferred to 2018/19.

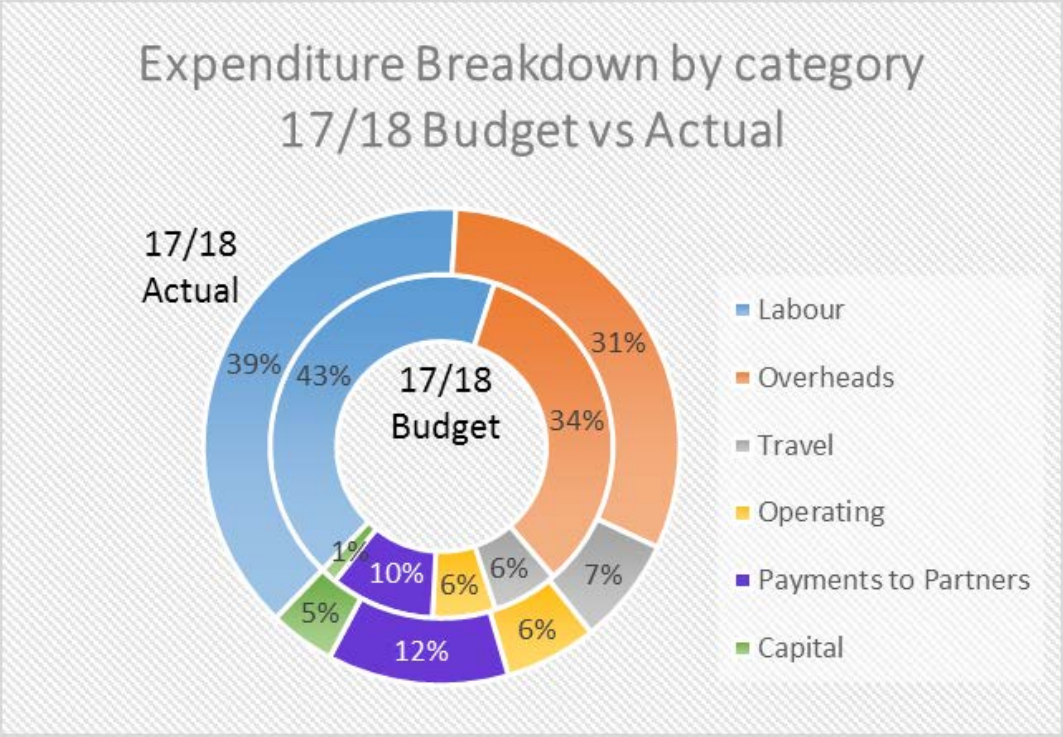

Figure 3 Expenditure 2017/18: budget vs actual

The cumulative Whole of Life Total Expenditure is $2,824,190, approximately 14% of total budget (Figure 4). Savings from recruitment delays and other operating under expenditure will be carried forward and use planned across remaining outyears.

