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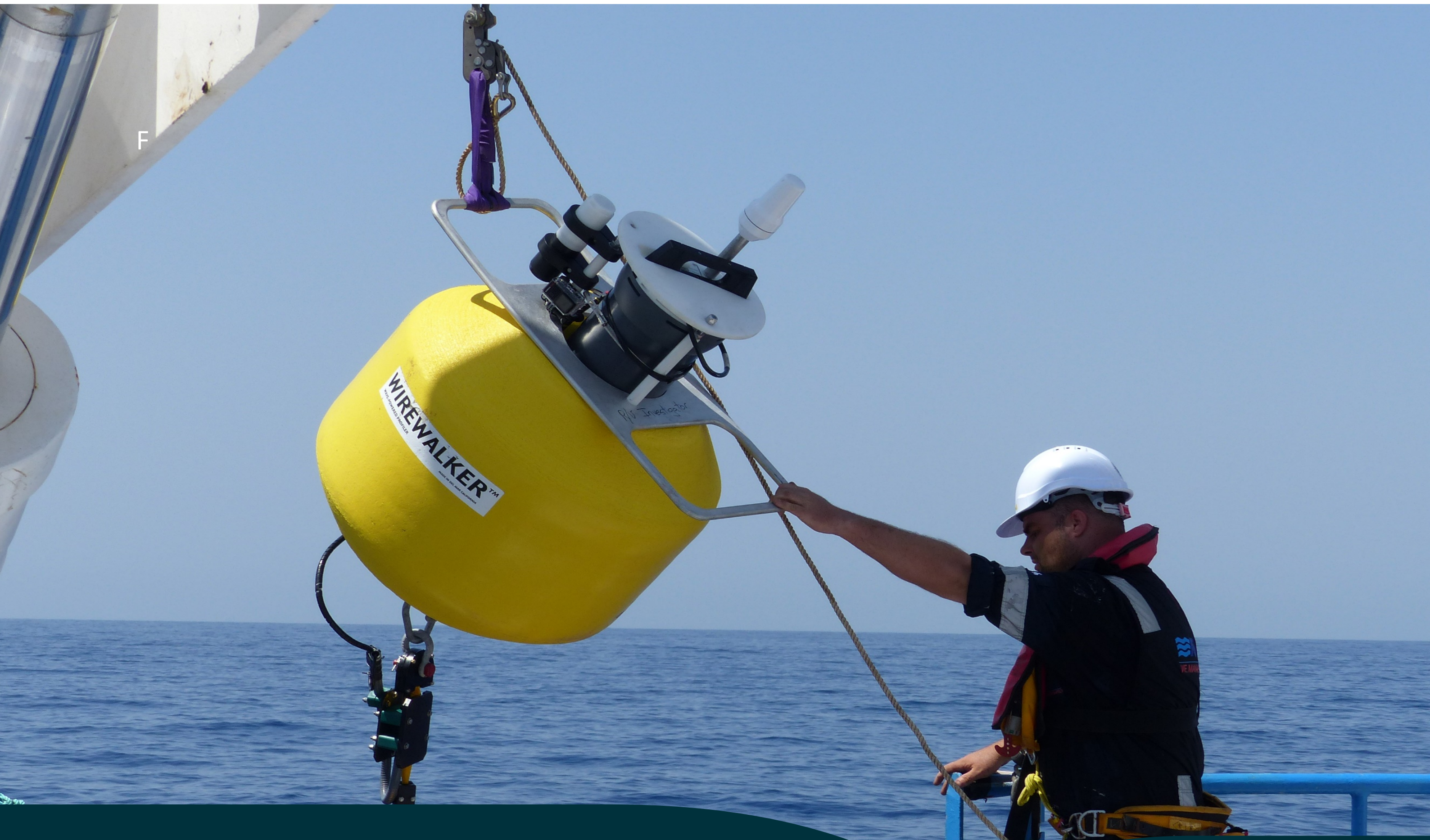
2019-20 Annual Report

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: Deployment of an RBR wire walker from *RV Investigator* (Image credit: Fangtao Zhang, Xiamen University, 2019).

Foreword

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

The Centre was launched in May 2017 with the purpose of conducting fundamental research into the role of the Southern Hemisphere ocean in regional and global climate systems. It is a collaborative research partnership between 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 high quality of the Centre's research is demonstrated in the achievements reported by the six project teams. Given the 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.

