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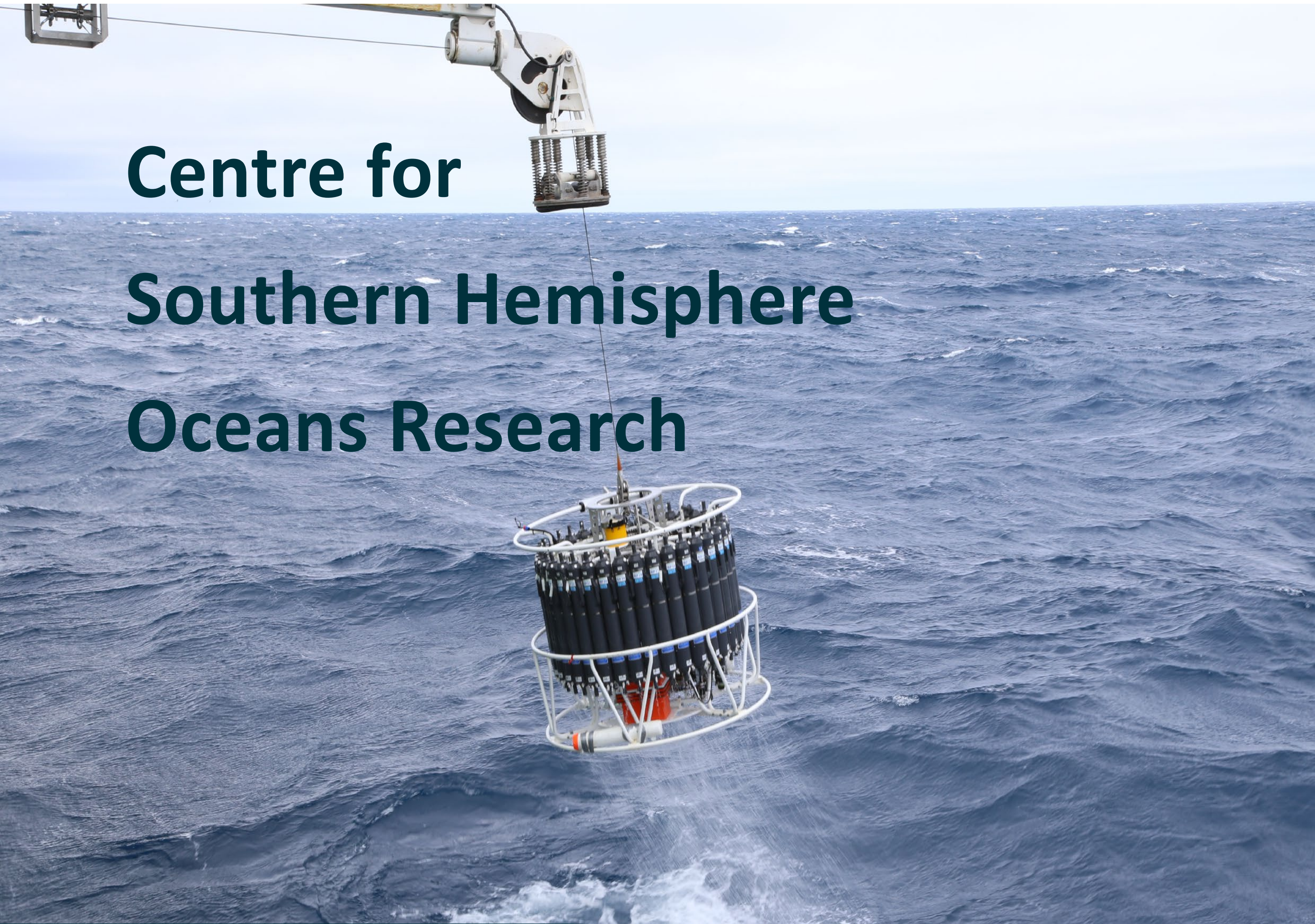
2020-21 Annual Report



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

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Cover Image

CTD retrieval - A CTD instrument measures conductivity, temperature, and depth. Image Source: Dr Ruhi Humphries, CSIRO, 2018.

Foreword

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

The high quality of the Centre's research is demonstrated in the achievements reported by the six project teams. Given the continued disruption caused by COVID-19, I have been impressed with how much work has been 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.

I hope you enjoy reading about the many accomplishments described in this report. CSHOR is enabling study of an area of the ocean that has been little researched and is important to the climate, weather, and ecosystems of the planet, with important implications for the future.

Congratulations to the team, the program, and all the scientists who conducted this work.

Kind regards,

Dr Susan Avery

CSHOR Steering Committee Chair

President Emerita, Woods Hole Oceanographic Institution

Professor Emeritus, University of Colorado Boulder

August, 2021

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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 fourth year of CSHOR's scientific research program.

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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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Dr Xiaobing Zhou, BoM

1 Executive summary

The CSHOR Annual Report is a record of the Centre's activities, achievements, and financial management during the period from 1 July 2020 to 30 June 2021.

The Centre was launched in May 2017 with the purpose 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 the CSIRO, China's Qingdao National Laboratory for Marine Science and Technology (QNLM), the University of New South Wales and the University of Tasmania.

The fourth year of CSHOR operation furthers our scientific understanding of the southern hemisphere oceans from the tropics to the Antarctic. The Centre was able to take advantage of the fast development of high-resolution models in the assessment of the Southern Ocean warming rate, increased marine heatwaves, intensifying oceanic eddies in a warming climate, and in quantifying mixing in the Indonesian Throughflow passage. The latter is an order of magnitude above background level because of converging energy that enters the Indonesian Seas.

CSHOR has begun to harvest results from the investment in observations over the previous years. Our deployment of Deep Argo floats near Antarctica is revealing spreading paths, interactions, and variability of two sources of Antarctic Bottom Water. In just two years, the floats have increased the number of winter profiles by a factor of 5, enabling much needed understanding of variability and change, including off East Antarctica, where the ice sheet is losing mass.

Further, using observations and models, CSHOR scientists show that concurrence of two-year consecutive positive Indian Ocean Dipole (IOD) events and two-year-consecutive central Pacific El Niño events during 2018-2019 conspired to induce droughts that precondition the 2019-20 Australian Black Summer bushfires, and that prediction of the impact from El Niño and the IOD would benefit from memory of sea-surface salinity and soil moisture as shown in a deep machine learning framework.

Using outputs of the latest climate models from around the world, our scientists have shown that the Intergovernmental Panel on Climate Change (IPCC) sea level projections are consistent with observations in terms of both trend and acceleration, have assessed the likelihood of extreme sea level increase, and have made advances in assessing uncertainty sources of the projected changes. The results reveal a future El Niño frequency increase if past internal variability is lower, and an opposite response of extreme positive IOD, which will increase under greenhouse warming, to that of moderate positive IOD, which is projected to decrease. The scientific outcomes will contribute to our further success in the fifth year of CSHOR.

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 2020-21 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 six high profile research articles for the *Nature* group. In total, there were 45 journal articles, four book chapters, and one book (CSHOR staff contributing as editors) Publications are listed in Appendix E .

Dynamics of El Niño Southern Oscillation and the Indian Ocean Dipole

A paper published in *Nature Climate Change* (Cai et al. 2020a) solves a long-standing issue surrounding the lack of model consensus in the projected change in the Indian Ocean Dipole (IOD) sea surface temperature (SST) variability. An implication of the study is that climate extremes seen in 2019-20 associated with strong pIOD are likely to occur more frequently under greenhouse warming.

Another paper published in *Nature* (Cai et al. 2020b) found that the El Niño Southern Oscillation (ENSO) possesses a self-regulation mechanism. The study offers a new perspective for understanding the dynamics of ENSO variability across timescales in a changing climate.

ENSO was the focus of a new book, *El Niño Southern Oscillation in a Changing Climate* (McPhaden, Santoso, Cai (Eds.) 2020), published by Wiley as part of the centennial celebration of the American Geophysical Union. The book is the first comprehensive examination of how ENSO cycle dynamics and impacts may change under the influence of rising greenhouse gas concentrations in the atmosphere. CSHOR researchers contributed to three of the book's chapters, one of these as lead-author.

The Indo-Pacific

A study published in *Frontiers in Marine Science Ocean* (Cowley et al., 2021) described the rationale behind the uncertainty specification provided for all in situ ocean temperature observations in the International Quality-controlled Ocean Database (IQuOD) v0.1, a value-added data product served alongside the World Ocean Database (WOD). The provision of a consistent set of observation uncertainties will provide a more complete understanding of historical ocean observations used to examine the changing environment.

CSHOR researchers pioneered research using ocean salinity to aid the prediction of Australian rainfall, based on improved understanding of moisture transport from the Indo-Pacific warm pool onto the Australian continent. The study found that salinity variability in the Pacific warm pool, associated with extreme El Niño Southern Oscillation (ENSO), can serve as a good predictor for the Australian rainfall at two seasons ahead of the summer, in addition to the ENSO index (Rathore et al., 2021).

The Southern Ocean

A study published in *Nature Geoscience* (Silvano et al., 2020) documents an increase in the supply of bottom water to the deep Indian and Pacific Oceans. New measurements reveal a surprising increase in the amount of dense water sinking near Antarctica, following 50 years of decline. The study highlights the sensitivity of Antarctic Bottom Water (AABW) formation to remote forcing and shows that climate anomalies can drive episodic increases in local sea ice formation that counter the tendency for increased ice-sheet melt to reduce AABW formation.

In another study, researchers found evidence that poleward shift of Antarctic Circumpolar Current fronts are linked to increased flow of warm water onto the Antarctic continental shelf, explaining the observed increase in basal melt of East Antarctic ice shelves (Herraiz-Borreguero et al.).

The Southern Ocean project team conducted the first comprehensive analysis of Deep Argo data near Antarctica, showing unanticipated variability on short space- and time-scales and allowing pathways of bottom water export to be identified for the first time (Foppert et al.)

The Southern Ocean and sea level change

A study published in *Nature Communications* (Wang et al., 2021) finds climate model projections of sea level rise in the early 21st century are in good agreement with observed sea level data in the corresponding period.

Another study, accepted by *Nature Climate Change* (Lyu et al. 2021), is the first application of emergent constraints methodology in future ocean warming and sea level rise. The Emergent Constraints methodology is applied to constrain both ocean warming and thermosteric sea level by 2100 in the Coupled Model Intercomparison Project 6 (CMIP6) ensemble, based on the multi-model relationship between current and future climate, and Argo array observations since 2005.

1.2 Communication and outreach highlights

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

Media and communication

Unlike the summer of 2019-20, the climate and environmental conditions in Australia were not the primary driver of media enquiries to CSHOR scientists. However, the broad interest in understanding more about climate drivers like El Niño and the Indian Ocean Dipole prevailed, providing opportunities to use new science to explain our research.

The publication of the book *El Niño Southern Oscillation in a Changing Climate* (2020), was a key moment, and was welcomed by some media, including coverage by EOS (American Geophysical Union Science News) and an El Niño explainer in The Sydney Morning Herald reaching over 155,000 potential readers.

Key scientific papers were a great source of media opportunity this year. Also, some key papers were discussed with scientific peers and news outlets via Twitter.

The paper by Cai et al., 2020b (September 2020) was covered by nine news outlets, including syndication across the major Fairfax publications nationally (The Age, Brisbane Times, and Sydney Morning Herald). In his story El Nino lulls lead to harsh floods, fires and droughts, journalist Peter Hannam demonstrated how our science provides significant and valuable input into understanding extreme climate events in Australia. Total media coverage reached over 70,000 people, with an additional 2,000 through the agricultural trade press. A CSIROscope blog about this research has been read by over 2650 people and reached around 100,000 through social media promotion.

Another paper that sparked the interest of the press was Cai et al., 2020a (November 2020). It focused on the impact of the negative Indian Ocean Dipole on Australia's rainfall patterns, the paper received coverage in seven news stories including national syndicated media coverage in the Sydney Morning Herald, The Age (Melbourne) and Brisbane Times. Medium in the USA also covered the story. Estimated audience reach was over 60,000.

The paper by Silvano et al. (2020) was well received online after distribution of a news release by CSHOR partner University of New South Wales. The paper received coverage in 12 media outlets and, was shared by the British Antarctic Survey, demonstrating the global reach and interest in CSHOR science. The research was also well-shared on Twitter amassing 33 tweets, plus engagement.

Again pointing to the far reaching international interest in CSHOR science, the paper by Hayashida et al. (2020) was covered by international media, including by the widely read science publication COSMOS and in a 2020 round-up of Tasmanian climate science research. This was another paper which piqued interest amongst scientific peers, with 37 Tweeters engaged and promoting the outcomes of the paper. *Nature Communications*, who have over 150,000 followers, also promoted the paper on Twitter.

Prof England discussed results from work he published with colleagues at Australian National University that showed a significant increase in global eddy kinetic energy detected over the last three decades, with a particularly strong increasing trend signal over the Southern Ocean (Martínez-Moren et al., 2021). The work, which appeared in *Nature Climate Change*, was mentioned in 28 news outlets, including profiles in the Sydney Morning Herald, The Age, and The Guardian. It accumulated 107 tweets, plus engagement.

A unique opportunity to profile our CSHOR scientists was taken up in CSIRO's popular blog targeted at younger generations and a scientifically engaged public. Our "meet the researcher" blog profiling Dr Guojian Wang has been viewed over 1600 times.

The csiro.au web page for CSHOR has been viewed around 700 times during the reporting period.

Across all media activities during 2020-21 the estimated audience reach was over 430,000 in Australia.

Outreach – workshops and conferences

CSHOR research was presented at a host of national and international meetings during 2020-21. Meetings were held online due to the physical distancing requirements and travel restrictions associated the COVID-19 pandemic. CSHOR staff convened sessions at several meetings. Major conferences and workshops attended by CSHOR staff are listed in Appendix D . A selection is listed below:

- ORCHESTRA/RoSES program in July 2020 (Dr Steve Rintoul gave an invited Keynote talk titled, “Changes in Antarctic Bottom Water: a view from East Antarctica”);
- CLIVAR Pacific Regional Panel Meeting, August 2020;
- International Science Council Scientific Committee on Antarctic Research (SCAR): Antarctic Science – Global Connections Open Science Conference, August 2020 (Dr Rintoul gave an invited Keynote talk titled, “What does a warming world mean for the Southern Ocean?”);
- The Eleventh Indian Ocean Observing System (IndOOS) Resource Forum (IRF-11), August 2020: Dr Feng presented a talk titled, “Progress on international advocacy and support for the proposed RAMA Timor Sea Flux Station.”
- Southern Ocean Observing System (SOOS) Scientific Steering Committee, October/November 2020;
- American Geophysical Union (AGU) Fall Meeting, December 2020 (Dr Wenju Cai gave an invited talk titled, “Butterfly effect and a self-modulating El Niño response to global warming”);
- Australian Meteorological and Oceanographic Society (AMOS) Conference in February 2021 (CSHOR staff were well represented at the meeting. Prof Matthew England delivered a plenary talk titled, “Global-scale climate teleconnections” and Dr Wenju Cai an invited talk titled, “Butterfly effect and a self-modulating El Niño response to global warming.”); and
- The General Assembly of the European Geosciences Union (EGU) in April 2021 (Prof England was a co-author of several papers presented at this meeting).

Awards and special mentions

Dr Alessandro Silvano received the Uwe Radok Award for best PhD thesis by the Australian Meteorological and Oceanographic Society (AMOS). His PhD research at the Institute for Marine and Antarctic Studies (IMAS) focused on the ocean-ice shelf interaction at the Totten Glacier in East Antarctica; supervised by IMAS Associate Professor Guy Williams, and CSHOR’s Drs Rintoul and Peña-Molino. Dr Silvano was employed by CSHOR on a casual appointment following completion of his PhD.

Prof Matthew England was awarded the AMOS Morton Medal in recognition of his leadership in oceanography and climate and related fields, particularly through education and the development of young scientists, and through the building of research environments in Australia.

Prof John Church was elected to the American Geophysical Union (AGU) Fellows Class of 2020 for his exceptional contribution to the AGU’s Earth and space sciences community.

Dr Steve Rintoul, CSHOR Project Leader and CSIRO Fellow, was awarded an Officer of the Order of Australia (AO) for his service to climate science.

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. 2020-21 publications are emphasised in bold text and listed in Appendix E Abbreviations and acronyms are explained in Appendix A

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

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.