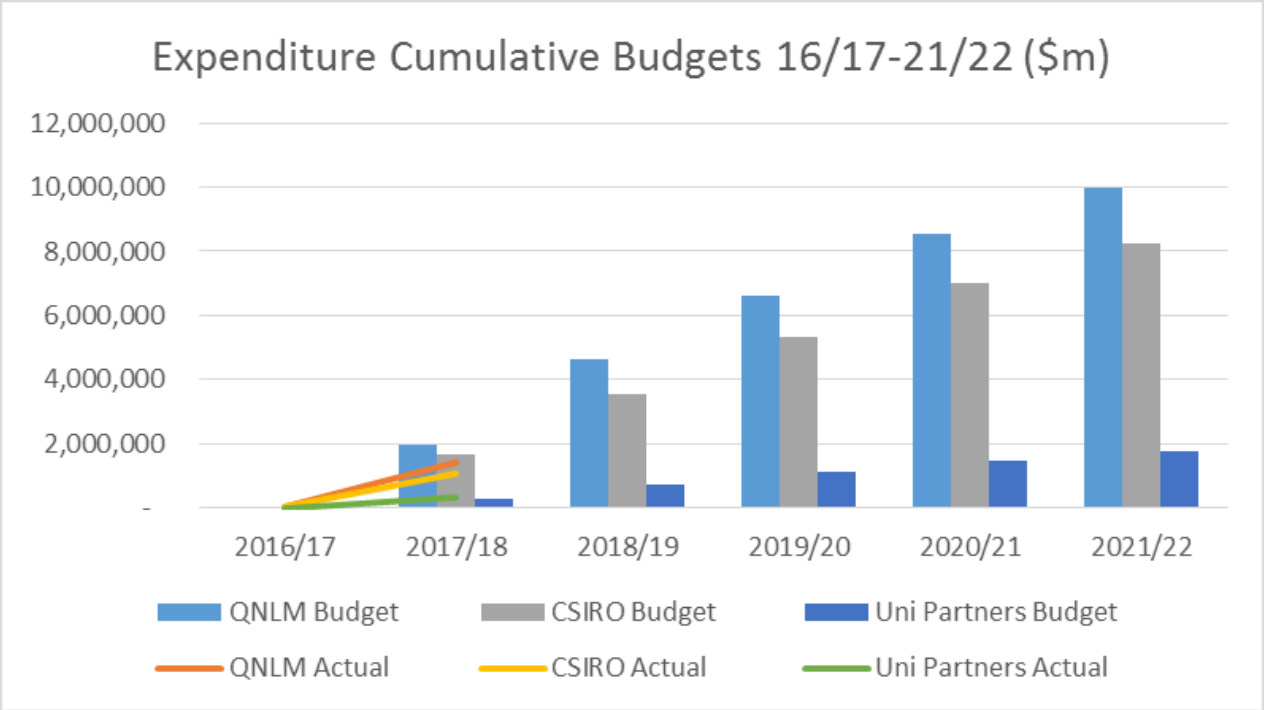

Figure 4 Expenditure: cumulative budgets to 2021/22

3.3 Partner in-kind contribution

For 2017/18 both Partners showed Actual contribution slightly ahead of annual budget (Figure 5).