Centre staff were busy during this funding period organising and sponsoring international workshops and seminars. I especially enjoyed hearing from the early career researchers at the CSHOR Science Seminar that was conducted online in July 2020. They presented an impressive body of work for the year.

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

Kind regards,

Dr Susan Avery

Steering Committee Chair

August 2020

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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 third year of CSHOR's scientific research program.

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1 Executive summary

The third year of CSHOR operation furthers our scientific understanding of the southern hemisphere oceans and their role in global and regional climate. We have explored the changing impact of El Niño and its predictability in the context of pantropical interaction, and the changing decadal predictability, under greenhouse warming. We have examined the role of tidal mixing in controlling the structure of the Indonesian throughflow, the impact of eddy-induced heat transport to the Antarctic shelf on variability and the fate of the ice shelf, and the relative importance of warming, freshening, and changing winds in global sea-level rise and the associated regional fingerprints. Importantly, we have identified a link between tropical variability and Antarctic circulation, revealing for the first time that the increased variability in the tropical Pacific, as manifested in the extreme El Niño of 2015-16, may have conspired with the persistent positive state of the Southern Annular Mode to reverse a multidecadal freshening and cooling trend of the Antarctic Deep Water.

Notwithstanding the extraordinary circumstance surrounding COVID-19, our international leadership and collaboration flourished. We contributed to the OceanObs19 conference, a once-a-decade event that charts innovative solutions to society's growing needs for ocean information in the coming decade. We were successful in a multi-investor and multi-institutional partnership proposal for 'Measuring and Modelling the Indonesian Throughflow International Experiment'. We participated in a China - Australia joint field campaign in the Indo-Pacific warm pool and RV *Investigator* Years of the Maritime Continent (YMC) voyage to study high-resolution air-sea interactions. The scientific stimuli and outcomes of these engagements will contribute to our further success in the upcoming years.

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 2019-20 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 eight high profile research articles published by the *Nature* group (six) and *Science Advances* (two). In total, there were 45 publications (Appendix E). A selection of research achievements is presented below.

1.1.1 ENSO and the IOD

A *Nature Reviews Earth & Environment* article detailing the climate impacts of El Niño-Southern Oscillation on the climate of South America was published. This work is based on an international collaboration involving South American scientists and highlights key advances in ENSO research, such as event diversity, inter-basin interactions, and greenhouse warming (Cai et al., 2020).

A *Science Advances* paper shows that prediction of extreme El Niño/La Niña could become more challenging under greenhouse warming as the Atlantic feedback to the Pacific weakens (Jia and Cai et al., 2019). Another paper published in *Nature Climate Change* by Li et al. (2020) found that the Pacific Decadal Oscillation might become less predictable under global warming.

A book on ENSO in a changing climate is due to appear in September 2020. It was commissioned by Wiley under the banner of the American Geophysical Union Centennial and is coordinated by Drs Santoso and Cai as editors. The book consists of 21 chapters with 98 contributing authors, covering the extensive aspects of ENSO research.

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

International collaboration has been at the forefront of the Centre's activity during 2019-20. CSHOR staff played a key role in advancing development of the ocean observing system. At the OceanObs'19 conference in September 2019, a significant contribution was made to the development of field study parameters in the western Pacific, Indonesian Seas and the Indian Ocean. The Indo-Pacific project team engaged with representatives of ocean observing platforms, such as Argo, the Global Ocean Ship-Based Hydrographic Program (GO-SHIP) and Gliders, and international science policy and governance agencies, such as The Global Ocean Observing System Ocean Observations Physics and Climate panel (GOOS OOPC), Indian Ocean Observing System (IndOOS) and Tropical Pacific Observing System (TPOS) 2020.

CSHOR, CSIRO and the Integrated Marine Observing System (IMOS) lead Australian involvement in an exciting new international collaborative study of the Indonesian Throughflow titled, 'Measuring and Modelling the Indonesian Throughflow International Experiment (MINTIE)'.

An important model development, bulk flux forcing in the high-resolution MITgcm (Massachusetts Institute of Technology numerical model designed for the study of the atmosphere, ocean, and climate) was completed this year, providing researchers with greater accuracy in assessing the impact of tidal mixing on upper ocean properties and air-sea interactions.