2.1.1 Year 4 highlights and progress against project objectives

A paper published in *Nature Climate Change* (Cai et al., 2020a) highlights that there is opposite response to greenhouse warming between strong positive Indian Ocean Dipole (pIOD) and moderate IOD events. This study finds a robust future increase in sea surface temperature (SST) variability of strong pIOD events characterised by strong cool anomalies in the equatorial eastern Indian Ocean, but a robust decrease in SST variability of moderate pIOD events which are dominated by warm anomalies in the western tropical Indian Ocean. This solves a long-standing issue surrounding the lack of model consensus in the projected change in IOD SST variability. An implication of the study is that climate extremes seen in 2019-20 associated with strong pIOD are likely to occur more frequently under greenhouse warming. Another paper published in *Nature* (Cai et al., 2020b) found that ENSO possesses a self-regulation mechanism under greenhouse warming. If ENSO variability is initially suppressed by internal variability, future ENSO variability is likely to be enhanced, and vice versa. This self-modulation offers a new perspective for understanding the dynamics of ENSO variability across timescales in a changing climate.

2.1.2 Project performance against milestones

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

Milestone 1: Using observations to examine processes leading to the occurrence of 2019 extreme positive Indian Ocean Dipole event and the possible impact of long-term warming trend in the Indian Ocean

Wang et al. (2020) examined the mechanism of the observed 2019 extreme positive Indian Ocean Dipole (pIOD) event and found that the occurrence of 2019 extreme pIOD event features the strongest easterly wind anomalies and southerly wind anomalies on record: leading to the strongest wind speed which facilitates the latent cooling to overcome the increased radiative warming over the eastern equatorial Indian Ocean; leading to the unique thermodynamical forcing. Wang & Cai (2020) found that the 2019-20 Australian black summer bushfires can be attributed to a two-year consecutive concurrence of the 2018 and 2019 positive Indian Ocean Dipole and the 2018 and 2019 Central Pacific El Niño, with the former affecting southeast Australia, and the latter influencing eastern and northeastern Australia. They also assessed the projected changes in such consecutive concurrences in the future. In addition, Yang et al. (2020) examined various datasets for assessing pIOD in observations.

Using the latest Coupled Model Intercomparison Project 6 (CMIP6) models, Cai et al. (2020a) examined the projected change in pIOD events, finding an opposite change between strong and moderate pIOD, with strong pIOD events exhibiting an increase in variability, but moderate pIOD events showing a decrease in the future, as illustrated in Figure 1. Wang et al. (2021) examined biases in CMIP6 models and found that the bias in the thermocline tilt over the tropical Indian Ocean can be a potential emergent constraint for future projection in sea surface temperature variability. Yang et al. (2021) further found that a preceding Central Pacific El Niño event from December to May can give rise to easterly anomalies and a shallow thermocline over the eastern Indian Ocean, which provides a preconditioning effect for the development of a strong Indian Ocean Dipole from June to August.

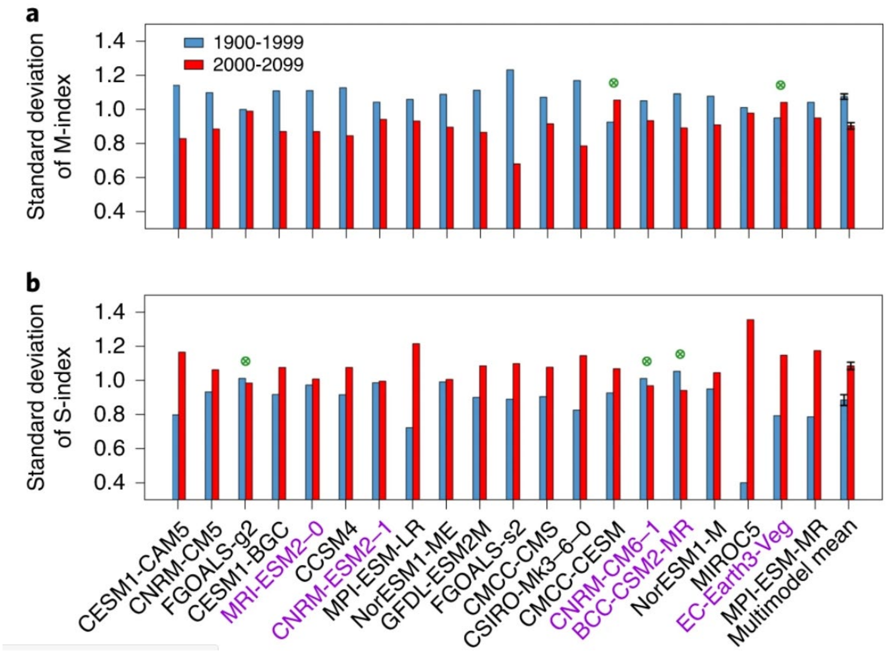

Figure 1 A decrease in moderate pIOD variability but an increase in strong pIOD variability in response to greenhouse forcing. a, A total of 18 out of the 20 selected models (90%) generate a reduction in moderate pIOD variability depicted by the M-index from the present-day (1900–1999, blue bars) to future (2000–2099, red bars) climate, except for two models generating an increase (indicated by green circles). The multimodel mean reduction of 16% is statistically significant above the 95% confidence level. b, A total of 17 out of the 20 models (85%) simulate an increase in variability of strong pIOD described by the S-index from the present-day to the future climate, except for three models generating a decrease (indicated by green circles). The multimodel mean increase of 22% is statistically significant above the 95% confidence level. CMIP6 models are indicated in purple. (Cai et al. ,2020a)

Milestone 2: Investigating whether there are emerged features of changes in tropical variabilities under greenhouse warming using CMIP5/6

Under greenhouse warming, climate models project an increase in the frequency of strong El Niño and La Niña events, but the change differs vastly across models, which is in part attributed to internal variability. Cai et al. (2020b) found that like a butterfly effect, an infinitesimal random perturbation to identical initial conditions induces vastly different initial El Niño Southern Oscillation (ENSO) variability, which systematically affects its response to greenhouse warming a century later. In experiments with higher initial variability, a greater cumulative oceanic heat loss from ENSO thermal damping reduces stratification of the upper equatorial Pacific Ocean, leading to a smaller increase in ENSO variability under subsequent greenhouse warming. This self-modulating mechanism operates in two large ensembles generated using two different models, each commencing from identical initial conditions but with a butterfly perturbation. It also operates in a large ensemble generated with another model commencing from different initial conditions, and across climate models participating in the Coupled Model Intercomparison Project.

Following Cai et al. (2020b), Ng et al. (2021) examined the Community Earth System Model Large Ensemble (CESM-LE), the Max Planck Institute Grand Ensemble (MPI-GE and the Coupled Model Intercomparison Project 5 (CMIP5) models and found that unforced natural variability can explain a large proportion of the Eastern Pacific ENSO index and Central Pacific ENSO index standard deviation and skewness spread in CMIP5 models. This means that considerable uncertainty within the CMIP5 ensemble may be caused by internal climate variability. Geng et al. (2020) investigated two types of ENSO varying in tandem facilitated by nonlinear atmospheric convection.

In addition, Cai, Santoso, and Wang contributed to three book chapters in the AGU monograph, *El Niño Southern Oscillation in a Changing Climate*. McPhaden, Santoso and Cai (2020) served as editors of the book.

Milestone 3: Investigating the impact of Southern Ocean on ENSO using long integration of climate experiments

The dynamics and behaviour of El Niño Southern Oscillation (ENSO) are not only influenced by processes within the tropical Pacific, but also those in other oceanic basins including at high latitudes. They are further complicated by interactions with modes of variability on different time scales, in particular the Interdecadal Pacific Oscillation (IPO). These interactions are difficult to disentangle, but useful insights can be gained using idealised experiments such as freshwater forcing to explore the mechanisms involved. A paper (Orihuela-Pinto et al., 2021) on the effect of an Atlantic meridional collapse on ENSO has been submitted and received positive reviews. The study found that hypothetical Atlantic meridional overturning collapse due to surface freshening leads to a significant reduction (~30%) of ENSO variability associated with a cooler tropical Pacific mean state. Another study (Santoso et al., 2021, to be submitted) found that the impact of multi-decadal changes sourced in the North Atlantic on tropical Pacific variability differs from those sourced in the Southern Ocean. The former has a stronger impact on ENSO-time scale variability, whilst the latter has a stronger impact on decadal-scale variability. Kajtar et al. (2021) show that climate models exhibit notable biases in the Southern Ocean which are more strongly linked to future change in global mean surface temperature than those in the northern hemisphere. Specifically, cold biased models tend to project stronger global warming. Considering future projection of El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) found in our projects, these results potentially highlight a link between Southern Ocean processes and changes in tropical climate variability in climate models.

Milestone 4: Examination of the impact of tropical variability, particularly of the Atlantic, in heat uptake of the Southern Ocean

Using Australian Community Climate and Earth System Simulator Climate Model 2 (ACCESS-CM2), one of Australia's Coupled Model Intercomparison Project 6 (CMIP6) models, Bi et al. (2021, in preparation) investigate the impact of tropical Atlantic variability on southern hemisphere climate. Two sets of experiments were run: standard CMIP6-type historical runs from 1970 to 2019 and pacemaker runs for the same period with external forcing, i.e., observed sea surface temperature (SST), imposed over the "target region," i.e., tropical Atlantic Ocean. Both the base and pacemaker experiments have 5-member ensembles. First focussing on the tropical Pacific Ocean, Bi et al. (2021) found that by imposing the observed SSTs in the tropical Atlantic Ocean, the teleconnection between the tropical Atlantic Ocean and the tropical Pacific Ocean, including the ENSO variability, is much improved.

2.1.3 Project publications[1]

Journal articles

Bi, D., Cai, W., Santoso, A., Sullivan, A., & Wang, G. Improved tropical Pacific-Atlantic teleconnection in a pacemaker experiment. *Journal of Climate*, to be submitted.

Cai, W., Yang, K., Wu, L., Huang, G., Santoso, A., Ng, B., Wang, G., & Yamagata, T. (2020a). Opposite response of strong and moderate positive Indian Ocean Dipole to global warming. *Nature Climate Change*. https://doi.org/10.1038/s41558-020-00943-1.

Cai, W., Ng, B., Geng, T., Wu, L., Santoso, A., & McPhaden, M. J. (2020b). Butterfly effect and a self-modulating El Niño response to global warming. *Nature*, 585, 68-73. https://doi.org/10.1038/s41586-020-2641-x.

Geng, T., Cai, W., & Wu, L. (2020). Two types of ENSO varying in tandem facilitated by nonlinear atmospheric convection. *Geophysical Research Letters*, 47, e2020GL088784. https://doi.org/10.1029/2020GL088784.

Kajtar, J., B., Santoso A., Collins M., Taschetto A. S., England M. H., Frankcombe L. M. (2021) CMIP5 intermodel relationships in the baseline Southern Ocean climate system and with future projections. *Earth's Future*, 9, e2020EF001873. http://dx.doi.org/10.1029/2020ef001873.

Ng, B., Cai, W., Cowan, T., & Bi, D. (2021). Impacts of Low-Frequency Internal Climate Variability and Greenhouse Warming on El Niño–Southern Oscillation, *Journal of Climate*, *34*(6), 2205-2218, doi.org/10.1175/jcli-d-20-0232.1.

Orihuela-Pinto, B., A. Santoso, M. H. England, A. Taschetto (2021). Reduced ENSO variability due to a collapsed Atlantic Meridional Overturning Circulation. *Journal of Climate*, submitted.

Santoso, A., Cai, W., England, M. (2021). Contrasting the response of tropical Pacific climate to multi-decadal variability sourced in the North Atlantic and Southern Ocean. *Journal of Climate*, to be submitted.

Wang, G., Cai, W., Yang, K., Santoso, A., & Yamagata T. (2020). A unique feature of the 2019 extreme positive Indian Ocean Dipole event. *Geophysical Research Letters*, 47. https://doi.org/10.1029/2020GL088615.

Yang, K., Cai, W., Huang, G., Wang, G., Ng, B., & Li, S. (2020). Oceanic processes in ocean temperature products key to a realistic presentation of positive Indian Ocean Dipole nonlinearity. *Geophysical Research Letters*,

[1] 2020-21 publications in bold text.

46, e2020GL089396. https://doi.org/10.1029/2020GL089396.

Wang, G., Cai, W. (2020). Two-year consecutive concurrences of positive Indian Ocean Dipole and Central Pacific El Niño preconditioned the 2019/2020 Australian "black summer" bushfires. *Geoscience Letters*, 7(1), 19, doi.org/10.1186/s40562-020-00168-2.

Wang, G., Cai, W., & Santoso, A. (2021). Simulated thermocline tilt over the tropical Indian Ocean and its influence on future sea surface temperature variability. *Geophysical Research Letters,* 48, e2020GL091902, doi.org/10.1029/2020GL091902.

Yang, K., Cai, W., Huang, G., Ng, B., & Wang, G. (2021). Is preconditioning effect on strong positive Indian Ocean Dipole by a preceding Central Pacific El Niño deterministic? *Geophysical Research Letters,* 48, e2020GL092223, doi.org/10.1029/2020GL092223.

Book and book chapters

El Niño Southern Oscillation in a Changing Climate (2020), 528pp, Geophysical Monograph Series, Vol. 253, American Geophysical Union, John Wiley & Sons, Print ISBN:9781119548126. Online ISBN:9781119548164, doi/book/10.1002/9781119548164.

Cai, W., A. Santoso, G. Wang, L. Wu, M. Collins, M. Lengaigne, S. Power, and A. Timmermann (2020). Chapter 13: ENSO Response to Greenhouse Forcing. AGU Monograph: ENSO in a Changing Climate. McPhaden, M., A. Santoso, W. Cai (Eds.), Wiley, doi.org/10.1002/9781119548164.ch13.

Karamperidou, C., M. F. Stuecker, A. Timmermann, K.-S. Yun, S.-S. Lee, F.-F. Jin, A. Santoso, M. J. McPhaden, and W. Cai (2020). Chapter 21: ENSO in a Changing Climate: Challenges, Paleo-Perspectives, and Outlook. AGU Monograph: ENSO in a Changing Climate. McPhaden, M., A. Santoso, W. Cai (Eds.), Wiley, doi.org/10.1002/9781119548164.ch21.

McPhaden, M., A. Santoso, and W. Cai (2020). Chapter 1: Introduction to ENSO in a Changing Climate. AGU Monograph: ENSO in a Changing Climate. McPhaden, M., A. Santoso, W. Cai (Eds.), Wiley, doi.org/10.1002/9781119548164.ch1.

2.2 Indo-Pacific inter-basin exchange (Project 2)

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, the dynamics of the Indonesian Seas, the strength and spatial patterns of tidally driven mixing and internal wave generation, and the modulation of the ITF by external ocean forcing.

2.2.1 Year 4 highlights and progress against project objectives

COVID-19 delayed the first voyage of the international Measuring and Modelling the INdonesian Throughflow International Experiment (MINTIE). We have used this time to complete voyage preparation and strengthen international links between the various partners. A major success was the awarding of an Australian Research Council (ARC) Discovery Project to CSIRO and UTAS CSHOR partners.

A study published in *Frontiers in Marine Science Ocean* (Cowley et al., 2021) describes the rationale behind the uncertainty specification provided for all in situ ocean temperature observations in the International Quality-controlled Ocean Database (IQuOD) v0.1, a value-added data product served alongside the World Ocean Database (WOD). This ocean product is used for a host of climate research and forecasting activities, such as climate monitoring, ocean reanalysis and state estimation, seasonal-to-decadal forecasts, and ocean forecasting. For all these applications, it is crucial to understand the uncertainty attached to each of the observations, accounting for changes in instrument technology and observing practices over time.

2.2.2 Project performance against milestones

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

Milestone 1: Provide moorings and floats to the International Collaborative Project amongst Australia, USA, and China: Measurements and Modelling of the Indonesian Throughflow (MINTIE)

We continued to progress the field observations of the MINTIE international project. Significant achievements include funding of an Australian Research Council (ARC) proposal which provided CSHOR funding leverage, the signing of the implementation agreement, building two CSHOR moorings and ordering floats. The ARC funding will enable us to add ocean mixing sensors to three floats.

COVID delayed the research voyage, but we are planning for a January-February 2022 voyage for installation of instrumentation and data collection.