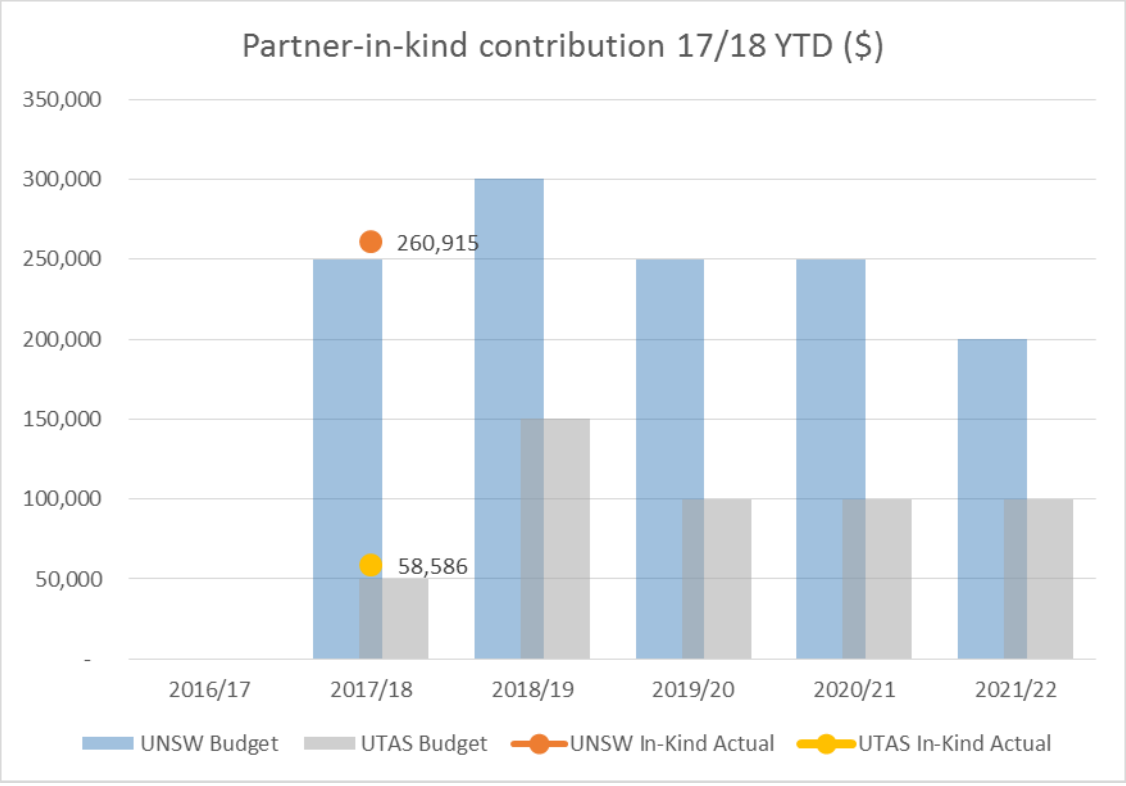

Figure 5 University partners 2017/18 in-kind contribution

4 Management and coordination

The Centre was established via a 5 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 2 representatives each from QNLM and CSIRO)
- Advisory Committee (6 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 on page 7. The Research Leadership Team consists of the Director and the Project Leaders listed in Appendix B.

The **CSHOR Steering Committee** met via teleconference on 18 January 2017 and face-to-face with the newly formed international **Advisory Committee** on 3 and 4 May 2018.

The **CSHOR Research Leadership Team** met on 4 October 2017, 7 December 2017, 2 March 2018 (science planning workshop with science and support staff) and 3 and 4 May 2018 (science seminar and joint Committee Meeting).

CSHOR Science Planning Workshop 2 March 2018

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 also met separately on 19 February 2018, 30 April 2018 and 30 May 2018.

The Director also attended several meetings at QNLM in Qingdao including internal budget planning meetings in November/December and the QNLM Annual Meeting in January.

5 Other activities

5.1 QNLM benchmarking exercise

QNLM representatives visited CSIRO on 6 and 7 December to conduct a benchmarking exercise with a view to improving the efficiency of QNLM management systems and tools, and to improve its ability to cooperate with other organisations, including CSIRO. The visit assisted QNLM to better prepare its staff for supporting the work of the Centre.

The delegation discussed the following topics with CSIRO representatives:

- staff development and promotion
- strategy and investment
- project monitoring and management
- capital expenditure
- online travel booking system and the associated reporting tool
- international travel approval system and the tool used to track travelling staff.

The delegation toured the RV *Investigator*, the Moored Sensor Systems Workshop, the Argo Laboratory and CSHOR offices.

Appendix A Recruitment

CSHOR Position	Name	Original Institution	C'ment date
Director	Wenju Cai	CSIRO	07/06/2017
Research Scientist – project 1 Understanding ENSO/IOD dynamics	Agus Santoso	UNSW	01/07/2017
Research Scientist - project 1 Understanding ENSO/IOD dynamics	Guojian Wang	CSIRO	01/08/2017
Postdoctoral Fellow – project 1 Understanding ENSO/IOD dynamics	Ben Ng	CSIRO	01/10/2017
Project Support Officer	Leonie Wyld	CSIRO	16/10/2017
Research scientist – project 2 Indo-Pacific interbasin exchange	Beatriz Peña-Molino	CSIRO	13/11/2017
Postdoctoral Fellow - project 4 Southern Ocean dynamics	Annie Foppert	University of Rhode Island US	29/01/2018
Postdoctoral Fellow - project 6 Sea level change	Kewei Lyu	University of California US	20/02/2018
Postdoctoral Fellow -project 2 Indo-Pacific interbasin exchange	Océane Richet	Laboratoire d'hydrodynamique (LadHyX)	20/02/2018
Postdoctoral Fellow – project 3 Coupled warm pool dynamics in the Indo-Pacific	Je-Yuan Hsu	University of Washington US	20/02/2018
Postdoctoral Fellow - project 4 Southern Ocean dynamics	Veronica Tamsitt[1]	Scripps Institution of Oceanography US	16/04/2018
Research Scientist – project 5 Southern Ocean observations	Laura Herraiz-Borreguero	National Oceanography Centre UK	04/06/2018
Postdoctoral Fellow – project 1 Understanding ENSO/IOD dynamics	Readvertised[2]		01/10/2018