We advanced our knowledge of how anthropogenic heat is redistributed in the world oceans. A research paper published in *Nature Communications* quantified the asymmetric pattern of the global ocean warming in the past decade, when the southern hemisphere oceans absorbed more than 90% of the anthropogenic heating of the ocean. While the greenhouse gas effect drove the overall warming trend of the ocean, the study shows the asymmetric warming pattern was most likely due to natural climate variability on the decadal time scale (Rathore et al., 2020).

The CSHOR field campaign, in collaboration with the First Institute of Oceanography, in the Indo-Pacific warm pool is completed. The IndOOS decadal plan has been revised, proposing an air-sea flux buoy in the Indonesian-Australian Basin, as an addition to the existing Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) array of the Indian Ocean.

The proposal is to maintain the sustained monitoring of the role of the Indian Ocean in the monsoon systems (Beal et al., 2019).

Along with collaborators from China, members of the Coupled warm pool dynamics project team joined the 2019 RV *Investigator* Years of the Maritime Continent (YMC) voyage. A wire walker was deployed to measure upper ocean variability in the warm pool of the Australian-Indonesian Basin. In conjunction with other oceanography and atmosphere shipboard measurements, the new data stream will further our understanding of the coupled ocean-atmospheric variability in the Indo-Pacific warm pool during pre-monsoon onset.

1.1.3 The Southern Ocean and Antarctica

The first comparison of air-sea heat fluxes at two Subantarctic Mode Water (SAMW) formation sites has led to a better understanding of the processes controlling SAMW formation and heat loss regimes in the southeast Pacific and the Southern Ocean south of Tasmania. The study improved the project team's understanding of the processes controlling interannual variability in mixed layer and SAMW formation at these regions (Tamsitt et al. 2020a). Seasonal-to-interannual variability in Southern Ocean surface mixed layer depth were also analysed and linked to both the Southern Annular Mode (Li et al., 2019) and ENSO (Li and England, 2020).

The biogeochemical structure of observed long-lived cold core mesoscale eddies in the Southern Ocean, south of Australia, has been characterised for the first time (Patel, Lenton et al., in press). This work showed that the distribution of nutrients in cold-core eddies is dominated by eddy dynamics below the mixed layer and by biological processes in the mixed layer. These eddies influence the concentration of nutrients exported from the Southern Ocean via mode waters. This water re-emerges at lower latitudes, driving productivity outside the Southern Ocean.

Regional variations of the eddy-induced overturning along the East Antarctic slope have been estimated using available hydrographic data collected by CTD-tagged seals (Foppert et al., *GRL*, 2019). Hot spots of eddy-driven transport of relatively warm, saline Circumpolar Deep Water were identified across the Antarctic slope. These hot spots influenced the reservoirs of heat and salt available at the shelf break.

Analysis of Southern Ocean change in the past year has focused on Antarctic Bottom Water (AABW). A unique long time-series of hydrographic observations was used to document a surprising rebound in the salinity and density of dense water formed on the Ross Sea continental shelf, after nearly 50 years of freshening (Castagno et al., 2019). A follow-up paper under review at *Nature Geoscience* uses repeat hydrography, deep Argo data, and reanalyses to identify the physical mechanisms responsible for the recovery of AABW formation (Silvano et al., 2020). The results show that an unusual combination of tropical and Southern Ocean forcing led to a temporary reversal in the long-term freshening trend driven by melt of Antarctic ice shelves.

The deep Argo floats deployed in 2018 continue to operate well and have survived winters under sea ice (this array is the first to demonstrate the feasibility of deep Argo operation under ice). Early data from the deep float array has been used in the Silvano et al. (2020) paper mentioned above and in a submitted paper using the deep float data to quantify pathways and changes in AABW (Thomas et al., 2020). A novel method to navigate floats under sea ice will increase the value of winter measurements made by deep floats (Wallace et al., 2020).

Two research papers provide important new insights into the physical processes that regulate the delivery of warm water to the base of floating ice shelves. A paper published in *Nature* by Wåhlin et al., shows the sharp change in water column thickness at the front of the ice shelf provides a dynamical barrier that restricts inflow of heat to the sub-ice shelf cavity by depth-independent (barotropic) motions. A paper submitted to *Journal of Geophysical Research: Oceans* shows that the oceanic heat content into the western Amundsen Sea is controlled by the Amundsen Sea Low. Although this research focused on West Antarctica, it shows that atmospheric variability should not be disregarded in favour of oceanic processes in other regions of Antarctica, such as East Antarctica.