Milestone 2: Targeted model studies investigating the influence of tidal mixing on the seasonal and mean properties of the Indonesian Sea

Dr Océane Richet applied tides to the 10km, 4m, and 1km regional models. To assess the impact of tides on the horizontal and vertical mixing we implemented the Massachusetts Institute of Technology General Circulation Model (MITgcm) tracer package in the model setup. A matrix of tracer models was developed with targeting the source waters of the Indonesian Throughflow (ITF) (North Pacific, South Pacific and South China Sea). The different vertical tracer concentrations enabled us to determine the impact of tides on the vertical property structure of the ITF. This work is in progress and in-depth analysis will be the focus of the coming year’s work.

Dr Richet also revised and resubmitted a manuscript detailing the response of the mean background state (time-mean circulation and mixed-layer properties) of the Indonesian Seas to seasonally variable forcing and investigated the contribution of the remote and local forcing to this mean background state using a high-resolution regional model (Richet et al., 2021). We show that the seasonal variability does not change the Indonesian Throughflow partitioning between the different routes, and that the main impact of the seasonal variability of the forcing is concentrated in the upper 300m of the water column and on the mean position of the jets.

Milestone 3: Analysis of observation and model data investigating the variability of the ITF transport and properties.

Dr Beatriz Peña Molino led a detailed analysis of the seasonal cycle of the Timor Throughflow (Peña Molino et al., 2021). This work described the seasonal cycle of the Indonesian Throughflow (ITF) based on new observations of velocity in the Timor passage collected between 2011 and 2015, combined with satellite altimetry and results from our high-resolution regional model of the Indonesian Seas. These new observations reveal a seasonal cycle in volume transport with an amplitude larger than previously estimated. The circulation in the Northwest Shelf on average opposes the ITF, reducing the overall transport by nearly 1 Sv at its peak in October. The timing of the seasonal cycle, with semiannual maxima (minima) in May and December (Feb. and Sep.), is controlled by the flow in the deep (>600m) layers associated with the passing of bi-annual Kelvin waves. The transport in the upper layer (<300m) is less variable than the deep flow but larger in amplitude. The seasonal cycle in this top layer is modulated remotely by cycles of convergence/divergence in the Banda Sea, and locally through Ekman transport, coastal upwelling, and the highly non-linear nature of the flow. The latter manifests through the formation of eddies that act to reduce the throughflow in the upper layers during the Southeast Monsoon, when transport is expected to be maximum. While the reduction in transport associated with this process is small relative to the total volume transport of the ITF, its impact on the heat transport is large, due to the surface intensified profile of the ITF. These non-linear dynamics develop over small scales (<10km), and without high enough resolution, both observations and models will fail to capture them. Refer to Figure 2 below.

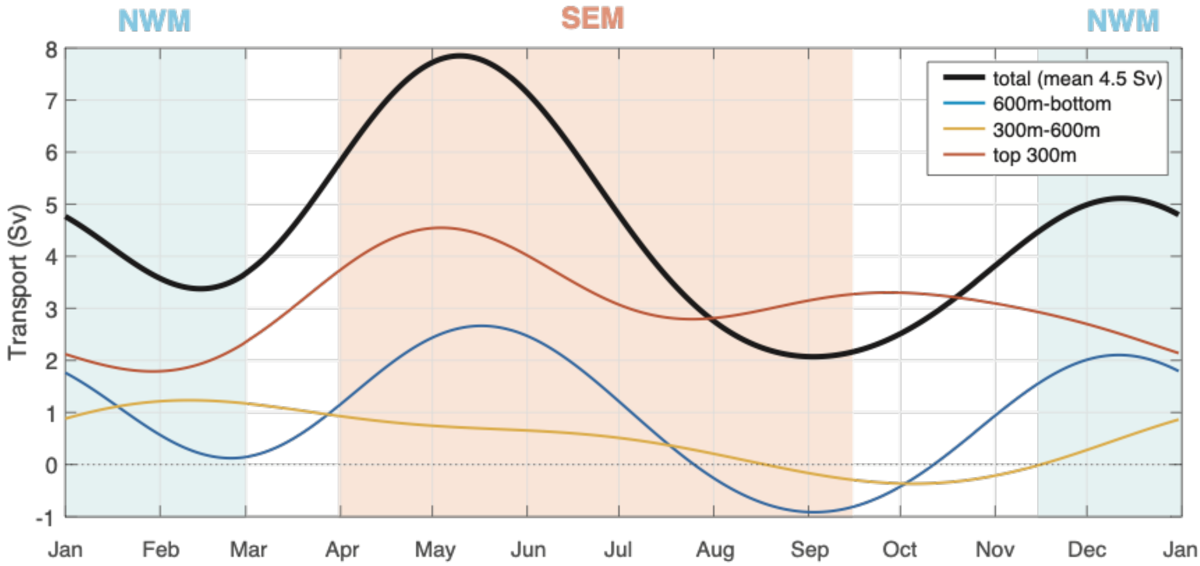

Figure 2 Seasonal cycle of the volume transport across Timor Passage as observed by the IMOS moored array. The black line shows the top-to-bottom transport, while colours show integrals across the surface, mid and deep layers. Orange and blue shading illustrate the periods of the different monsoon seasons (Northwest Monsoon (NWM), Southeast Monsoon (SEM), Sverdrup (Sv)) (Peña Molino et al., 2021).

Using our regional ocean simulations with different resolutions, 1/10° and 1/25° horizontal resolution, Chengyuan Pang, a University of Tasmania Honours student, estimated the eddy energy fluxes in the Indonesian Seas. The results show that the eddy energy propagates into the Indonesian Seas region through all major straits, suggesting that the Indonesian Seas region is a sink of eddy energy with up to 2GW of the total energy convergence in the region. On the Pacific Ocean side of the region, eddies and Rossby waves are the dominant energy source, while, on the Indian Ocean side, the Kelvin waves propagating from the Indian Ocean play the dominant role. Our results also show that most of the eddy energy flux is concentrated in the top 100m. The implication of our study is that, dissipated within the region, this energy can lead to turbulent energy dissipation and mixing an order of magnitude above their background values. A manuscript is being prepared.

Dr Bernadette Sloyan was involved in a study of the moisture source of Australian northwest cloudbands (Black et al., 2021). Northwest cloudbands have been shown to be associated with extreme rainfall over Australia. The rainfall for these events represented the wettest decile conditions of a 40-year period and impacted regions where yearly rainfall is typically low. Results from the backtracking of parcels located with respect to the subtropical jet for cloudbands in 2016 revealed moisture sources from the Timor, Arafura, and Coral Sea regions. These results indicate that the dynamical moisture transport associated with cloudband rainfall is not singularly tied to the Indian Ocean, as has been previously asserted.

We used the seasonal simulations at 10km, 4km and 1km to investigate the impact of the model resolution on the division of Indonesian Throughflow (ITF) transport through the western and eastern entrance pathways and outflow channels. A manuscript describing this work is under preparation. Analysis of our regional models, International Laboratory for High-Resolution Earth System (IHESP) model outputs and observations (Argo floats and moorings) focusing on atmospheric-ocean teleconnections was initiated during the year.

In collaboration with the CSHOR project, Coupled warm pool dynamics in the Indo-Pacific, Dr Helen Phillips has led an overview paper on Indian Ocean circulation and climate variability. This paper is now in open review for publication in an *Ocean Science* special issue of "Understanding the Indian Ocean system."

Milestone 4: Membership of International Laboratory for High-Resolution Earth System Prediction (iHESP) Science Advisory Committee

We coordinated collaboration between CSHOR projects, Indo-Pacific Interbasin Exchange and Coupled warm pool dynamics, and iHESP colleagues to gain access to their high-resolution control and transient models. Specific 2-D ocean and atmosphere model data for the equatorial region (+/- 20^{o}) continue to be used in our project.

2.2.3 Project publications[2]

Black, A. S., Risbey, J. S., Chapman, C. C., Monselesan, D. P., Moore, T. S., II, Pook, M. J., Richardson, D., Sloyan, B. M., Squire, D. T., & Tozer, C. R. (2021). Australian northwest cloudbands and their relationship to atmospheric rivers and precipitation. *Monthly Weather Review*, doi.org/10.1175/mwr-d-20-0308.1.

Cowley, R., Killick, R.E., Boyer, T., Gouretski, V., Reseghetti, F., Kizu, S., Palmer, M. D., Cheng, L., Storto, A., Le Menn, M., Simoncelli, S., Macdonald A. M., Domingues, C. M., (2021). International Quality-Controlled Ocean Database (IQuOD) v0.1: The Temperature Uncertainty Specification. *Frontiers in Marine Science, 8,* doi.org/10.3389/fmars.2021.689695.

Cyriac, A., Phillips, H. E., Bindoff, N. L., Mao, H., & Feng, M. (2021). Observational Estimates of Turbulent Mixing in the Southeast Indian Ocean. *Journal of Physical Oceanography*, 51(7), 2103-2128. doi.org/10.1175/JPO-D-20-0036.1.

Marin, M., Feng, M., Phillips, H. E., Bindoff, N. L. (2021). A global, multiproduct analysis of coastal marine heatwaves: Distribution, characteristics and long-term trends. *Journal of Geophysical Research: Oceans*, 126, e2020JC016708, doi.org/10.1029/2020JC016708.

Peña Molino, B., Sloyan., B. M., Nikurashin, M., Richet, O., Wijffels, S. E. (2021). Revisiting the seasonal cycle of the Timor Throughflow: circulation and transport. Submitted to *Journal of Geophysical Research: Oceans*.

Rathore, S., Bindoff, N.L., Ummenhofer, C.C., Phillips, H.E., Feng, M. (2020). Near-Surface Salinity Reveals the Oceanic Sources of Moisture for Australian Precipitation

[2] 2020-21 publications are shown in bold text.

through Atmospheric Moisture Transport. Journal of Climate, 33(15), pp. 6707-6730, doi.org/10.1175/JCLI-D-19-0579.1.

Rathore, S., Bindoff, N.L., Ummenhofer, C.C., Phillips, H.E. and Feng, M., Mishra, M. 2021, Improving Australian Rainfall Prediction Using Sea Surface Salinity. *Journal of Climate* 34 (7), 2473-2490, doi.org/10.1175/JCLI-D-20-0625.1.

Richet, O., Nikurashin, M., Peña Molino, B., Sloyan, B. M., Wijffels, S. E., (2021). The time-mean Indonesian Throughflow is modified by the seasonal forcing: Investigating the role of local and remote forcing. Submitted to *Journal of Geophysical Research: Oceans.*

Yang, L., Nikurashin, M., Hogg, A. McC., and Sloyan, B.M., (2021). The impact of lee waves on the Southern Ocean circulation. *Journal of Physical Oceanography*, under review

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

Project leader – Dr Ming Feng (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 modes of climate variability are likely the most important sources of enhanced weather and climate prediction on the globe.

This project is to advance 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 ocean-atmosphere model simulations. We also aim to better understand the roles of the Indonesian Throughflow in transmitting the Pacific ENSO/ Pacific decadal oscillation (PDO) signals into the Indian Ocean, in affecting the warming trend of the Indian Ocean and the meridional heat transport of the Indian Ocean. We explore drivers of the upper ocean salinity balance in the Indian Ocean and their role in the warm pool dynamics.

The project also contributes to an international community effort to design and implement a sustained ocean observing system in the Indian Ocean, especially on the coupled ocean-atmosphere processes in the Indo-Pacific warm pool and oceanic meridional heat transport.

2.3.1 Year 4 highlights and progress against project objectives

Year 4 research highlights include: (1) continued effort to utilise the 2018-19 field campaign data to understand MJO associated upper ocean variability, especially on the warming of sea surface temperature (SST) and enhancing diurnal SST variations during prolonged suppressed phase of the MJOs; (2) pioneered research using ocean salinity to aid the prediction of the Australian rainfall (See Figure 3 below); and (3) publication of two student papers on marine heatwave drivers off northwest Australia and marine heatwave trends along the coastlines of the global ocean.

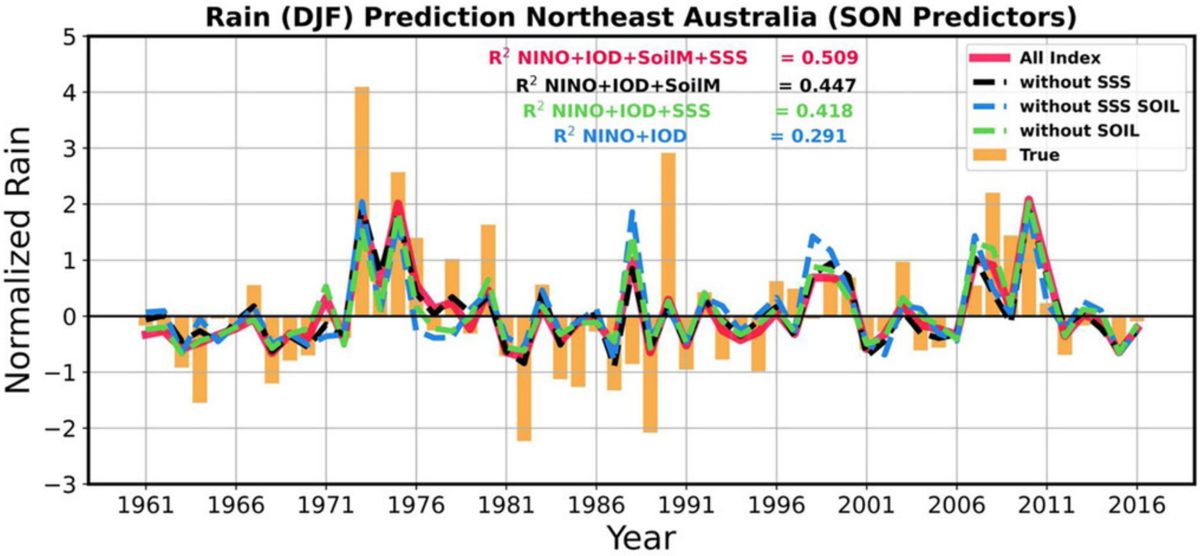

Figure 3 Sea surface salinity (SSS) in the Pacific warm pool improves rainfall prediction for northeast Australia. Normalized time series of DJF rainfall over northeastern Australia (130°–152°E, 25°S–0°) (yellow; identical in both panels) and predicted rainfall time series by incorporating the September-November indices of SSSP, SSSI, Niño-3.4, DMI, and soil moisture over northeastern Australia as predictors (red); predicted rainfall including all of the predictors except SSSP and SSSI (black); predicted rainfall including all of the predictors except soil moisture (green); and predicted rainfall without incorporating SSSP, SSSI, and soil moisture indices (blue). The variance explained by the prediction model is shown as the R2 value (Rathore et al., 2021).

2.3.2 Project performance against milestones

All project milestones were met, except a research paper on the profiling float observations couldn't pass the second round of a review process. A revised manuscript with more focus on the observations is to be prepared for another journal. An overview of project performance against each milestone follows.

Milestone 1: Continue to analyse 2018-19 field campaign data to improve our understanding of the intraseasonal variability of air-sea heat and moisture fluxes, and ocean mixed layer processes in the Indonesian-Australian Basin, in response to the MJO forcing.

Diurnal sea surface temperature variations in the Indonesian-Australian Basin, associated with the Madden-Julian Oscillation (MJO) evolutions, have been quantified using Himawari-8 geostationary satellite data for the two austral summer seasons, 2015-16 and 2016-17. This study identified hot spots of diurnal sea surface temperature (SST) variations in the Indonesian-Australian Basin, which provided guidance for the design of the 2018-19 field campaign. It has been identified that the high diurnal SST variation and mean SST were associated with prolonged MJO suppressed phase in the region, and the 2015-16 El Niño significantly weakened the MJO and prolonged its suppressed phase. A paper has been published in a special issue of the International Indian Ocean Expedition-2 (Huang and Feng, 2021).

Two manuscripts based on the 2018-19 field campaign data were submitted for journal publication. One manuscript was led by our departed postdoctoral fellow, Dr Andy Hsu, on the diurnal variations of the ocean surface warm layer observed in the profiling float data, driven by air-sea heat fluxes. It has been identified that under low wind and sunny conditions, the nocturnal convective mixing cannot completely erode the strong diurnal warm layer, resulting in quick re-stratification of the water column. SST can then be warmed further to aid the development of the MJO deep convections. After the unsuccessful review process, Dr Hsu plans to refocus the manuscript and resubmit to another journal in the coming months. Another manuscript is led by Dr Yongliang Duan (Feng as co-author), from the First Institute of Oceanography (FIO), on the MJO-induced upper ocean variability during the 2018-19 field campaign based on the moored observations. The data tended to support the theory that the first eastward propagating MJO triggered the onset of the Australia-Maritime Continent monsoon.