[1] UNSW staff based at CSHOR Hobart

[2] The initial round of applicants were not suitable

Appendix B Full staff list

Kate Berry	Senior Experimental Scientist – project 5 Southern Ocean observations
Wenju Cai	Director
Matthew England[3]	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
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
Kewei Lyu	Postdoctoral Fellow - project 6 Sea level change
Craig Neill	Senior Experimental Scientist – project 5 Southern Ocean observations
Ben Ng	Postdoctoral Fellow – project 1 Understanding ENSO/IOD dynamics
Beatriz Peña-Molino	Research Scientist – project 2 Indo-Pacific interbasin exchange
Océane Richet	Postdoctoral Fellow -project 2 Indo-Pacific interbasin exchange
Steve Rintoul	Project Leader - project 5 Southern Ocean observations
Agus Santoso[4]	Project Co-leader - project 1 Understanding ENSO/IOD dynamics
Bernadette Sloyan	Project Leader - project 2 Indo-Pacific interbasin exchange
Veronica Tamsitt[5]	Postdoctoral Fellow - project 4 Southern Ocean dynamics
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 Sea level change

[3] UNSW Scientia Professor of Climate Dynamics

[4] UNSW senior research associate and CSIRO adjunct science leader

[5] UNSW staff based at CSHOR Hobart

SUPPORT STAFF[6]	
Chris Gerbing	Communications 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

[6] Provided by CSIRO

Appendix C Conference and workshop participation

CSHOR staff attended the following conferences and workshops during the reporting period. As many of our staff work on multiple projects, not all of the conference attendance and associated travel listed below is fully funded by CSHOR.

C.1 First Quarter (July to September)

- **WCRP/IOC Regional Sea Level Changes and Coastal Impacts Conference, New York, USA, 10-14 July:** Dr Xuebin Zhang
- **1st International MSAT Conference "Ocean Science and Technology Toward a Global Maritime Axis", Bali, Indonesia, 3–5 August:** Dr Agus Santoso and Prof Matthew England
- **AOGS 14th Annual Meeting, 6-11 August, Singapore:** Drs Wenju Cai, Ming Feng and Agus Santoso
- **ICDC10 Interlaken, 21-25 August:** Dr Andrew Lenton
- **The 25th GCOS Steering Committee Meeting, Hangzhou, China, 25-29 September:** Dr Bernadette Sloyan (Co-Chair, OOPC)

C.2 Second Quarter (October to December)

- **SCAR Antarctic Climate Change in the 21st Century Meeting (Ant-Clim21), Scripps, USA 8-12 October:** Prof Matthew England
- **CEC'17 Berlin, Germany, 9-12 October:** Dr Andrew Lenton
- **Climate Variability and Air-Sea Interaction Workshop, National Taiwan University, Taipei, 12-13 October:** Drs Wenju Cai and Agus Santoso
- **1st Session of CLIVAR Research Focus on ENSO in a Changing Climate, 12th Session of CLIVAR Pacific Panel, and ENSO Complexity Workshop, Busan, South Korea, 15-21 October:** Drs Wenju Cai, Guojian Wang, Xuebin Zhang and Agus Santoso
- **ENSO Dynamics Workshop, UNSW, Sydney, Australia, 20-21 November**: Dr Agus Santoso and Prof Matthew England
- **CLIVAR SSG-23, Pune, India, 27-30 November:** Dr Wenju Cai
- **Impacts of tropical variabilities to polar circulation workshop, Qingdao, China, 12th-18th November:** Dr Guojian Wang
- **CAS and CMA Tropical-Subtropical Weather, Climate and Oceans Workshop in Guangzhou, China, 18-20 November:** Dr Ming Feng

C.3 Third Quarter (January to March)