1.1.4 Sea-level rise

Sea-level output from Coupled Model Intercomparison Project (CMIP) 5/6 ensembles were analysed and compared (Lyu et al., 2020b; Grose et al., 2020; Wu et al., 2020). The Ice Sheet System Model (ISSM) sea-level module with unstructured mesh grid developed by NASA/JPL was installed and tested extensively to various resolutions and underlying Earth models. The CMIP 5/6 sea-level analysis and the ISSM sea-level fingerprint modelling work set a solid foundation to provide next-generation total sea-level projection.

Significant progress has 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 submitted to *Nature Communications* (Wang et al., 2020).

Natural variability in Antarctic surface mass balance (net snow accumulation) was examined, focusing on the testing the sensitivity to different noise models (King and Watson, 2020).

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 (Phipps et al. 2020, in preparation).

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.

1.2.1 Media and communication

In summer 2019-20, Australia was struck by a severe and widespread bushfire season. This arrived during a period of sustained drought and led to an increase in enquiries related to seasonal climate research conducted at the Centre. There was media focus on the role of the Indian Ocean Dipole (IOD) in driving these events (droughts and fires) and how climate change would affect this in the future. Dr Cai contributed to numerous popular media articles citing CSHOR research, which were published by ABC News Australia, The Financial Review, Stock Journal Australia/The Land and Sciencenews.org (international).

Before the Austral summer had begun, reporters sought CSHOR perspectives on the drought in Australia. High-profile environmental journalist Peter Hannam published an article on 20 October 2019 in Australian premier national daily newspaper the Sydney Morning Herald (SMH). In this story, 'The culprit behind east Australia's big dry', CSHOR's Dr Cai and Prof. Matthew England discuss the role of the IOD and again the interaction with climate change. In March 2020, Peter Hannam again published in SMH a feature story on droughts in Australia, utilising Dr Cai and Prof. England expertise.

The Wåhlin et. al. study 'Ice front blocking of ocean heat transport to an Antarctic ice shelf' in *Nature* (February 2020) was well publicised and we profiled the contributions of CSHOR researcher Dr Herraiz-Borreguero through a blog published on CSIRO's website.

During the year, CSHOR's broad ranging ocean science expertise was often requested by media. An example of this was in March 2020 when an outbreak of locusts in east Africa was connected to seasonal climate patterns. Journalists reached out to CSHOR experts for comments and Drs Cai and Santoso explained their research on Indian Ocean Dipole. This was reported in National Geographic and Carbon Brief.

CSHOR scientists were also called on for media commentary about sea-level rise and Antarctica. National broadcaster ABC interviewed Dr Xuebin Zhang several times during the year about future sea-level rise locally and the accelerating rate of global sea-level rise. In early January, Dr Steve Rintoul discussed the importance of Antarctica for the Earth's climate on a leading national radio science show for ABC.

Across all CSHOR media activities during 2019-20 the estimated audience reach was over 730,000 in Australia.

1.2.2 Outreach – workshops and conferences

CSHOR research was presented at a host of national and international meetings during the first half of 2019-20. CSHOR staff convened sessions at several of these meetings. Major conferences and workshops attended by CSHOR staff are listed in Appendix C. A selection of highlights follow.

In July 2019, Drs Sloyan, Richet, Zhang and Prof King attended the 27th International Union of Geodesy and Geophysics (IUGG) General Assembly in Montreal, Canada. Dr Sloyan was invited to present to the Ocean Boundary Current session.

Drs Cai, Wang and Hsu attended the July 2019 Asia Oceania Geosciences Society (AOGS) Annual Meeting in Singapore. Dr Cai gave the Ocean Sciences Distinguished Lecture in which he presented recent findings showing that the frequency of extreme La Niña and variability of eastern Pacific El Niño sea surface temperature is expected to increase in response to unabated greenhouse gas emissions.

In September 2019, QNLM and CSIRO hosted a special session at OceanObs'19 in Hawaii. The session focused on building an international transparent ocean community by encouraging nations to share data, develop innovative observing technologies, and build a cost-effective global observing system. Dr Cai, Wang and Tilbrook attended the conference.

Also, in September 2019, Drs Cai and Wang attended the World Marine Science and Technology Conference in Qingdao. Dr Cai chaired the plenary session.

Drs Santoso, Wang, Ng, Feng and Zhang chaired a CSHOR session at the February 2020 meeting of the Australian Meteorological and Oceanographic Society (AMOS). Dr Cai gave an AMOS plenary talk. Drs Lyu, Foppert, and Ms Jinping Wang also attended.