Dr Christopher Chapman has completed preliminary investigations of the oceanic conditions, both surface and subsurface, that proceed and follow MJO events. These observations are being interpreted using a modern "data driven" approach known as Dynamic Mode Decomposition (DMD). Part of this work was presented at the AMOS conference. Dr Chapman is also involved in research to which identifies that an enhanced sea surface temperature gradient over the Indian Ocean was a key composite cloudband feature that feeds into Australian rainfall.

Milestone 2: Quality control and preliminary analysis of the R/V Investigator cruise data for the Years of Maritime Continent program during October-November 2019

Standard quality control (QC) procedures have been applied to the RBR wire walker data. Refinement of the QC procedure for the salinity sensor is under further discussion. Wire walker data are ready to be made available via the CSIRO Data Access Portal with a Digital Object Identifier (DOI).

Milestone 3: Contribute to Indian Ocean observation review, and International Indian Ocean Expedition-2 (IIOE-2) research and review publications

An overview paper on the Indian Ocean circulation and climate variability, led by Dr Helen Phillips, with Dr Feng and several CSHOR collaborators as contributing authors, is now in the pipeline for open review, for publication in *Ocean Science*, a special issue of "Understanding the Indian Ocean system." The paper has received three positive reviews. Issues relevant to CSHOR research, the Indonesian Throughflow variability, eastern Indian Ocean circulation, and the Ningaloo Niño, are well covered in the review.

A review book chapter on the Ningaloo Niño, led by Dr Tomoki Tozuka, with Dr Feng as a co-author, was published in the book "Tropical and Extratropical Air-Sea Interactions." In the chapter, the mechanisms, and relationship with other climate modes in the Indo-Pacific, are reviewed, which provides guidance for the study of regional air-sea interaction in the eastern Indian Ocean warm pool region.

Other progress in the Indian Ocean research is a better quantification of turbulent mixing efficiencies in the southern Indian Ocean based on previous observation, a study on the decadal changes of Subantarctic Mode Water properties in the Indian Ocean, and a comprehensive description of mesoscale eddies in the Indonesian Seas.

Milestone 4: Improved assessment on the influences of the Indo-Pacific warm pool on Australian rainfall variability and predictability

Saurabh Rathore has finalised his PhD thesis and is now working in France as a postdoctoral fellow. Two papers out of the thesis are published, with one on the statistical relationship and moisture pathways in the Indo-Pacific warm pool, in relation with the variability of northern Australian rainfall. The other paper utilised the statistical relationship to formulate a forecasting model for northeast Australian rainfall variability. It is found that salinity variability in the Pacific warm pool, associated with extreme El Niño Southern Oscillation (ENSO), can serve as a good predictor for the Australian rainfall at two seasons ahead of the summer, in addition to the ENSO index.

Milestone 5: Assessing the 2013 northwest shelf marine heatwave event simulated in a model and analyse the roles of ocean dynamics in driving the peak warming

The paper led by Ms Maggiorano is published in the *Journal of Geophysical Research* (Maggiorano et al., 2021). A research paper on the wind effects on the Darwin Harbour sediment dynamics is published by the UNSW group.

A research paper led by another PhD student, Maxime Marin, is published in the *Journal of Geophysical Research* (Marin et al., 2021). The study assessed the marine heatwave risks along the global coastlines and attributed the long-term trends to climate variability and change.

Dr Feng has been leading an effort to review marine extremes in the Indian Ocean, which will become a contribution to a book on the Indian Ocean oceanography.

2.3.3 Project publications[3]

Journal articles

Black, A. S., Risbey, J. S., Chapman, C. C., Monselesan, D. P., Moore, T. S., II, Pook, M. J., Richardson, D., Sloyan, B. M., Squire, D. T., & Tozer, C. R. (2021). Australian northwest cloudbands and their relationship to atmospheric rivers and precipitation. *Monthly Weather Review*, doi.org/10.1175/mwr-d-20-0308.1.

[3] 2020-21 publications are shown in bold text.

Cyriac, A., Phillips, H. E., Bindoff, N. L., Mao, H., & Feng, M. (2021). Observational Estimates of Turbulent Mixing in the Southeast Indian Ocean. *Journal of Physical Oceanography*, 51(7), 2103-2128, doi.org/10.1175/JPO-D-20-0036.1.

Hao, Z., Xu, Z., Feng, M., Li, Q. and Yin, B. (2021). Spatiotemporal Variability of Mesoscale Eddies in the Indonesian Seas. *Remote Sensing*, *13*(5), p.1017, doi.org/10.3390/rs13051017.

Huang, Z., and Feng, M. (2021). MJO induced diurnal sea surface temperature variations off the Northwest Shelf of Australia observed from Himawari geostationary satellite. *Deep Sea Research Part II: Topical Studies in Oceanography*, 183, 104925, doi.org/10.1016/j.dsr2.2021.104925.

Maggiorano, A., Feng, M., Wang, X., Stark, C., Colberg, F., Greenwood, J. (2021). Hydrodynamic drivers of the 2013 marine heatwave on the North West Shelf of Australia. *Journal of Geophysical Research: Oceans,* 126(3), e2020JC016495, doi.org/10.1029/2020JC016495.

Marin, M., Feng, M., Phillips, H. E., & Bindoff, N. L. (2021). A global, multiproduct analysis of coastal marine heatwaves: Distribution, characteristics and long-term trends. *Journal of Geophysical Research: Oceans*, 126, e2020JC016708, doi.org/10.1029/2020JC016708.

Rathore, S., Bindoff, N.L., Ummenhofer, C.C., Phillips, H.E. and Feng, M. (2020). Near-Surface Salinity Reveals the Oceanic Sources of Moisture for Australian Precipitation through Atmospheric Moisture Transport. *Journal of Climate*, *33*(15), pp. 6707-6730, doi.org/10.1175/JCLI-D-19-0579.1.

Rathore, S., Bindoff, N. L., Ummenhofer, C. C., Phillips, H. E., Feng, M., & Mishra, M. (2021). Improving Australian Rainfall Prediction Using Sea Surface Salinity, *Journal of Climate*, 34(7), 2473-2490, doi.org/10.1175/JCLI-D-20-0625.1.

Yang, G., Wang, X., Zhong, Y., Cheng, Z., and Andutta, F. P. (2020). Wave effects on sediment dynamics in a macro-tidal estuary: Darwin Harbour, Australia during the monsoon season. *Estuarine, Coastal and Shelf Science*, 244, doi.org/10.1016/j.ecss.2020.106931.

Zhang, Y., Du, Y., Qu, T., Hong, Y., Domingues, C. M., & Feng, M. (2021). Changes in the Subantarctic Mode Water Properties and Spiciness in the Southern Indian Ocean based on Argo Observations. *Journal of Physical Oceanography*, 51(7), 2203-2221, doi.org/10.1175/JPO-D-20-0254.1.

Book chapter

Tozuka, T., Feng, M., Han, W., Kido, S. and Zhang, L. (2021). The Ningaloo Niño/Niña: Mechanisms, relation with other climate modes and impacts. In Tropical and Extratropical Air-Sea Interactions, pp.207-219. Elsevier, Ed. S. K. Behera, doi.org/10.1016/B978-0-12-818156-0.00006-X.

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

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 Year 4 highlights and progress against project objectives

The overall objective of the project is to explore the drivers and dynamics of circulation and water-mass formation in the Southern Ocean including around the Antarctic margin, particularly focusing on processes that regulate ocean heat and carbon uptake, and the delivery of heat to the Antarctic margin. Highlights of progress made against the project objectives include: (1 New Lagrangian estimates of the pathways and time-scales of warm Circumpolar Deep Water onto the Antarctic continental shelf using a high-resolution global ocean model; (2 An eddy-resolving ocean model was evaluated to analyse the pathways for Southern Ocean heat and carbon uptake through the 21st century; (3) The seasonal evolution of Sub-Antarctic Mode Water (SAMW) volume was analysed using a new kinematic estimate of subduction combined with a thermodynamic estimate of the air-sea formation rate; and (4 Recent and future projected Southern Ocean surface temperature trends were analysed in the framework of an interplay between wind-driven cooling, upwelling of warm Circumpolar Deep Water (CDW), and radiative warming of the ocean surface. All completed work has successfully progressed to paper submissions in high-quality international peer-review journals.

In Year 4 we welcomed Dr Kathy Gunn as a new CSHOR postdoctoral fellow. Dr Gunn began work at the start of March 2021, replacing Dr Annie Foppert who moved to the Australian Antarctic Program Partnership (AAPP) after successful completion of her 3-year CSHOR appointment.

2.4.2 Project performance against milestones

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

Milestone 1: Develop and test a strategy for investigating exchange across the Antarctic continental shelf break, using observations and models

Particle tracking experiments were configured to track warm Circumpolar Deep Water (CDW) on the Antarctic continental shelf using a global 0.1 degree resolution ocean model with forcing derived from a repeat year that includes seasonal variability, synoptic weather systems and other sub-annual variations. We found that CDW residence times on the Antarctic shelf range from a month to several years. Water mass transformation was found to limit CDW access to ice shelves in Dense Shelf Water formation regions despite strong onshore CDW transport. Water mass evolution in Dense Shelf regions shows initial isopycnal cooling and freshening followed by diapycnal cooling and salinication. This work has been completed and submitted to *Geophysical Research Letters*. A summary of the major factors controlling the rate of intrusion of warm CDW onto the shelf is indicated in the Figure 4.

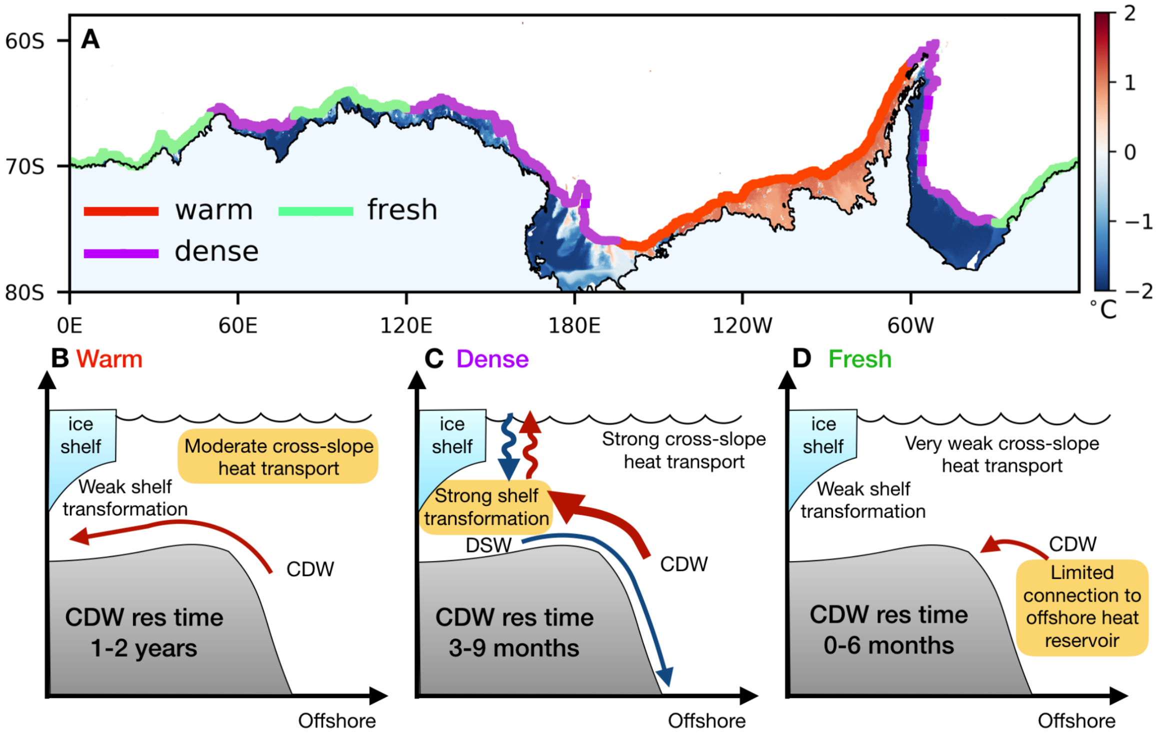

Figure 4 Schematic illustrating the limiting factors on Circumpolar Deep Water (CDW) heat available to melt ice shelves in three different continental shelf/slope regimes. a) Map of 10-year mean Antarctic continental shelf bottom temperature from the MOM01 model, with colours along the 1000 m isobath indicating the classification of the shelf into Warm Shelf (red), Dense shelf (purple), or Fresh shelf (green) regimes. Vertical shelf and slope cross-sections for each of the b) Warm shelf, c) Dense shelf, and d) Fresh shelf, describing key processes and showing the limiting step (highlighted in orange) controlling the CDW on the continental shelf (Tamsitt et al., 2021).

Milestone 2: Investigation of dynamics, mixing and cross-front exchange in a standing meander of the Antarctic Circumpolar Current from an in situ hydrographic survey

The work found that in the region of the Polar Front where the front position was stable, the sea surface temperature (SST) front resulted in a wind stress curl anomaly, which in turn lead to upwelling of colder water in a band along the core of the front. This upwelling-driven cold anomaly led to a depression in the turbulent ocean heat loss at the core of the front, demonstrating that multiple steps of air-sea interaction result in a complex cross-front structure of air-sea fluxes. This work, Bharti, Tamsitt et al., is complete and is under review in a special issue of *Frontiers in Marine Science*. In addition, analysis of submesoscale-resolving transects across the Polar Front has been completed, showing strong submesoscale instabilities and strong upward vertical heat transport on the southern side of the Polar Front co-located with the upwelling of Circumpolar Deep Water. This analysis is complete, and a manuscript by Wang, Tamsitt et al. in the final stages of preparation for submission to the *Journal of Geophysical Research: Oceans*.

Milestone 3: Analysis of the decoupling between heat and carbon in the Southern Ocean in an eddy resolving simulation

The Southern Ocean is a major sink of both anthropogenic heat and carbon dioxide (CO2). Projecting how, when, and where future uptake and storage of both will occur is essential to preparing for climate change and ocean impacts. An eddy-resolving (0.1°) ocean model under a high-emission (Representative Concentration Pathway (RCP) 8.5) scenario was used to analyse the pathways for Southern Ocean heat and carbon uptake throughout the 21st century. In particular, to explore how the decoupling of anthropogenically-derived heat and carbon differentially impact the environment, sea surface temperature increases and pH decreases (due to increased uptake of CO2, e.g., ocean acidification) were assessed relative to the mean global changes over the 21st century. The Southern Ocean is particularly striking in terms of the differences between heating and acidification, with relatively large decreases in pH but smaller changes in temperature (less than 2°C). This is due to the region's link to the deep ocean, where dissolved inorganic carbon is relatively high and ocean temperature is low. These results, and their further development via coupling with atmospheric and/or more complex ecosystem models, provide a tool for identification of where the changes to ocean heat and carbon will be most pronounced, informing the design of observing systems and management efforts. This analysis is complete and a manuscript by Mortenson, Lenton, Shadwick et al., is in the final stages of preparation.

Milestone 4: Analysis of the future evolution of the Southern Ocean carbon cycle changes under low and high emission pathways

Good progress was made on this milestone, with a manuscript in preparation involving analysis of Coupled Model Intercomparison Project 6 (CMIP6) simulations with the Australian Community Climate and Earth System Simulator Climate Model (ACCESS-ESM), exploring carbon uptake and changes in ocean chemistry. All simulations have been completed, and analysis is ongoing, with a final draft manuscript anticipated in December 2021.

Dr Lenton has taken up a new role at CSIRO and will not be able to contribute to CSHOR in 2021-22 as planned. Project Objective 4 (Carbon uptake of the Southern Ocean) and the Year 5 Deliverable (Write up paper on Southern Ocean carbon cycle) will be fully met by the work described above and papers to be published in 2021-22 on, "Impacts of climate change on the ocean through warming and acidification," "Meridional transport of physical and biogeochemical tracers by Southern Ocean eddies," and an update on the Global Carbon Budget.