- **QNLM Academic Annual Conference and Youth Forum, Qingdao, China, 10-25 January**: Dr Guojian Wang. The goal of the annual conference is to review progresses in previous year on marine science and technology, and to discuss the grand challenges in deep ocean observations.
- **Tropical Interbasin Interactions: a review workshop, Xiamen, China, January:** Drs Wenju Cai, Agus Santoso and Benjamin Ng. The workshop aim was to publish a review study on tropical interbasin interactions.
- **AMOS-ICSHMO 2018, UNSW Sydney, 5-9 February:** Drs Wenju Cai, Agus Santoso, Guojian Wang and Benjamin Ng convened a CSHOR session. Dr Xuebin Zhang presented a talk on the increasing rate of global sea level during altimetry era, based on the recent publication by Nature Climate Change. John Church (UNSW) also gave an invited talk in this session on his recent work on multi-decadal oscillation in sea level. Prof Matthew England gave a keynote presentation on Antarctic water-mass trends over the past four decades. He also presented at the CSHOR session. Drs Bernadette Sloyan, Ming Feng, Annie Foppert and Andrew Lenton also attended.
- **AGU Ocean Sciences Meeting, Portland, USA, 11-16 February:** Drs Wenju Cai, Annie Foppert and Andrew Lenton and Prof Matthew England delivered presentations. Prof England also convened a session at the meeting.
- **OOPC-21, Mar del Plata, Argentina, 13-16 March:** Dr Bernadette Sloyan
- **IOGOOS-14/IORP-14/SIBER-8/IRF-8/IIOE-2 SC2, Jakarta, Indonesia, 19-24 March:** Drs Ming Feng and Susan Wijffels
- **2nd IndOOS Review Workshop, Jakarta, Indonesia, 22-23 March:** Drs Ming Feng, Bernadette Sloyan and Susan Wijffels
- **Understanding the relationship between coastal sea level and large-scale ocean circulation workshop, March, Switzerland**. Dr Xuebin Zhang attended and will contribute to 2 coastal sea level review papers for a Space Sciences Series of ISSI by Springer Verlag.

C.4 Fourth Quarter (April to June)

- **Maritime Order in the Indian Ocean, 30 April – 1 May:** Dr Xuebin Zhang
- **Consortium for Ocean-Sea Ice Modelling in Australia (COSIMA) Annual Workshop, 7-8 May:** Drs Max Nikurashin, Steve Rintoul, Veronica Tamsitt, Annie Foppert and Kewei Lyu. Prof Matthew England presented a proposal for future projection simulations using COSIMA ocean-ice models.

- **NPOCE OSS3 WPOC, Qingdao, China, 8-10 May:** Drs Wenju Cai, Guojian Wang, Océane Richet, Ming Feng, Susan Wijffels (Dr Bernadette Sloyan unable to attend, presentation given by Dr Feng)
- **CAS-CSIRO Marine Science and Blue Economy Workshop, Qingdao, China, May:** Dr Ming Feng
- **International summer school on the polar climate system, Hohai University, Nanjing, China 21-25 May**: Prof Matthew England was an invited lecturer.
- **QNLM Seminar, Qingdao, China, 22 May**: Prof Matthew England presented a talk on Antarctic water-mass changes over the last four decades.
- **Ocean University of China, Qingdao, 23 May**: Prof Matthew England presented a talk on the role of trade wind variations in Pacific and global decadal climate variability.
- **Asia Oceania Geosciences Society (AOGS) 15th Annual Meeting, 3-8 June:** Drs Wenju Cai and Xuebin Zhang
- **NASA ISSM sea level workshop, 11-12 June**: Dr Xuebin Zhang
- **Xi'an Workshop on tropical variability and monsoon, 18-21 June:** Drs Wenju Cai and Guojian Wang
- **SCAR POLAR2018 - XXXV SCAR Meetings and SCAR/IASC Open Science Conference, Davos, Switzerland, 15-27 June:** Dr Steve Rintoul
- **The Climate and Ocean: Variability, Predictability, and Change (CLIVAR) - First Institute of Oceanography (FIO) Summer School on "Past, present and Future Sea Level changes", 25-30 June:** Prof Matt King

Appendix D Full list of datasets

Project 2: Indo-Pacific interbasin exchange

- SSTAARS, including the contributing harmonics, and percentiles of non-seasonal residuals, is available at https://portal.aodn.org.au.
- IMOS mooring data and XBT are available at https://portal.aodn.org.au

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

- 2 high-frequency profiling float data off northwest Australia will be publicly available at AODN 3 years after data validation
- ACCESS model outputs for certain MJO experiments. 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 (to be available in August from AODN and CCHDO)

Appendix E Full list of publications

Abellán, E., McGregor, S., England, M. H., & Santoso, A. (2017). Distinctive role of ocean advection anomalies in the development of the extreme 2015–16 El Niño. *Climate Dynamics*. doi:10.1007/s00382-017-4007-0

Benthuysen, J. A., Oliver, E. C. J., Feng, M., & Marshall, A. G. (2018). Extreme Marine Warming Across Tropical Australia During Austral Summer 2015–2016. *Journal of Geophysical Research: Oceans, 123*(2), 1301-1326. doi:10.1002/2017JC013326