In February 2020, Drs Foppert and Tamsitt and Prof England convened conference sessions at the Ocean Sciences Meeting. Dr Wenju Cai, as Climate and Ocean: Variability, Predictability, and Change (CLIVAR) Scientific Steering Group Co-chair, hosted the CLIVAR Town Hall Meeting.

CSHOR researchers, Drs Zhang, Lyu, Foppert and Tamsitt, hosted the online annual Consortium for Ocean-Sea Ice Modelling in Australia (COSIMA) workshop in May 2020, which was converted from a physical to virtual workshop due to COVID-19.

Unfortunately, the face-to-face meetings scheduled for February 2020 onwards were cancelled due to the physical distancing requirements and travel restrictions associated the COVID-19 pandemic.

1.2.3 Awards and special mentions

In November 2019, Dr Rintoul was awarded the Premier's Tasmanian STEM Researcher of the Year prize for his pioneering work on climate research in the Southern Ocean.

Dr Steve Rintoul receiving his award from The Hon. Michael Ferguson MP.

Prof England was awarded the 2019 Royal Society of New South Wales James Cook Medal for outstanding contributions to science and human welfare in and for the southern hemisphere.

Dr Santoso received the American Meteorological Society (AMS) Editor’s award for his reviews in the *Journal of Climate*, “For consistently high-quality reviews on various topics in tropical climate dynamics.” The 100th AMS Annual Meeting 2020 convened during January 2020 in Boston, USA.

Dr Cai was among 24 top Australian scientists inducted in May 2020 as Fellows of the Australian Academy of Science (AAS).

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, 2019-20 publications are emphasised in bold text. Appendix E comprises a list of CSHOR manuscripts published in 2019-20. Datasets produced by CSHOR projects are recorded in Appendix D .

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

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

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

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

2.1.1 Year 3 highlights and progress against project objectives

A review paper (Cai et al., 2020) documenting the climate impacts of El Niño-Southern Oscillation on the climate of South America is published in *Nature Reviews Earth & Environment*. This work, based on an international collaboration involving South American scientists, highlights the key advances in ENSO research such as event diversity, inter-basin interactions, and greenhouse warming, which are apparent when examining the ENSO impact on South American climate. A paper published in *Science Advances* by Jia and Cai et al. (2019) shows that prediction of extreme El Niño/ La Niña could become more challenging under greenhouse warming as the Atlantic feedback to the Pacific weakens. Another paper published in *Nature Climate Change* by Li and Cai et al. (2020) found that the Pacific Decadal Oscillation could become less predictable under global warming as the warming-induced intensification of oceanic stratification, which accelerates propagation of Rossby waves, shortens the PDO lifespan and suppresses its amplitude by limiting its growth time. A chapter for the American Geophysical Union Monograph (Cai et al., 2020) provided a review on ENSO response to greenhouse forcing, detailing the community efforts throughout the past decades in studying ENSO projection and its uncertainties, and presenting the most recent results for projected increase in the frequency of ENSO extremes.

2.1.2 Project performance against milestones

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

Milestone 1: Recruit one postdoctoral research fellow

The recruitment process for a postdoctoral research fellow is underway to commence in early 2021. It is a 3-year position under supervision of Drs Cai, Santoso and Wang.

Dr Benjamin Ng will continue to work as a postdoctoral research fellow until October 2020, before taking up a 3-year research scientist position with CSHOR.

Milestone 2: Using data collected and experiments conducted from last financial year to examine the link between wind surges and extreme ENSO events, including the modulating effect of decadal variability

Westerly wind events (WWEs), abrupt abatements or reversals of the Trade Winds, are integral to the development of El Niño. WWEs cause an eastward displacement of the west Pacific warm pool, which in turn promotes more WWEs and an eastward shift of atmospheric convection that can lead to development of strong El Niño events. However, factors influencing WWE generation are not fully understood. Cai et al., 2020a shows that decadal mean surface ocean temperatures in the tropical Pacific associated with a warm phase of the Pacific Decadal Oscillation (PDO) is one potential key factor that boosts development of WWEs and thus the frequency of strong El Niño events. Given that the positive PDO itself is partially a consequence of the decadal modulation of El Niño, such linkage implies a positive feedback between weather and decadal variability, influencing the frequency of strong El Niño from one decade to another.