Milestone 5: Quantify subduction rates of Subantarctic Mode Water and Antarctic Intermediate Water using Argo data in combination with both Lagrangian and Eulerian approaches

Using a gridded Argo product and the ERA-Interim reanalysis for years 2004-2018, the seasonal evolution of Subantarctic Mode Water (SAMW) volume was analysed using a kinematic estimate of the subduction rate combined with a thermodynamic estimate of the air-sea formation rate (all defined by regional potential vorticity and density constraints). The seasonal SAMW volume changes were separately estimated within the monthly mixed layer and in the interior below it. The seasonal volume variability of SAMW in the mixed layer was found to be controlled by formation due to air-sea buoyancy fluxes (45%, lasting from July to August), entrainment (35%), and northward Ekman transport across the Subantarctic Front (10%). The interior SAMW formation was shown to be controlled by exchanges between the mixed layer and the interior (i.e., instantaneous subduction), which occurs mainly during August-October. The annual mean subduction estimate from a Lagrangian approach showed strong regional variability with hotspots of large SAMW subduction, as revealed by the distribution of SAMW thickness, interior potential vorticity structure, and export pathways of SAMW over the central and eastern parts of the south Indian and Pacific Oceans. Hotspots in the south Indian Ocean produce strong subduction of 8 and 9 Sv for the light and southeast Indian SAMWs, respectively, while SAMW subduction of 6 and 4 Sv occurs for the central and southeast Pacific SAMWs, respectively. This work is in press with *Journal of Physical Oceanography* (Li, England et al., 2021).

Milestone 6: Examine the two-time scale response of the Southern Ocean to global warming and wind intensification across ocean model simulations at 1, 0.25- and 0.1-degree resolutions

Recent Southern Ocean surface temperature trends have been described as an interplay between wind-driven cooling, upwelling of warm Circumpolar Deep Water (CDW), and radiative warming of the ocean. In Li, England et al. (2021), idealised wind and thermal perturbations were analysed in a global ocean–sea ice model at two horizontal resolutions: nominally, 1 degree and 0.1 degree. The sea surface temperature (SST) response shows a clear transition from a wind-driven cooling phase to a warming phase. This warming transition is largely attributed to meridional and vertical Ekman heat advection, which are both sensitive to model resolution due to the model-dependent components of temperature gradients. At higher model resolution, due to a more accurate representation of near-surface vertical temperature inversion and upward Ekman heat advection around Antarctica, the anomalous SST warming is stronger and develops earlier. The mixed layer depth at midlatitudes initially increases due to a wind-driven increase in Ekman transport of cold dense surface water northward, but then decreases when the thermal forcing drives enhanced surface stratification; both responses are more sensitive at lower model resolution. With the wind intensification, the residual overturning circulation increases less in the high-resolution model because of the adequately resolved eddy compensation. These findings have implications for understanding the ocean response to the combined effects of southern hemisphere westerly wind changes and anthropogenic warming.

Milestone 7: Analyse the dynamics of topographic upwelling hotspots in the Antarctic Circumpolar Current

Analyses were completed focused on the dynamics of topographic upwelling hotspots in the Antarctic Circumpolar Current. The results confirmed some of the original findings appearing in Tamsitt et al., 2017. Lagrangian experiments were then configured and integrated to understand circum-Antarctic exchanges around the continental margin, to quantify transit times for flow around the continental shelf. This research is important for quantifying meltwater pathways around the margin, and their impact on dense shelf water formation. Of particular interest is the time taken for water to flow between adjacent sectors, and what water-mass transformation occurs along these pathways. This project has identified chokepoints where alongshore flow is limited by reduced cross-shore shelf extent and/or enhanced overturning of surface waters. The results are presently being written up for publication. Future work will examine meltwater pathways away from the major ice shelf melt regions and their impact on dense water overturning and lateral circulation.

Milestone 8: Investigation of deep-water properties, including quantifying the spatial and temporal variability of Antarctic Bottom Water

Dr Kathy Gunn was recruited as a postdoctoral fellow and began work at the start of March 2021, replacing Dr Annie Foppert who moved to the Australian Antarctic Program Partnership (AAPP) after successful completion of her 3-year CSHOR appointment. Dr Gunn has developed analysis codes that interpolate historical hydrographic bottle data into cross-sections. These cross-sections map Antarctic Bottom Water (AABW) at multiple locations and times. These sections can be used to determine the physical mechanisms causing property variability in AABW. Preliminary results indicate that changes in both the properties and volume transport of dense shelf water contribute to variability in AABW. Importantly, this preliminary work suggests that volume transport changes in dense shelf water have an important effect on the amount of oxygen reaching the abyssal ocean. The next step is to untangle the relative contributions and impacts of property and volume transport variability. We expect this work to be written up for publication toward the end of 2021, with a submission date of late 2021 or early 2022.

After completing this project, Dr Gunn will spend the first half of 2022 quantifying the effect of AABW variability on the abyssal ocean. She will specifically investigate the effect of changes in area of AABW on the heat content of the Australian Antarctic Basin, as well as oceanic basins to the north. This analysis will combine observation-based results with model output. We expect this analysis to be written up and submitted to a journal by the end of June 2022.

Milestone 9: Presentations at national and international conferences

Over the past year, our project members participated in several (virtual) national and international conferences, including the 2021

Australian Meteorological and Oceanographic Society (AMOS) Conference, 2020 American Geophysical Union (AGU) Fall Meeting, the 2021 European Geosciences Union (EGU), and the 2021 Australian Community Climate and Earth System Simulator (ACCESS) Science Workshop. At each of these meetings talks from the group were presented, including an AMOS keynote presentation, regular session talks, and several sessions were convened. Prof England co-convened an Antarctic Margin and Southern Ocean session at the 2021 virtual AMOS conference in February. The CSHOR Southern Ocean Dynamics (Project 4) team co-authored ~10 different talks at this conference. Prof England also gave several outreach talks at high schools during the past year, including a talk for United Nations World Oceans Day. Several virtual seminars were also presented, including at Imperial College London and at the Leibniz-Institut für Ostseeforschung Warnemünde in Germany.

Appendix D lists major conferences and workshops attended by CSHOR staff.

2.4.3 Project publications[4]

Bharti, V., Tamsitt., V, Philips, H.E., and Bindoff, N.L. (2021). The imprint of the Southern Ocean Polar Front on air-sea fluxes, *Frontiers in Marine Science*, in review

Hauck, J., Zeising, M., Le Quéré, C., Gruber, N., Bakker, D. C. E., Bopp, L., Chau, T. T. T., Gürses, Ö., Ilyina, T., Landschützer, P., Lenton, A., Resplandy, L., Rödenbeck, C., Schwinger, J., and Séférian, R. (2020). Consistency and Challenges in the Ocean Carbon Sink Estimate for the Global Carbon Budget. *Frontiers in Marine Science*, 7, 1–33, doi.org/10.3389/fmars.2020.571720.

Goyal, R., Gupta, A. S., Jucker, M., & England, M. H. (2021). Historical and projected changes in the Southern Hemisphere surface westerlies. *Geophysical Research Letters*, 48, e2020GL090849, doi.org/10.1029/2020GL090849.

Goyal, R., Jucker, M., Sen Gupta, A., & England, M. H. (2021). Generation of the Amundsen Sea Low by Antarctic orography. *Geophysical Research Letters*, 48, e2020GL091487, doi.org/10.1029/2020GL091487.

Goyal R., M. Jucker, A. Sen Gupta, H. Hendon, M. H. England (2021). Zonal Wave 3 Pattern in the Southern Hemisphere generated by tropical convection (reference number: NGS-2020-07-01758), *Nature Geoscience*, in press.

Li, Q., & England, M. H. (2020). Tropical Indo-Pacific teleconnections to Southern Ocean mixed layer variability. *Geophysical Research Letters*, 47, e2020GL088466, doi.org/10.1029/2020GL088466.

Li, Q., England, M. H., & McC. Hogg, A. (2021). Transient Response of the Southern Ocean to Idealized Wind and Thermal Forcing across Different Model Resolutions,

[4] 2020-21 publications are shown in bold text.

Journal of Climate, 34(13), 5477-5496, doi.org/10.1175/JCLI-D-20-0981.1.

Martínez-Moreno, J., Hogg, A.M., England, M.H. Constantinou, N. C., Kiss, A. E., and Morrison, A. K. (2021). Global changes in oceanic mesoscale currents over the satellite altimetry record. _Nature Climate Change_, 11, 397–403, doi.org/10.1038/s41558-021-01006-9.

Patel, R. S., Llort, J., Strutton, P. G., Phillips, H. E., Moreau, S., Conde Pardo, P., & Lenton, A. (2020). The biogeochemical structure of Southern Ocean mesoscale eddies. _Journal of Geophysical Research: Oceans_, 125, e2020JC016115, doi.org/10.1029/2020JC016115.

Shimura, T., Hemer, M., Lenton, A., Chamberlain, M. A., & Monselesan, D. (2020). Impacts of ocean wave-dependent momentum flux on global ocean climate. _Geophysical Research Letters_, 47, e2020GL089296, doi.org/10.1029/2020GL089296.

Tamsitt, V., England, S., Rintoul, S., and Morrison, A. K. (2021). Residence time of warm Circumpolar Deep Water on the Antarctic continental shelf, in review.

Tamsitt, V., Bushinsky, S., Li, Z., du Plessis, M., Foppert, A., Gille, S., Rintoul, S.R., Shadwick, E., Silvano, A., Sutton, A., Swart, S., Tilbrook, B., and Williams, N.L. (2021). The Southern Ocean [in “State of the Climate in 2020”], Bulletin of the American Meteorological Society, in press.

2.5 Southern Ocean observations and change – Antarctic observations (Project 5)

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 Year 4 highlights and progress against project objectives

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.

Progress made against specific project objectives is highlighted below. The small team has made good progress overall.

Notable discoveries include: (1) evidence that poleward shift of Antarctic Circumpolar Current fronts are linked to increased flow of warm water onto the Antarctic continental shelf, explaining the observed increase in basal melt of East Antarctic ice shelves (Herraiz-Borreguero et al.); (2) the first comprehensive analysis of Deep Argo data near Antarctica, showing unanticipated variability on short space- and time-scales and allowing pathways of bottom water export to be identified for the first time (Foppert et al.); (3) studies of water mass formation and seasonal dynamics of East Antarctic coastal polynyas; and (4) new insights into the factors regulating the seasonal cycle and net sink of carbon dioxide on the Antarctic continental shelf.

In addition to the science achievements, the group continues to seek and secure logistical support for future field programs, including an expansion of the Deep Argo array in the Australian Antarctic Basin, a major multidisciplinary voyage planned for early 2023, and two field programs in collaboration with the Australian Antarctic Program Partnership (AAPP): a marginal ice zone experiment and a study of ocean – ice shelf interaction at the Denman Glacier.

2.5.2 Project performance against milestones

Most of the project milestones were met. The two exceptions include a study of changes in primary productivity following iceberg calving in Prydz Bay and a study of the Ross Gyre using Argo floats. The priority of the iceberg calving project was reduced because changes in sea ice concentration induced by the calving event, as well as the timing of the exit of the iceberg from the continental shelf, makes it difficult to isolate the effect of iron-rich melt-water. The Ross Gyre project has been delayed from the original timeline to allow inclusion of an additional year of float data and to include complementary information from satellite altimetry using a new method appropriate for ice-covered seas.

An overview of performance against each milestone follows.

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

The sensitivity of Antarctic Bottom Water formation to changes in forcing has been examined in three recent papers. Silvano et al. (*Nature Geoscience*, 2020) used repeat hydrographic sections and Deep Argo data to document a strong rebound in salinity of Antarctic Bottom Water formed in the Ross Sea. The rebound in salinity was shown to result from an unusual combination of climate anomalies. A second paper (Thomas et al., *GRL*, 2020) extended this work to the west using Deep Argo data. A third paper (Foppert et al., to submitted to *Journal of Geophysical Research: Oceans* in July 2021) also uses Deep Argo data to document the detailed pathways and temporal variability of Antarctic Bottom Water in unprecedented detail. This project is also involved in the work led by Dr Kathy Gunn, described in Milestone 8 of the CSHOR project led by Prof England. Refer to Figure 5 below.

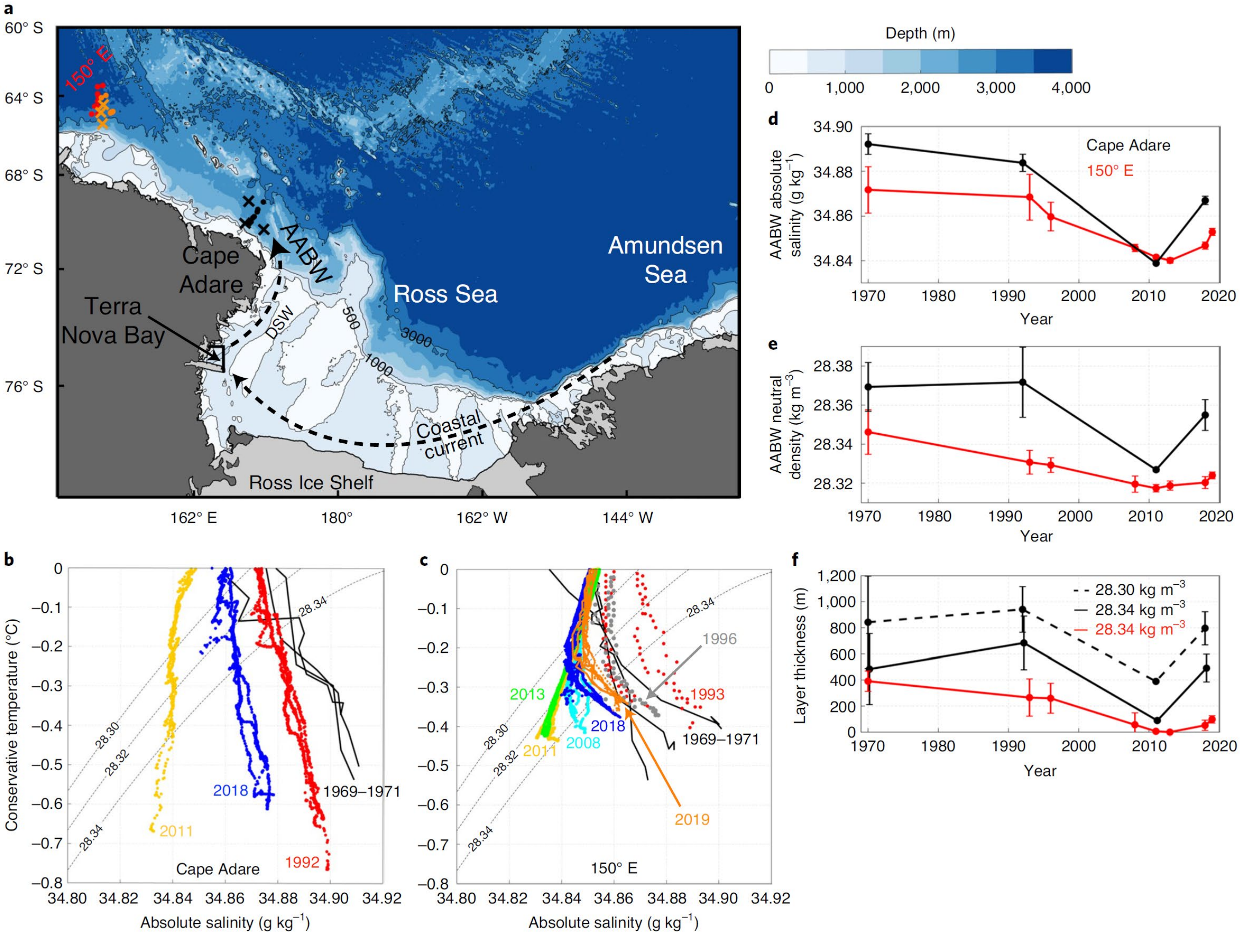

Figure 5 Recovery of Antarctic Bottom Water formed in the Ross Sea. (a) Map showing sampling locations at Cape Adare and at 150E. (b) Temperature – salinity profiles at Cape Adare. (c) Temperature – salinity profiles at 150E. Changes in the salinity (d), density (e) and thickness (f) of AABW at Cape Adare and 150E. AABW freshened between the 1970s and 2015, then rapidly rebounded to levels previously seen in the 1990s. The rebound in AABW formation was traced to an unusual teleconnection pattern to lower latitudes (Figure from Silvano et al., 2020).

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

Analysis of Argo float data in the Ross Gyre confirms the existence of a double-gyre structure. Recent advances in the use of altimeter data in ice-covered seas by overseas colleagues has opened a new direction for this study, allowing altimeter data to be used to complement the sparse float data. A paper describing these results is expected to be submitted in early 2022.