Cai, W., Wang, G., Gan, B., Wu, L., Santoso, A., Lin, X., Chen, Z., Jia, F., & Yamagata, T. (2018). Stabilised frequency of extreme positive Indian Ocean Dipole under 1.5 °C warming. *Nature Communications, 9*(1), 1419. doi:10.1038/s41467-018-03789-6

Cai, W., Wang, G., Santoso, A., Lin, X., & Wu, L. (2017). Definition of Extreme El Niño and Its Impact on Projected Increase in Extreme El Niño Frequency. *Geophysical Research Letters, 44*(21), 11,184-111,190. doi:10.1002/2017GL075635

Chen, X. Y., Zhang, X. B., Church, J. A., Watson, C. S., King, M. A., Monselesan, D., Legrésy, B., & Harig, C. (2017). The increasing rate of global mean sea-level rise during 1993-2014. *Nature Climate Change, 7*(7), 492-497. doi:10.1038/Nclimate3325

Cougnon, E. A., Galton-Fenzi, B. K., Rintoul, S. R., Legrésy, B., Williams, G. D., Fraser, A. D., & Hunter, J. R. (2017). Regional Changes in Icescape Impact Shelf Circulation and Basal Melting. *Geophysical Research Letters*, 44(22), 11,519-11,527. doi:10.1002/2017GL074943

Feng, M., Zhang, N., Liu, Q., & Wijffels, S. (2018). The Indonesian throughflow, its variability and centennial change. *Geoscience Letters, 5*(1), 3. doi:10.1186/s40562-018-0102-2

Gao, L., Rintoul, S. R., & Yu, W. (2017). Recent wind-driven change in Subantarctic Mode Water and its impact on ocean heat storage. *Nature Climate Change*, 8, 58-63. doi:10.1038/s41558-017-0022-8

Herold, N., & Santoso, A. (2017). Indian Ocean warming during peak El Niño cools surrounding land masses. *Climate Dynamics*. doi:10.1007/s00382-017-4001-6

Langlais, C. E., Lenton, A., Matear, R., Monselesan, D., Legrésy, B., Cougnon, E., & Rintoul, S. (2017). Stationary Rossby waves dominate subduction of anthropogenic carbon in the Southern Ocean. *Scientific Reports, 7*(1), 17076. doi:10.1038/s41598-017-17292-3

Purich, A., England, M. H., Cai, W., Sullivan, A., & Durack, P. J. (2018). Impacts of Broad-Scale Surface Freshening of the Southern Ocean in a Coupled Climate Model. *Journal of Climate, 31*(7), 2613-2632. doi:10.1175/jcli-d-17-0092.1

Rintoul, S. R. (2018). The global influence of localized dynamics in the Southern Ocean. *Nature, 558*(7709), 209-218. doi:10.1038/s41586-018-0182-3

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:10.1038/s41586-018-0173-4

Santoso, A., McPhaden, M. J., & Cai, W. (2017). The Defining Characteristics of ENSO Extremes and the Strong 2015/2016 El Niño. *Reviews of Geophysics, 55*(4), 1079-1129. doi:10.1002/2017RG000560

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:10.1002/2017GL076195

Wang, G. J., Cai, W. J., Gan, B. L., Wu, L. X., Santoso, A., Lin, X. P., Chen, Z. H., & McPhaden, M. J. (2017). Continued increase of extreme El Niño frequency long after 1.5 degrees C warming stabilization. *Nature Climate Change, 7*(8), 568-572. doi:10.1038/Nclimate3351

Wang, G. J., Cai, W. J., & Santoso, A. (2017). Assessing the Impact of Model Biases on the Projected Increase in Frequency of Extreme Positive Indian Ocean Dipole Events. *Journal of Climate, 30*(8), 2757-2767. doi:10.1175/Jcli-D-16-0509.1

Zhang, Y., Du, Y., & Feng, M. (2017). Multiple Time Scale Variability of the Sea Surface Salinity Dipole Mode in the Tropical Indian Ocean. *Journal of Climate, 31*(1), 283-296. doi:10.1175/jcli-d-17-0271.1

Zhong, W. X., Zheng, X. T., & Cai, W. J. (2017). A decadal tropical Pacific condition unfavorable to central Pacific El Niño. *Geophysical Research Letters, 44*(15), 7919-7926. doi:10.1002/2017GL073846

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