Work on decadal variability has been extended and is ongoing. The Pacific Decadal Oscillation (PDO), or the closely related Interdecadal Pacific Oscillation (IPO), is the most prominent form of decadal variability over the Pacific which exerts significant influence on marine ecosystems, fisheries, and agriculture on a global scale. It modulates global mean temperature and is shown by Bordbar et al. (2019; published in *Nature Communications*) to contribute to uncertainty in predicting near-term global mean temperature rise (e.g., the recent global warming hiatus). The study suggests that the uncertainty can be significantly reduced if the state of the IPO is known and incorporated at the initialisation phase of prediction models. Given the significant ramifications, determining the predictability of the PDO in a warming climate is of great importance. By analysing future climate under different emission scenarios simulated by the Coupled Model Intercomparison Project phase 5 (CMIP5), Li et al., 2020 (published in *Nature Climate Change*) shows that the prediction lead time and the associated amplitude of the PDO decreases sharply under greenhouse warming conditions. This decrease is largely attributable to a warming-induced intensification of oceanic stratification, which accelerates propagation of Rossby waves, shortening the PDO lifespan and suppressing its amplitude by limiting its growth time. Our results suggest that greenhouse warming will make prediction of the PDO more challenging, with far-reaching ramifications. Putting aside the influence of greenhouse warming on natural variability, a study by Hu et al. (2020) found a deep-reaching acceleration of the global ocean circulation since the early 1990s that appears to be part of a long-term trend beyond the wind-intensification effect of the recent negative PDO/IPO.

Milestone 3: Review the dynamical mechanisms and teleconnections for ENSO's influence on South America

The concept of an El Niño, originally describing a warmer than normal oceanic condition off the tropical western South American coast with severe impacts on local fisheries, weather, and ecosystems, has evolved remarkably over the past decades. The widely accepted importance of El Niño-Southern Oscillation in the climate system together with the realisation of its dynamical complexity, event diversity, and two-way interactions with other oceans, has triggered renewed interest in its impact on South America. Cai et al. (2020a) conducted a detailed review and analysis covering various issues, including ocean-atmosphere processes governing the impact, its inter-event and decadal variability, and possible changes associated with greenhouse warming-induced climate change. The paper concludes that a co-ordinated international effort is required to close the observational, theoretical and modelling gaps currently limiting progress on these issues. This work (Cai et al., 2020b) involved an international collaboration with many well-known scientists and is published in *Nature reviews: Earth & Environment*.

An extended work relating to teleconnections under this milestone includes a study by Jia et al., 2019 (published in *Science Advances*) that found greenhouse warming leads to a weakened influence from the Atlantic Niño/Niña on the Pacific ENSO. In response to anomalous equatorial Atlantic heating, ascending motion over the equatorial Atlantic is weaker due to an increased tropospheric stability in the mean climate, resulting in a weaker impact on the Pacific Ocean. As greenhouse warming continues, Pacific ENSO is projected to be less affected by the Atlantic Niño/Niña and more challenging to predict.

Milestone 4: Investigating climate drivers of Indonesian Throughflow variability in observation and CMIP5 models

The Pacific and Indian Oceans are linked by an oceanic gateway that allows voluminous flow of water from the Pacific to the Indian Ocean termed the Indonesian Throughflow (ITF). How the ITF variability is influenced by ENSO and IOD, and how climate models simulate the interplay, are not well understood. Santoso et al. (2020a) examined the issue in 20 CMIP5 models and an ocean reanalysis. The analysis has been completed and the results written up. The study details the complex links between ITF variability with ENSO and IOD, as well as ENSO-IOD interaction, through identification of ITF variability vertical modes. It further reveals how model biases in simulating ENSO, IOD, and their linkage, can impact the representation of ITF variability in climate models.

Extended work on the topic of Indo-Pacific linkage involves ongoing projects with Dr Santoso's PhD student at UNSW, Ms Shreya Dhame, who investigates the impact of Indian Ocean warming on climate. The Indian Ocean has exhibited the most rapid warming among other oceanic basins. Dhame et al. (2020) conducted sensitivity experiments with an atmospheric model forced with either spatially uniform or varying pattern of Indian Ocean warming trends. The spatial pattern of the warming is found to exert significant impact on rainfall trends in the basin, easterly wind trend in the western Pacific, and intensity of Hadley Circulation changes. The magnitude of the warming trend is found to influence the drying over tropical Atlantic and trends in extratropical variability. The impact on ENSO variability will be examined in a future study.