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

A model study explored the processes responsible for ocean heat uptake and their sensitivity to a changing climate (Dias et al., 2020). The Southern Ocean makes the dominant contribution to global ocean heat storage. The results highlight that the distribution of ocean heat storage reflects both passive uptake of heat and active redistribution of heat by changes in ocean circulation processes.

Quality control has been completed on data recorded by instruments on a tall mooring deployed in a standing meander of the Antarctic Circumpolar Current (ACC). Data return was excellent. Analysis of the moored records has begun and will continue in the next financial year, in a joint project with Dr Annie Foppert (ex-CSHOR) at the Australian Antarctic Program Partnership. Drs Foppert and Rintoul are also working on analysis of the lowered Acoustic Doppler Current Profiler (LADCP) data collected on the voyage, with the aim of quantifying the along- and cross-stream velocity structure of the Polar Front.

A study of a standing meander of the Subantarctic Front was submitted to the *Journal of Physical Oceanography* and accepted pending revision (Meijer et al., 2021). The study uses shipboard and satellite data to demonstrate the flow in the curving meander is in gradient wind balance and the resulting ageostrophic divergence drives large vertical velocities and cross-stream flow.

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

Two Deep Argo floats purchased by CSIRO will be deployed near 140°E next austral summer. The new floats will enhance the array of Deep Argo floats that was deployed in the Australian-Antarctic Basin near the beginning of CSHOR. As part of the MISO proposal (see Milestone 5), 15 Deep Argo floats funded by the Australian Antarctic Program Partnership will be deployed in early 2023, extending and enhancing the present array.

Milestone 5: Develop plan for future observations in CSHOR, in collaboration with other groups in Australia and overseas

Joint experiments to study marginal ice zone dynamics and ocean-ice shelf interaction at the Denman Glacier are being planned in conjunction with the Australian Antarctic Program Partnership, the Australian Centre for Excellence in Antarctic Science, and international collaborators.

A proposal was submitted to study Antarctic Bottom Water (AABW) formation processes in the Cape Darnley polynya, in East Antarctica, to study the processes involved in the past, present and future AABW formation within this polynya, using sediment cores, hydrographic data and model outputs. The outcome of the Australian Research Council (ARC) proposal is expected in the next couple of months. The cruise will occur in January 2022 and planning is currently underway.

A proposal for a major multidisciplinary voyage to the Southern Ocean on *RV Investigator* was submitted on 30 June 2021. The project title is, "Multidisciplinary Investigations of the Southern Ocean (MISO): Linking physics, biogeochemistry, plankton, aerosols, clouds, and climate." The goal of the MISO project is to improve our understanding of how the Southern Ocean region influences the Earth system and use this knowledge to improve climate models. The MISO proposal is unusual in its breadth - covering the deep ocean to the troposphere; observations and modelling; and biology, chemistry, and physics. The MISO experiment will characterise the properties of aerosols, clouds, radiation, and precipitation over the Southern Ocean south of Australia and investigate how they are shaped by interactions between the ocean, atmosphere, and biosphere. Repeat observations will be used to discover how and why the region is changing, and the consequences of Southern Ocean changes for climate, biogeochemical cycles, biological productivity, and the future of the Antarctic Ice Sheet. MISO seeks new insights into the processes controlling the availability of iron and other trace elements and their role in regulating productivity in the Southern Ocean and the production of marine organic aerosols that can drive cloud nucleation. The observations and insights gained from the voyage will be used to develop, test, and implement new parameterisations for models used for weather forecasts and climate projections. The voyage is planned for January 2023.

Milestone 6: Investigate ice shelf-ocean interactions

Analysis of a comprehensive data set of hydrographic observations in the Southern Ocean led to the discovery of a warming signal along the Australian East Antarctic sector. This warming is explained by a southward migration of the southernmost fronts of the Southern Ocean as well as a southward migration of the westerlies/easterlies. The change in the location of the winds is likely behind the recent acceleration in the ice mass loss from the East Antarctic Ice Sheet: more upwelling-favouring winds are located near the continental shelf, allowing warmer Circumpolar Deep Water to reach the ice shelves. A revised paper is near completion for submission to *Nature*.

Changes in the water masses that surround the Shackleton ice shelf in East Antarctica were analysed using all the publicly available data to-date. The system has shifted from an intense Dense Shelf Water (DSW) production region to a weak DSW one followed by increased upwelling of warm Circumpolar Deep Water since the 1990s. The final part of the analysis will occur in the next couple of months in conjunction with the drafting of a manuscript for submission to *Nature Geoscience*.

The two Argo floats deployed in Prydz Bay in February 2020 resurfaced and sent data back covering 13 months of full water column temperature and salinity profiles. Initial quality-controlled analysis show the floats worked well and the analysis of the data has commenced. Assessment of changes in the sea ice conditions in the Bay will occur in parallel to the analysis of the float data.

Milestone 7: Assess seasonal water mass transformation within an Antarctic coastal polynya

A paper showing how Circumpolar Deep Water upwells into Vincennes Bay, causing a large enough melt of the local ice shelves to stop formation of Dense Shelf Water, was submitted to the *Journal of Geophysical Research: Oceans* and re-submitted after revision.

Water mass transformation within the McKenzie polynya in Prydz Bay, in East Antarctica, has shown an unexpected spatial variability in the formation of Dense Shelf Water within the polynya. A paper showing this spatial variability and sea ice production estimates from seal data is underway and expected to be submitted in the coming weeks.

COVID-19 has prevented a PhD student from QNLM from continuing his work on the mooring array in Prydz Bay. Regular meetings were scheduled during the year. We expect to recommence the work but are uncertain of when this may occur.

Milestone 8: Quantify the impact of ice shelf melt on primary productivity in Prydz Bay

This milestone was considered lower priority. The calving of a large iceberg from the Amery ice shelf, with a 200m thick marine ice layer provided a potential opportunity to investigate the impact of the melting marine ice layer on primary productivity in Prydz Bay. The analysis of satellite-derived estimates of Chlorophyll-a before, during and after the calving of a marine ice layer-rich iceberg in Prydz Bay were examined. However, the iceberg interfered with the natural sea ice export paths during the austral summer resulting in an unusually high summer sea ice concentration in the Bay. The iceberg left the Bay during the autumn-winter months when phytoplankton activity was at a minimum.

Milestone 9: Improve our understanding of cross-shelf exchange

A high-resolution model is being used to develop the best observational framework to study the dynamics and variability of the Antarctic Slope Current, a key frontal feature that precludes warm Circumpolar Deep Water (CDW) from entering the Antarctic continental shelf. The model is also currently used to investigate CDW pathways towards several East Antarctic ice shelves. This analysis is being compared to data from instrumented seals to identify areas where warm CDW upwells, and thus, guiding the analysis of the model output.

Milestone 10: Assess the seasonality of biogeochemical processes in the continental shelf waters of the West Antarctic Peninsula

Observations from the Antarctic continental shelf were used to document a "continental shelf pump" transporting carbon dioxide into the deep ocean (Arroyo et al., 2020). Dense shelf water formed on the shelf is exported and sinks to the deep ocean, mixing and forming Antarctic Bottom Water. The carbon dioxide transferred to the deep ocean in this way is sequestered for centuries.

For the first time the biogeochemical seasonality on the West Antarctic Peninsula shelf was observed using a subsurface mooring carrying pCO_2 and pH sensors. The temporal evolution of the mixed layer dissolved inorganic carbon was investigated via a mass balance, revealing significant carbon drawdown in the spring and summer, which was replenished by diapycnal eddy diffusion, entrainment and air-sea CO_2 exchange. The seasonality in air-sea fluxes was also evaluated and autumn and winter outgassing were found to be suppressed by the presence of sea ice. Model projections indicate that sea ice formation is likely to occur later in the season in the coming decades, potentially weakening the net sink for CO_2 in this region. This work, which has been published in two recent papers (Yang, Shadwick et al., 2021 and Shadwick et al., 2021) has implications for other coastal Antarctic regions and our growing understanding of the evolving Southern Ocean carbon sink.

2.5.3 Project publications[5]

Arroyo, M. C., E. H. Shadwick, B. Tilbrook, S. R. Rintoul, and K. Kusahara (2020). A continental shelf pump for CO2 on the Adélie Land coast, East Antarctica. *Journal of Geophysical Research: Oceans*, 125(10), e2020JC016302, doi.org/10.1029/2020JC016302.

Dias, F. B., M.D.; R. Fiedler, S. J. Marsland, C. M. Domingues, L. Clément, S. R. Rintoul, E. L. McDonagh, M. M. Mata, A. Savita (2020). Ocean heat storage in response to changing ocean circulation processes. *Journal of Climate*, 33(21), 9065-9082, doi.org/10.1175/JCLI-D-19-1016.1.

Foppert, A., S. R. Rintoul, S. G. Purkey, T. Kobayashi, J-B Sallée, E. M. Van Wijk, L. O. Wallace (2021). Deep Argo reveals bottom water properties and pathways in the Australian-Antarctic Basin. Submitted to *Journal of Geophysical Research: Oceans*.

Herraiz-Borreguero, L. and A. C. Naveira Garabato (2021). Poleward shift of Circumpolar Deep Water threatens East Antarctic Ice Sheet, under revision.

Jiang, J., J. Shi, and S. R. Rintoul (2021). Opposing trends of Subantarctic Mode Water subduction in the central and eastern South Indian Ocean. Submitted to *Geophysical Research Letters*.

Meijer, J. J., H. E. Phillips, N. L. Bindoff, S. R. Rintoul, A. Foppert (2021). Cyclogenesis in a standing meander of the Subantarctic Front inferred from along-stream changes in temperature and salinity. Submitted to *Journal of Physical Oceanography.*

Ribeiro, N., L. Herraiz-Borreguero, S. Rintoul, C. R. McMahon, M. Hindell, R. Harcourt, G. Williams, 2021. Modified Circumpolar Deep Water intrusions in Vincennes Bay, East Antarctica. Submitted to *Journal of Geophysical Research: Oceans.*

Shadwick, E. H., De Meo, O. A., Schroeter, S., Arroyo, M. C., Martinson, D. G., & Ducklow, H. (2021). Sea ice suppression of CO2 outgassing in the West Antarctic Peninsula: Implications for the evolving Southern Ocean carbon sink. *Geophysical Research Letters*, 48, e2020GL091835, doi.org/10.1029/2020GL091835.

Silvano, A., A. Foppert, S. R. Rintoul, P. R. Holland, T. Tamura, N. Kimura, P. Castagno, P. Falco, G. Budillon, F. A. Haumann, A. Naveira Garabato and A. Macdonald (2020). Recent recovery of Antarctic Bottom Water formation in the Ross Sea driven by climate anomalies. *Nature Geoscience*, 13, 780-786, doi.org/10.1038/s41561-020-00655-3.

Tamsitt, V., Bushinsky, S., Li, Z., du Plessis, M., Foppert, A., Gille, S., Rintoul, S.R., Shadwick, E., Silvano, A., Sutton, A., Swart, S., Tilbrook, B., and Williams, N.L. (2021). The Southern Ocean [in “State of the Climate in 2020”], *Bulletin of the American Meteorological Society,* in press

Thomas, G., S. G. Purkey, D. Roemmich, A. Foppert, S. R. Rintoul (2020). Spatial

[5] 2020-21 publications are shown in bold text.

Variability of Antarctic Bottom Water in the Australian Antarctic Basin from 2018-2020 captured by Deep Argo. *Geophysical Research Letters*, 47(23), e2020GL089467, doi.org/10.1029/2020GL089467.

Yang, B., Shadwick, E. H., Schultz, C., & Doney, S. C. (2021). Annual mixed layer carbon budget for the West Antarctic peninsula continental shelf: Insights from year-round mooring measurements. *Journal of Geophysical Research: Oceans*, 126(4), e2020JC016920, doi.org/10.1029/2020JC016920.

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

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.

The project team has made significant progress towards addressing the key objectives. In the past four years, the team has been mainly working on: (1) examining ocean heat uptake and redistribution in the Southern Ocean through analysing available observations, and phases 5 and 6 of Coupled Model Intercomparison Project (CMIP5/6) models; (2) tuning up a suite of ocean models and carrying out carefully-designed numerical experiments with certain forcing being turned on or off; (3) quantifying uncertainty in Antarctic surface mass balance and carrying ice sheet modelling to project future contribution of Antarctic Ice Sheet to sea level rise; (4) analysing sea level and related climate variables in the latest CMIP6 ensemble; and (5) producing high-resolution sea level fingerprints due to land ice mass changes using the NASA-JPL Ice Sheet System Model (ISSM) sea level module on unstructured mesh grid.

In the next year, the project will work to put all sea level 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 the latest CMIP6 models, refined sea level fingerprints and new projections of Antarctic Ice Sheet mass loss.

2.6.1 Year 4 highlights and progress against project objectives

It has been another successful year for the sea level project. Ten journal manuscripts were published (including two by *Nature Communications*) and three manuscripts were submitted (including one accepted by

Nature Climate Change) and a further three are in various stages of preparation.

A suite of ocean-only perturbation experiments following the Flux-anomaly-forced model intercomparison project (FAFMIP) protocol were carried out to separate buoyancy and momentum forcing on heat and sea level distributions. Findings have been wrapped into one community ocean-only FAFMIP paper (Todd et al., 2020), and another manuscript focusing on comparison between model perturbation experiments and a theoretical framework (Lyu et al., *Journal of Physical Oceanography*, in preparation).

Significant progress has also been made in regional sea level budget for both historical and future periods. A manuscript comparing regional sea level trend and acceleration between observations and projections was published by *Nature Communications* (Wang et al., 2021) in February 2021. The study was featured in *Nature Communications* Editors' Highlights at this link. Another manuscript achieving excellent local sea level budget closure at 173 tide gauges distributed globally over 1958-2015 was submitted to *Geophysical Research Letters*, and recently reviewed favourably by two peer-reviewers (Wang et al., *Geophysical Research Letters*, in revision).

Sea level output from CMIP5/6 ensembles were analysed and compared, with one manuscript published (Wu et al., 2021) and another one submitted (Lyu et al., 2021, *Nature Climate Change*, accepted). Wu et al. (2021) discussed different sea level patterns, unknown before, in response to transient and stabilisation emission pathways up to 2300. Lyu et al. (2021) adopted the Emergent Constraints methodology to constrain future ocean warming and thermal expansion from CMIP6 ensembles, based on the relationship between current and future climate and high-quality Argo observations since 2005 (Figure 6). This study is the first application of Emergent Constraints methodology in future ocean warming and sea level rise, which received very positive comments from anonymous reviewers.

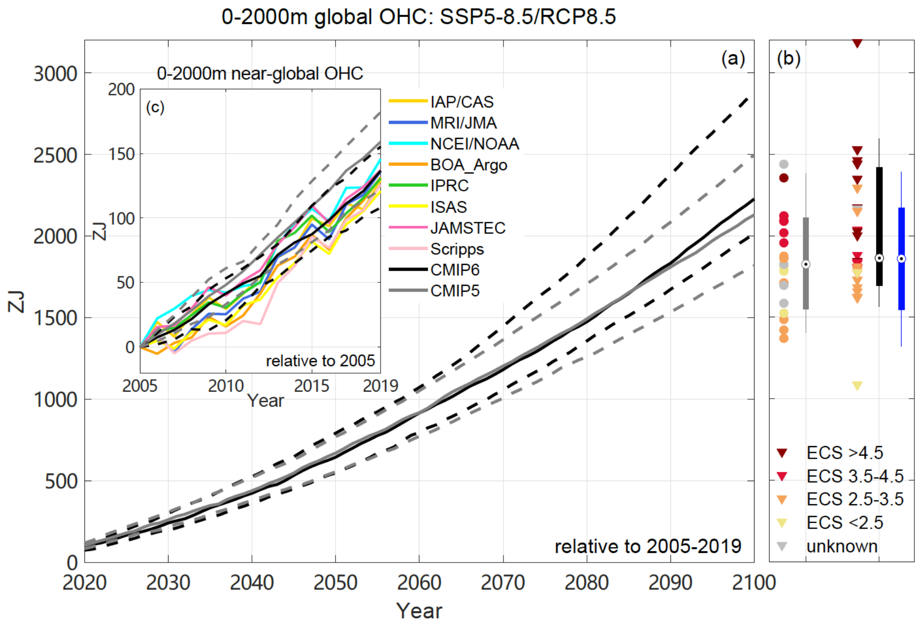

Figure 6 Ocean heat content changes in observations and climate model simulations. (a) Multi-model median (solid lines) and likely range (dashed lines; 17–83%) for 0–2000 m global OHC anomalies relative to 2005–2019 projected by the CMIP5 (grey) and CMIP6 (black) models under high-emission scenarios. (b) Projected 0–2000 m global OHC changes (2081–2100 relative to 2005–2019) under high-emission scenarios. The dots (triangles) are for the individual CMIP5 (CMIP6) models, with colours indicating the equilibrium climate sensitivity (ECS) range. The boxplots show the median, 17–83% range, and 5–95% range from the original CMIP5 projections (grey), the original CMIP6 projections (black), and the constrained CMIP6 projections (blue). (c) Multi-model median (solid lines) and likely range (dashed lines) for 0–2000 m near-global OHC anomalies relative to 2005 over 2005–2019 from the CMIP5 (grey) and CMIP6 (black) historical and high-emission scenario simulations along with the observed time series (coloured) from eight observational datasets (from Lyu et al. 2021).

The Ice Sheet System Model (ISSM) sea level module with unstructured mesh grid developed by NASA/JPL was tested extensively to produce high-resolution sea level fingerprints in response to polar ice sheet mass change projections (Zhang et al., *Journal of Geophysical Research*, in preparation). The above CMIP5/6 sea level analysis and this ISSM sea level fingerprint modelling work set solid foundation to provide next-generation total sea level projection.

Parallel Ice Sheet Model (PISM) was configured to simulate Antarctic Ice Sheet. A large ensemble of PISM experiments have been run to simulate from the Last Glacial Maximum to present, and present to 2500 under different emission scenarios, which quantify the Antarctic contribution to global sea level with estimated uncertainties. A manuscript summarising this part of work has been submitted to *Geoscientific Model Development* and accepted after revision (Phipps et al., 2021).

Several papers first-authored by postdoctoral and other students under our supervision or a result of collaboration have also been published or submitted (Hayashida et al., 2020; Irving et al., 2020; Jin et al., 2021; Li et al., 2021; Niphadkar et al., 2020; Sohail et al., 2021; Wang et al., 2021).

Over the past year, our project members attended several national and international conferences (2021 Australian Meteorological and Oceanographic Society (AMOS), 2020 American Geophysical Union (AGU) Fall Meeting and Australian Community Climate and Earth System Simulator (ACCESS) Science Workshop to deliver talks and chair sessions. With several other CSHOR scientists, Dr Zhang co-convened the CSHOR session at the 2021 virtual AMOS conference in February. The CSHOR sea level project team presented four abstracts at this conference. With several international colleagues, Dr Zhang co-convened a sea level session at the upcoming 2021 Asia Oceania Geosciences Society (AOGS) annual conference. Dr King will give an invited talk there. In September 2020, Dr Zhang was interviewed by Australian Broadcasting Corporation (ABC) TV about flooding in Tamar Valley (Northern Tasmania), focusing on possible impact of sea level rise on future flooding.

2.6.2 Project performance against milestones

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

Milestone 1: Running numerical perturbation experiments based on a suite of ocean models using the FAFMIP protocol to investigate mechanisms about how various forcings (e.g., atmospheric momentum and buoyancy forcing, freshwater discharge from Antarctica) drive the ocean heat uptake and redistribution, ocean circulation and sea level changes in the Southern Ocean

Various perturbation experiments have been designed and run to separate impacts from different forcing (e.g., wind stress and buoyancy forcing) following the Flux-anomaly-forced model intercomparison project (FAFMIP) protocol. Two manuscripts have been produced, one is a community ocean-only FAFMIP paper (Todd et al., 2020) and the other is a *Journal of Physical Oceanography* manuscript comparing FAFMIP experiments with a theoretical framework (Lyu et al., 2021, finished and under internal revision). Moreover, different climatological iceberg melting schemes have been applied in a global ocean-sea ice model to test the impacts on ocean dynamics and sea level, to test whether better representation of iceberg melting can help to reduce mean state biases in the Southern Ocean simulations.

Milestone 2: Analysing global and regional sea level changes from the latest CMIP6 climate model simulations, with focuses on quantifying internally-generated variability vs externally-forced changes, distinctions between high-emission and mitigation scenarios, differences between high and low climate sensitivity model results

Climate model simulations from the Coupled Model Intercomparison Project 5/6 (CMIP5/6) ensembles have been extensively analysed focusing on sea level related variables. A manuscript discussing distinct sea level patterns between transient and stabilisation emission pathways up to 2300 was published by *Climate Dynamics* (Wu et al., 2021). This is the first study to not only point out two sea level patterns but also give underlying mechanisms for those two patterns. Emergent Constraints (EC) methodology is a quickly developing technique to constrain future projections and narrow down projection ranges, e.g., suggesting the strong surface warming projected by models with high climate sensitivities is unrealistically high. We also applied the Emergent Constraints methodology to constrain both ocean warming and thermosteric sea level by 2100 in the CMIP6 ensemble, based on the multi-model relationship between current and future climate, and Argo array observations since 2005. This study was submitted to *Nature Climate Change* (Lyu et al., 2021) and received overall positive reviews and is currently under revision. Using a novel water-mass framework, a publication by *Geophysical Research Letters* has directly linked 50-year trends since 1970 in ocean heat content increases to surface fluxes in the sub-polar oceans (Sohail et al., 2021). A detailed analysis of a suite of CMIP5/6 climate models has identified deficiencies in mass and energy conservation, published by *Journal of Climate* (Irving et al., 2021).

Milestone 3: Progress toward producing next generation of total sea level projections, by summing up all contributing global and regional sea level components, such as updated dynamic sea level and refined regional sea level fingerprints related to land ice melting

A manuscript is finished and is currently under internal revision (Zhang et al., *Journal of Geophysical Research*, in preparation). The study is about future sea level fingerprints driven by the ensemble simulation of Antarctic ice sheet based on the Parallel Ice Sheet Model (PISM) carried out by UTAS team (Phipps et al., 2021). Regional sea level projection methodology has been modified and tuned up further, e.g., by producing updated sea level projections based on the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), which lays a solid foundation for the project to deliver a new regional sea level projection dataset by combining all contributing components, such as new CMIP6 dynamic sea level and refined sea level fingerprints due to land ice melting.

Milestone 4: Study of regional 20th century sea level budget based on observed estimates of mass contributions to the ocean, vertical land motion and estimates of regional dynamic (steric) sea level change

A study comparing sea level trend and acceleration between observations and projections over the recent decades, first of such kind, has been published by *Nature Communications* (Wang et al., 2021), and was well received by the public and research community. The study was featured in Nature Communications Editors' Highlights at this link. Another study, examining local sea level budget since 1958 at tide gauges distributed globally, and getting much better closure than previously published results, was submitted to *Geophysical Research Letters* and reviewed favourably, and is currently under revision.

Milestone 5: Commencing analysis of GRACE and GRACE-Follow On time series to produce estimates of Antarctic and Greenland ice mass change and, particularly robust uncertainty estimates considering time-variable change and temporal correlations. Advertising of PhD project to work on this and subsequent milestones

We focused on analysing the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-on data for Antarctica and this analysis has been progressing well. We have undertaken analysis of mass change over the whole ice sheet and drainage basins within, with a particular focus on the role of climate variability in the observed trends in ice sheet mass change. We have found, through Empirical Orthogonal Function (EOF) analysis of the GRACE data, that the two dominant variability modes are closely related to the cumulative Southern Annular Mode (SAM) and El Niño Southern Oscillation (ENSO) indices, and that about half of the 2003-2021 GRACE mass trend can be associated with SAM. A paper is being drafted (King et al., in preparation). There is no progress on recruiting a PhD student, in part due to COVID, and this work is being progressed with existing researchers and collaborators.

2.6.3 Project publications[6]

Hayashida, H., R.J. Matear, P. G. Strutton and X. Zhang (2020). Insights into projected changes in marine heatwaves from a high-resolution ocean circulation model. *Nature Communications*, 11, 4352, doi.org/10.1038/s41467-020-18241-x.

Irving, D., W. Hobbs, J. Church, and J. Zika (2021). A Mass and Energy Conservation Analysis of Drift in the CMIP6 Ensemble. *Journal of Climate*, 34, 3157-3170, doi.org/10.1175/JCLI-D-20-0281.1.

Jin, Y., X. Zhang, J. A. Church and X. Bao (2021). Projected sea-level changes in the marginal seas near China based on dynamical downscaling. *Journal of Climate*, doi.org/10.1175/JCLI-D-20-0796.1.

King, M. A., K. Lyu and X. Zhang, Climate variability as a major source of time-dependent Antarctic ice mass loss from space gravimetry, in preparation for *Nature Climate Change*.

Li, S., W. Liu, K. Lyu and X. Zhang (2021). The effects of stratospheric ozone depletion on Southern Ocean heat uptake and storage. *Climate Dynamics*, doi.org/10.1007/s00382-021-05803-y.

Lyu, K., X. Zhang and J. A. Church, Future ocean warming constrained by the sustained ocean observational record, *Nature Climate Change*, accepted.

Lyu, K., X. Zhang, J. A. Church and Q. Wu, Drivers of the Southern Ocean heat and salt redistribution: revisiting a theoretical framework based on model perturbation experiments. In preparation and to be submitted to *Journal of Physical Oceanography*.

Niphadkar, P., M. Bowen, X. Zhang, Sea level around the New Zealand coast: trends, variability and future projections. *Frontiers in Marine Science*, under revision.

Phipps, S. J., Roberts, J. L., and King, M. A. (2021). An iterative process for efficient optimisation of parameters in geoscientific models: a demonstration using the Parallel Ice Sheet Model (PISM) version 0.7.3, *Geoscientific Model Development*, doi.org/10.5194/gmd-2020-382.

Sohail, T., D. B. Irving, J. D. Zika, R. M. Holmes and J. A. Church (2021). Fifty year trends in global ocean heat content traced to surface heat fluxes in the sub-polar ocean.

[6] 2020-21 publications are shown in bold text.

***Geophysical Research Letters*, 48, e2020GL091439, doi.org/10.1029/2020GL091439.**

Todd, A., L. Zanna, M. Couldrey, J. Gregory, Q. Wu, J. A. Church, R. Farneti, R. Navarro-Labastida, K. Lyu, O. Saenko, D.Yang and X. Zhang (2020). Ocean-only FAFMIP: understanding regional patterns of ocean heat content and dynamic sea level change. *Journal of Advances in Modelling Earth Systems,* 12(8), doi.org/10.1029/2019MS002027.

Wang, L., Lyu, K., Zhuang, W., Zhang, W., Makarim, S., & Yan, X. H. (2021). Recent shift in the warming of the southern oceans modulated by decadal climate variability. *Geophysical Research Letters*, 48, e2020GL090889, doi.org/10.1029/2020GL090889.

Wang, J., J.A. Church, X. Zhang, and X. Chen (2021). Reconciling global mean and regional sea level change in projections and observations, *Nature Communications*, 12, 990, doi.org/10.1038/s41467-021-21265-6.

Wang, J., J.A. Church, X. Zhang, J. M. Gregory**,** L. Zanna and X. Chen, Evaluation of the regional sea level budget at tide gauges since 1958, *Geophysical Research Letters, under revision*.

Wu, Q., X. Zhang, J.A. Church, J. Hu, J. Gregory (2021). Evolving patterns of sterodynamic sea-level rise under mitigation scenarios and insights from linear system theory. *Climate Dynamics*, doi.org/10.1007/s00382-021-05727-7.

Zhang, S., X. Zhang, M. A. King and S. J. Phipps, Sea level fingerprints associated with future Antarctic ice sheet melting in the 21st Century. In preparation and to be submitted to *Journal of Geophysical Research.*

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 2020-21 is provided below.

3.1 Revenue

Total Revenue was $3,466m comprising contributions of $2m from QNLM funds and $1,466m from CSIRO funds (Figure 7). Since the Centre's inception, CSIRO has contributed $5,610m (68% of Agreement funds) and QNLM $10m (100% of Agreement funds) (Figure 8). CSIRO currently holds $3,006m funds in trust to be rolled over the 2021-22 operations.

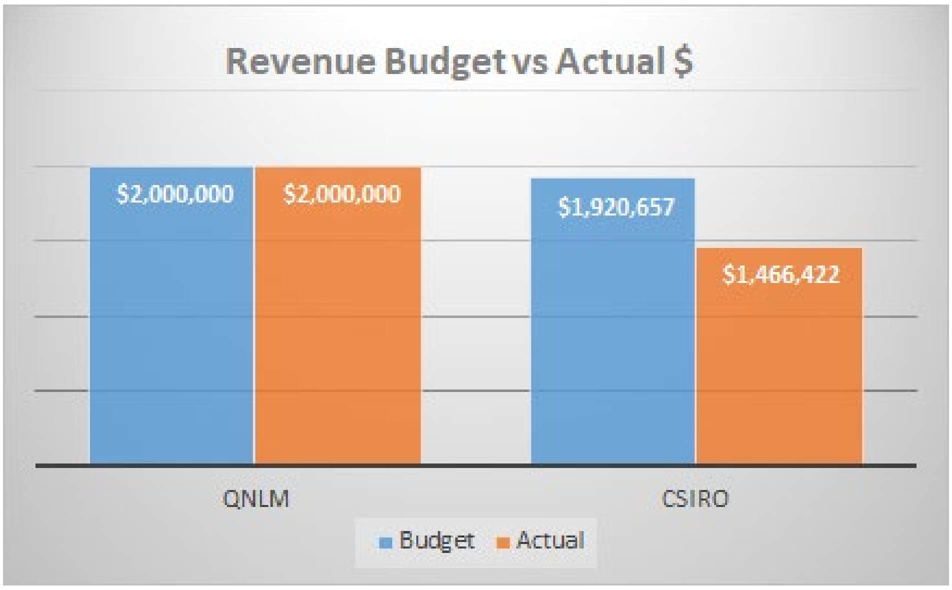

Figure 7 Revenue 2020-21 Budget vs actual $

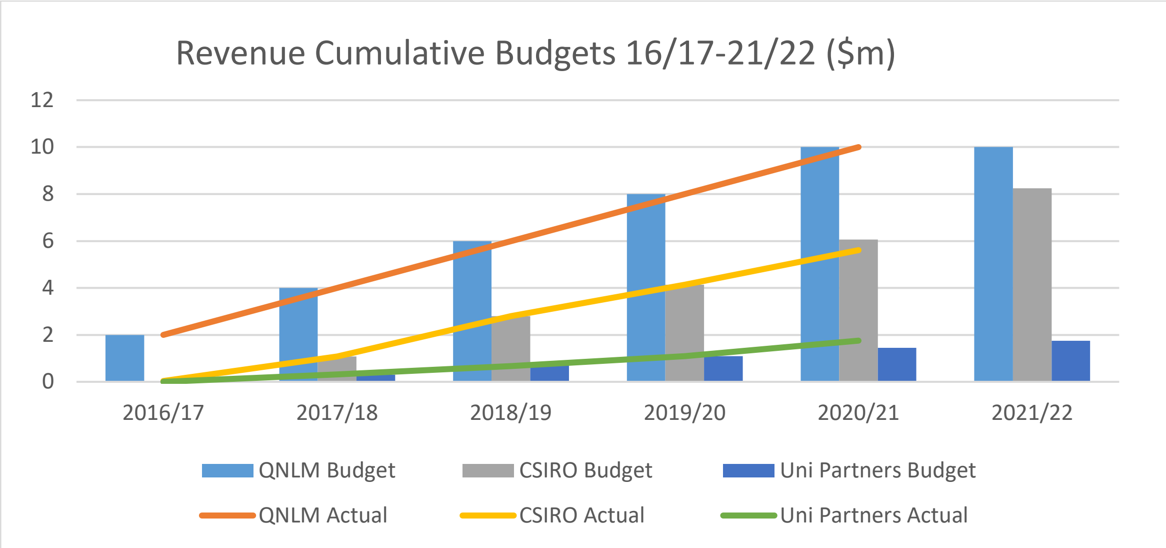

Figure 8 Revenue: cumulative budgets to 2021-22 ($m)

3.2 Expenditure

The total 2020-21 expenditure incurred was $3,875,924 acquitted to each partner as shown in Table 1 below. The underspent variance on QNLM/CSIRO funds was -$1,120,333, which is the result of the ongoing COVID-19 impact to the work environment. The movement of $292,146 QNLM-funded capital was deferred to 2021-22 due to postponement of the MINTIE voyage until January 2022. The floats are on order with delivery due by the end of September 2021. There is a $828,187 underspend in normal operations, particularly in travel expenditure. Travel restrictions associated with the COVID-19 pandemic have seriously hampered holding face-to-face workshops or gatherings and attending science conferences. Travel restrictions have also delayed commencement of the ENSO and IOD project Postdoctoral Fellowship. CSIRO policy prohibited international travel during the 2020-21 financial year. This restriction is due to continue for the foreseeable future. Domestic travel is also limited due to the various Interstate border restrictions and lockdowns, the result was minimal expenditure incurred (Table 2).