Milestone 5: Understanding ENSO and IOD characteristics in climate models; and examining modes of variability under greenhouse warming

An improved identification of extreme El Niño events is important for a better understanding of how ENSO will change in the future. Our previous work defined extreme El Niño events as Niño3 rainfall exceeding 5 mm per day (Cai et al., 2014), and an index representing the sea surface temperature variability of eastern Pacific El Niño greater than 1.5 standard deviation (Cai et al., 2018). We found that extreme El Niño events based on both definitions are projected to occur more frequently under greenhouse warming. This motivated a new study examining whether there is any difference between strong convective El Niño events and strong warm El Niño events that correspond to each of the definitions. This work led by Dr Wang (Wang et al., 2020 published in *Journal of Climate*) reconciles the two definitions for extreme El Niño events for the first time, one by total rainfall (convective El Niño) and one by sea surface temperature anomalies (warm El Niño) over eastern tropical Pacific Ocean. The two types of events do not always coincide with each other, and the disassociation becomes more distinct under greenhouse warming, when most of the climate models examined project a higher increase in extreme convective El Niño than extreme warm El Niño events.

Further work on the topic has been conducted. A large book project on ENSO in a changing climate commissioned by Wiley under the banner of the AGU Centennial is coordinated by Drs Santoso and Cai as editors. The book is recently completed with 3 chapters authored by Drs Santoso and Cai (McPhaden et al., 2020, Cai et al., 2020, and Karamperidou et al., 2020). The book consists of 21 chapters with 98 contributing authors, covering the extensive aspects of ENSO research including theories, observations, paleo-reconstructions, modelling, prediction, future projections, teleconnections and various impacts such as weather extremes, fisheries, and global carbon cycle. It is due to appear in September 2020. A review and analysis on the linkage between ENSO and IOD in observations and models are being conducted considering the recent strong positive IOD in 2019 (Santoso et al., 2020b). Dr Santoso's Honours student at UNSW investigated IOD and linkage with ENSO in CMIP5 and CMIP6 models (McKenna et al., 2020; published in *Scientific Reports*), finding some modest improvements from CMIP5 to CMIP6, and systematic changes in the impact of mean state biases on the strength of the IOD.

Milestone 6: Conducting model experiments to investigate Southern Ocean role on tropical variability

Various experiments have been conducted using the CSIRO Mk3L climate model which is set up to enable millennium-long model integration for studying large-scale climate variability on long time scales. This includes experiments with freshwater hosing with differing intensities applied to the Southern Ocean and North Atlantic to investigate the impact on tropical climate variability, including the interactions between ENSO and decadal variability. The experiments have been completed and more detailed analysis is underway.

2.1.3 Project publications[1]

Bordbar, M. H., England, M. H., Sen Gupta, A., Santoso, A., Taschetto, A. S., Martin, T., Park, W. Latif, M. (2019). Uncertainty in near-term global surface warming linked to tropical Pacific climate variability. *Nature Communications*, 10(1), 1990. doi:10.1038/s41467-019-09761-2.

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, in press.

Cai, W., et al. (2020a). Westerly wind events boosted by a Pacific Decadal Oscillation warm phase, to be submitted.

Cai, W., McPhaden, M. J., Grimm, A. M., Rodrigues, R. R., Taschetto, A. S., Garreaud, R. D., . . . Vera, C. (2020b). Climate impacts of the El Niño–Southern Oscillation on South America. *Nature Reviews Earth & Environment*, 1(4), 215-231. doi:10.1038/s43017-020-0040-3.

Dhame., S., A. Taschetto, A. Santoso, K. Meissner (2020). Indian Ocean warming modulates global atmospheric circulation trends. *Climate Dynamics*, accepted.

Hu, S., Sprintall, J., Guan, C., McPhaden, M. J., Wang, F., Hu, D., & Cai, W. (2020). Deep-reaching acceleration of global mean ocean circulation over the past two decades. *Science Advances*, 6(6), eaax7727. doi:10.1126/sciadv.aax7727.

Jia, F., Cai, W., Wu, L., Gan, B., Wang, G., Kucharski, F., . . . Keenlyside, N. (2019). Weakening Atlantic Niño–Pacific connection under greenhouse warming. *Science Advances*, 5(8), eaax4111. doi:10.1126/sciadv.aax4111.

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, in press.