These funds will be carried forward to 2021-22 operations (Figure 9).

Table 1 Total expenditure in 2020-21

Fund Source	2020-21 Budget	2020-21 Actuals	Variance
QNLM	$2,409,759	$1,743,660	-$666,099
CSIRO	$1,920,657	$1,466,423	-$454,234
UNSW (In-kind)	$240,000	$514,182	+$274,182
UTAS (In-kind)	$100,000	$151,659	+$51,659

Table 2 Expenditure breakdown by category: 2020-21 budget vs actual

Expenditure by Category	20/21 Budget	20/21 Actual	WOL Budget	WOL Actual
Labour	2,117,973	2,115,278	9,427,199	6,762,402
Overheads	1,399,229	1,204,233	5,931,378	4,250,373
Travel	289,284	12,960	1,203,973	655,074
Operating	246,785	168,453	1,087,450	931,461
Payments to Partners	325,000	375,000	1,750,000	1,500,000
Capital	292,146	-	550,000	257,854
Total Expenditure	**4,670,417**	**3,875,924**	**19,950,000**	**14,357,165**

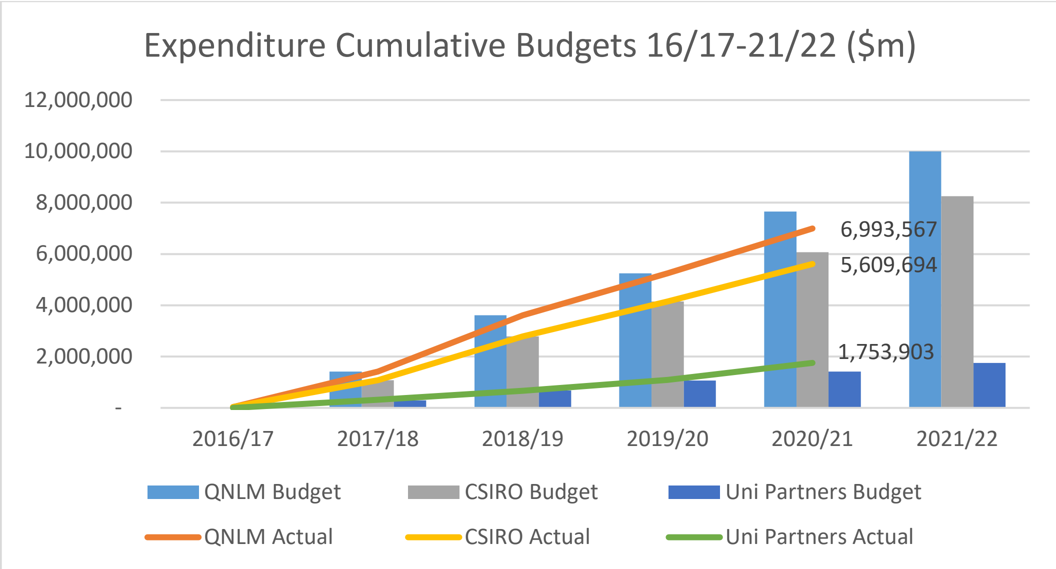

Figure 9 Expenditure: cumulative budgets to 2021-22 ($m)

3.3 Partner in-kind contribution

UNSW 2020-21 in-kind contribution was $514,812, +$274,182 above budget. UTAS 2020-21 in-kind contribution was $151,659, +$51,659 above budget. This reflects the Universities willingness to contribute more effort than originally planned. This bears no financial impact to QNLM or CSIRO. In-kind contributions since the Centre commenced are UNSW +100% at $1,297,081 and UTAS 91% at $456,822 (Figure 10).

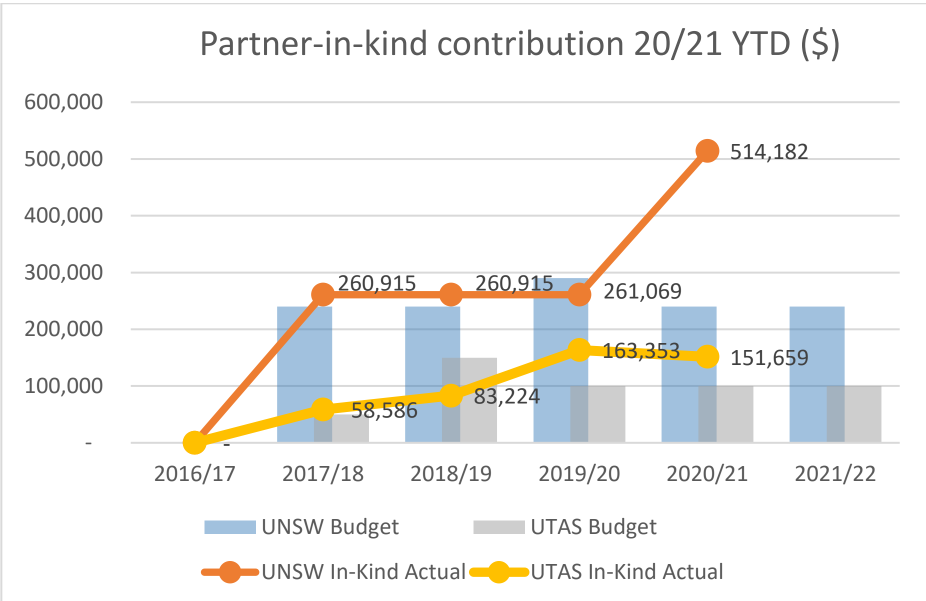

Figure 10 University partners in-kind contributions to 2020-21 ($)

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 8).

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

The **CSHOR Steering Committee** convened via video conference on 29 January 2021 and on 8 and 9 July 2021. Due to international travel restrictions associated with the COVID-19 pandemic it was not possible for the Steering and Advisory Committees to meet face-to-face, as planned for 2020-21.

The **CSHOR Research Leadership Team** met on 23 and 24 July 2020 (With the Steering Committee), 16 February 2021 and 28 May 2021.

The **CSHOR Management Team**, comprising the Director, Project Support Officer and representatives from CSIRO Finance, Contracts, Communications and Business Development, met on 17 March and 14 April 2021.

The Director also attended various virtual meetings at QNLM in Qingdao including CSHOR budget review and planning meetings in November and December 2020, and the QNLM Annual Meeting in January 2021.

Appendix A Abbreviations and acronyms

AABW	Antarctic Bottom Water
AAPP	Australian Antarctic Program Partnership
ACC	Antarctic Circumpolar Current
ACCESS-CM	Australian Community Climate and Earth System Simulator Climate Model
AGU	American Geophysical Union
AMOS	Australian Meteorological and Oceanographic Society
AOGS	Asia Oceania Geosciences Society
ARC	Australian Research Council
CESM-LE	Community Earth System Model Large Ensemble
CDW	Circumpolar Deep Water
CLIVAR	Climate and Ocean - Variability, Predictability, and Change
CMIP	Coupled Model Intercomparison Project
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DMD	Dynamic Mode Decomposition
DOI	Digital Object Identifier
DSW	Dense Shelf Water
EGU	European Geosciences Union
ENSO	El Niño Southern Oscillation
EOF	Empirical Orthogonal Function
FAFMIP	Flux-anomaly-forced model intercomparison project
GMSL	Global mean sea level
GRACE	Gravity Recovery and Climate Experiment
iHESP	International Laboratory for high-resolution Earth System
IndOOS	Indian Ocean Observing System
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation

IQuOD	International Quality-controlled Ocean Database
ISSM	Ice Sheet System Model
ITF	Indonesian Throughflow
LADCP	Lowered Acoustic Doppler Current Profiler
MINTIE	Measuring and Modelling the INdonesian Throughflow International Experiment
MITgcm	Massachusetts Institute of Technology General Circulation Model
MJO	Madden-Julian Oscillation
MPI-GE	Max Planck Institute Grand Ensemble
NASA JPL	National Aeronautics and Space Administration Jet Propulsion Laboratory
PDO	Pacific decadal oscillation
pIOD	Positive Indian Ocean Dipole
PISM	Parallel Ice Sheet Model
QNLM	Qingdao National Laboratory for Marine Science and Technology Development Center
RCP	Representative Concentration Pathway
SAM	Southern Annular Mode
SAMW	Sub-Antarctic Mode Water
SCAR	International Science Council Scientific Committee on Antarctic Research
SOOS	Southern Ocean Observing System
SST	Sea Surface Temperature
UNSW	University of New South Wales
UTAS	University of Tasmania
WCRP	World Climate Research Programme
WOD	World Ocean Database

Appendix B Project and support staff

Dave Bi	Senior Research Scientist - project 1 Understanding ENSO/IOD dynamics
Wenju Cai	Director
Chris Chapman	Research Scientist - project 3 Coupled warm pool dynamics in the Indo-Pacific
Rebecca Cowley	Scientific Programmer & Ocean Data Analyst - project 3 Coupled warm pool dynamics
Matthew England[7]	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
Kathy Gunn	Postdoctoral Fellow - project 4 Southern Ocean dynamics
Laura Herraiz-Borreguero	Research Scientist – project 5 Southern Ocean observations
Andrew Lenton	Principal Research Scientist - project 4 Southern Ocean dynamics
Yuehua (Veronica) Li[8]	Research Associate - project 6 Southern Ocean sea level change
Kewei Lyu	Postdoctoral Fellow - project 6 Southern Ocean sea level change
Ben Ng	Research Scientist – 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[9]	Project Co-leader - project 1 Understanding ENSO/IOD dynamics
Elizabeth Shadwick	Senior Research Scientist - project 5 Southern Ocean observations
Bernadette Sloyan	Project Leader - project 2 Indo-Pacific inter-basin exchange
Mark Snell	Senior Technical Services Officer - project 3 Coupled warm pool dynamics in the Indo-Pac.
Veronica Tamsitt[10]	Postdoctoral Fellow - project 4 Southern Ocean dynamics
Guojian Wang	Project Co-leader - project 1 Understanding ENSO/IOD dynamics
Leonie Wyld	Project Support Officer
Xuebin Zhang	Project Leader - project 6 Southern Ocean sea level change

[7] UNSW Scientia Professor of Climate Dynamics

[8] UNSW Research Associate

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

[10] UNSW staff based at CSHOR Hobart

SUPPORT STAFF[11]	
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
Sophie Schmidt	Communication Advisor, CSIRO Oceans and Atmosphere
Brenda Tuckwood	Finance and Projects Advisor, CSIRO Oceans and Atmosphere

[11] Provided by CSIRO

Appendix C PhD Students

Hannah Dawson	UNSW, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Saisai Hou[12]	Ocean University of China Project 5 Southern Ocean observations and change team member
Zhi Li[13]	UNSW, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Anna Maggiorano	UNSW Canberra, Australia Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
Maxime Marin	University of Tasmania, Australia Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
Julia Neme	UNSW, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Saurabh Rathore	University of Tasmania, Australia Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
Jinping Wang[14]	Ocean University of China Project 6 Southern Ocean sea level change project team
David Webb	UNSW, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Jingwei Zhang	University of Tasmania, Australia Project 6 Southern Ocean sea level change project team
Shujing Zhang	University of Tasmania, Australia Project 6 Southern Ocean sea level change project team

[12] Sponsored by the China Scholarship Council.

[13] Sponsored by the China Scholarship Council.

[14] Sponsored by the China Scholarship Council.

Appendix D Conference and workshop participation

Due to COVID-19 restrictions the meeting listed below were held online.

D.1 First Quarter (July to September)

ORCHESTRA/RoSES Program, United Kingdom, July 2020: Dr Rintoul gave an invited Keynote talk titled, “Changes in Antarctic Bottom Water: a view from East Antarctica.”

CLIVAR Pacific Regional Panel Meeting, August 2020: Dr Cai attended.

International Science Council Scientific Committee on Antarctic Research (SCAR): Antarctic Science – Global Connections Open Science Conference, August 2020: Dr Rintoul gave an invited Keynote talk titled, “What does a warming world mean for the Southern Ocean?” Dr Tamsitt gave a talk titled, “Lagrangian pathways and residence time of warm Circumpolar Deep Water on the Antarctic continental shelf.”

The Eleventh Indian Ocean Observing System (IndOOS) Resource Forum (IRF-11), August 2020: Dr Feng presented a talk titled, “Progress on international advocacy and support for the proposed RAMA Timor Sea Flux Station.”

BlueLink Ocean Forecasting 2020 Science Meeting, September 2020: Prof England, Dr Lenton, Dr Feng, Dr Chapman, Ms Cowley, and Dr Zhang attended. Dr Chapman and Ms Cowley presented a talk on the XBT network.

SOLAS (Surface ocean and lower atmosphere study) Indian Ocean Meeting, September 2020: Dr Feng attended.

OceanSITES Annual Meeting, September 2020: Dr Sloyan attended.

D.2 Second Quarter (October to December)

Southern Ocean Observing System (SOOS) Scientific Steering Committee, October/November 2020: Drs Shadwick and Herraiz Borreguero attended.

American Geophysical Union Fall Meeting, December 2020: Drs Cai, Santoso, Wang, Ng, Lyu, and students, Ms Jinping Wang, Ms Shujing Zhang attended. Drs Sloyan and Peña Molino where co-authors on presentations by Dr Wijffles. Professor England and Dr. Tamsitt were co-authors of several papers presented at the AGU Fall meeting.

Professor England presented a public lecture at the Royal Society of NSW annual general meeting.

D.3 Third Quarter (January to March)

AMOS Annual Meeting, February 2021, was attended by the majority of CSHOR staff and students including Drs Wang, Santoso, Zhang, Ng, Richet, Peña Molino, Sloyan, Rebecca Cowley, Feng, Chapman, Herraiz-Borreguero, Tamsitt; Mr Rathore; Prof England; Ms Jinping Wang; Mr Jingwei Zhang; and Ms Shujing Zhang. In addition to presenting papers and posters, CSHOR staff and students convened several sessions.

WCRP-CLIVAR Workshop on Climate Interactions among the Tropical Basins, February 2021: Dr Santoso was invited to present.

26th session of the CLIVAR Scientific Steering Group Meeting, March 2021: Dr Wenju Cai, a member of the Group, attended.

D.4 Fourth Quarter (April to June)

The General Assembly of the European Geosciences Union (EGU), April 2021: Drs. Sloyan, Chapman and Richet presented. Prof England was a co-author of several papers presented at this meeting.

GFD applications to climate research, May 2021: Prof England presented.

Japan Geoscience Union Meeting (JpGU), June 2021: Dr. Guojian Wang was invited to present an oral talk.

UN World Oceans Day, June 2021: Prof England presented at an outreach event.

Global climate teleconnections seminar, June 2021: Prof England presented a seminar.

ACCESS Science Day, June 2021: Prof England and Dr Zhang attended.

Appendix E Publications

E.1 Journal Articles

1. **Arroyo, M. C., E. H. Shadwick, B. Tilbrook, S. R. Rintoul, and K. Kusahara (2020). A continental shelf pump for CO2 on the Adélie Land coast, East Antarctica. *Journal of Geophysical Research: Oceans*, 125(10), e2020JC016302, doi.org/10.1029/2020JC016302.**

2. **Black, A. S., Risbey, J. S., Chapman, C. C., Monselesan, D. P., Moore, T. S., II, Pook, M. J., Richardson, D., Sloyan, B. M., Squire, D. T., & Tozer, C. R. (2021). Australian northwest cloudbands and their relationship to atmospheric rivers and precipitation. *Monthly Weather Review*, doi.org/10.1175/mwr-d-20-0308.1.**

3. **Cai, W., Ng, B., Geng, T., Wu, L., Santoso, A., & McPhaden, M. J. (2020b). Butterfly effect and a self-modulating El Niño response to global warming. *Nature*, 585, 68-73, doi.org/10.1038/s41586-020-2641-x.**

4. **Cai, W., Yang, K., Wu, L., Huang, G., Santoso, A., Ng, B., Wang, G., & Yamagata, T. (2020a). Opposite response of strong and moderate positive Indian Ocean Dipole to global warming. *Nature Climate Change,* doi.org/10.1038/s41558-020-00943-1.**

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