Li, S., Wu, L., Yang, Y., Geng, T., Cai, W., Gan, B., Chen, Jing, Z., Wang, G., Ma, X. (2020). The Pacific Decadal Oscillation less predictable under greenhouse warming. *Nature Climate Change*, 10(1), 30-34. doi:10.1038/s41558-019-0663-x.

[1] 2019-20 publications in bold text.

McKenna, S., A. Santoso, A. Sen Gupta, A. Taschetto, W. Cai (2020). Indian Ocean Dipole in CMIP5 and CMIP6: Characteristics, biases, and links to ENSO. *Scientific Reports* 10(1), 11500. doi: 10.1038/s41598-020-68268-9.

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, in press.

Santoso, A., et al. (2020a). Indonesian Throughflow variability and its link with ENSO and IOD in CMIP5 models ensemble, *JGR Oceans*, to be submitted.

Santoso, A., et al. (2020b). El Niño Southern Oscillation, the Indian Ocean Dipole, and their interactions, *Nature Communications*, to be submitted.

Wang, G., Cai, W., & Santoso, A. (2020). Stronger Increase in the Frequency of Extreme Convective than Extreme Warm El Niño Events under Greenhouse Warming. *Journal of Climate*, 33(2), 675-690. doi:10.1175/jcli-d-19-0376.1.

2.2 Project 2: Indo-Pacific inter-basin exchange

Project leader – Dr Bernadette Sloyan (CSIRO)

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

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

2.2.1 Year 3 highlights and progress against project objectives

CSHOR's strong leadership at OceanObs'19 (Hawaii, September 2019) in writing community white papers and conference participation, provided a focus on the need for observations of the southern hemisphere oceans. This is required in order to advance our understanding and improve prediction of the Earth's climate. The project team made a valuable contribution to discussion of the western Pacific, Indonesian Seas and Indian Ocean observations. Input was also provided to various ocean observing platforms (e.g. Argo, GO-SHIP and Gliders) and international science policy and governance (e.g. OOPC, GOOS, INDOOS, TPOS2020). Overall, the CSHOR project team played a key role in advancing development of the ocean observing system.

The implementation of bulk flux forcing in the high-resolution MITgcm was successfully completed this year. This important model development enables us to more accurately assess the impact of tidal mixing on upper ocean properties and air-sea interactions. The timely and successful implementation of bulk forcing was more remarkable given it was undertaken during a period of considerable change of computing infrastructure. The Australian High-Performance Computing System, which manages the National Computing Infrastructure (NCI), transitioned to a new computing structure.

The analysis of in-hand mooring observations continued, and the project team was invited to present these findings at several fora. Unfortunately, the travel and physical distancing restrictions associated with COVID-19 prevented meeting attendance between March and June.

The Measuring and Modelling the Indonesian Throughflow International Experiment (MINTIE) has progressed, and while the voyages are delayed, the mooring build is complete, and staff are ready to order floats.

Finally, Ms Ana Berger, a student associated with CSHOR, was awarded her PhD from the University of Tasmania.

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, US and China: Measuring and Modelling the Indonesian Throughflow (MINTIE)

It has been a challenging year for the planning and implementation of the fieldwork component of this project. While the USA, CSHOR, Australian IMOS, Indonesian and other international partner funding was secured in 2019, confirmation of voyage dates has been delayed due to COVID-19. It is hoped the date for the first of three voyages will fall in late-2020. The other voyages are planned for September-October 2021 or January-February 2022.

The design and build of two Australian moorings are completed. These moorings will join two American moorings and will extend the MINTIE Timor Passage mooring array to the south, enabling complete observational coverage of the Indonesian Throughflow outflow via the Timor Passage (Figure 1 and Figure 2). The moorings will be stored at CSIRO Oceans & Atmosphere's storage facility in Hobart, until they can be shipped to the USA for consolidation into the MINTIE mooring equipment store, and then shipped to Indonesia prior to the first mooring voyage.

Argo float requirements are finalised, and manufacturer's quotes received. Given the likely voyage schedule, we plan to order these floats in either late-2020 or early-2021.

An Australian Research Council (ARC) Linkage Proposal, led by Dr Helen Phillips is submitted. If successful, the proposal will enhance our float sensor capability to include an ocean mixing sensor. The proposal also includes funds for a postdoctoral fellow and a PhD student scholarship. An announcement regarding successful bids is expected in November 2020.

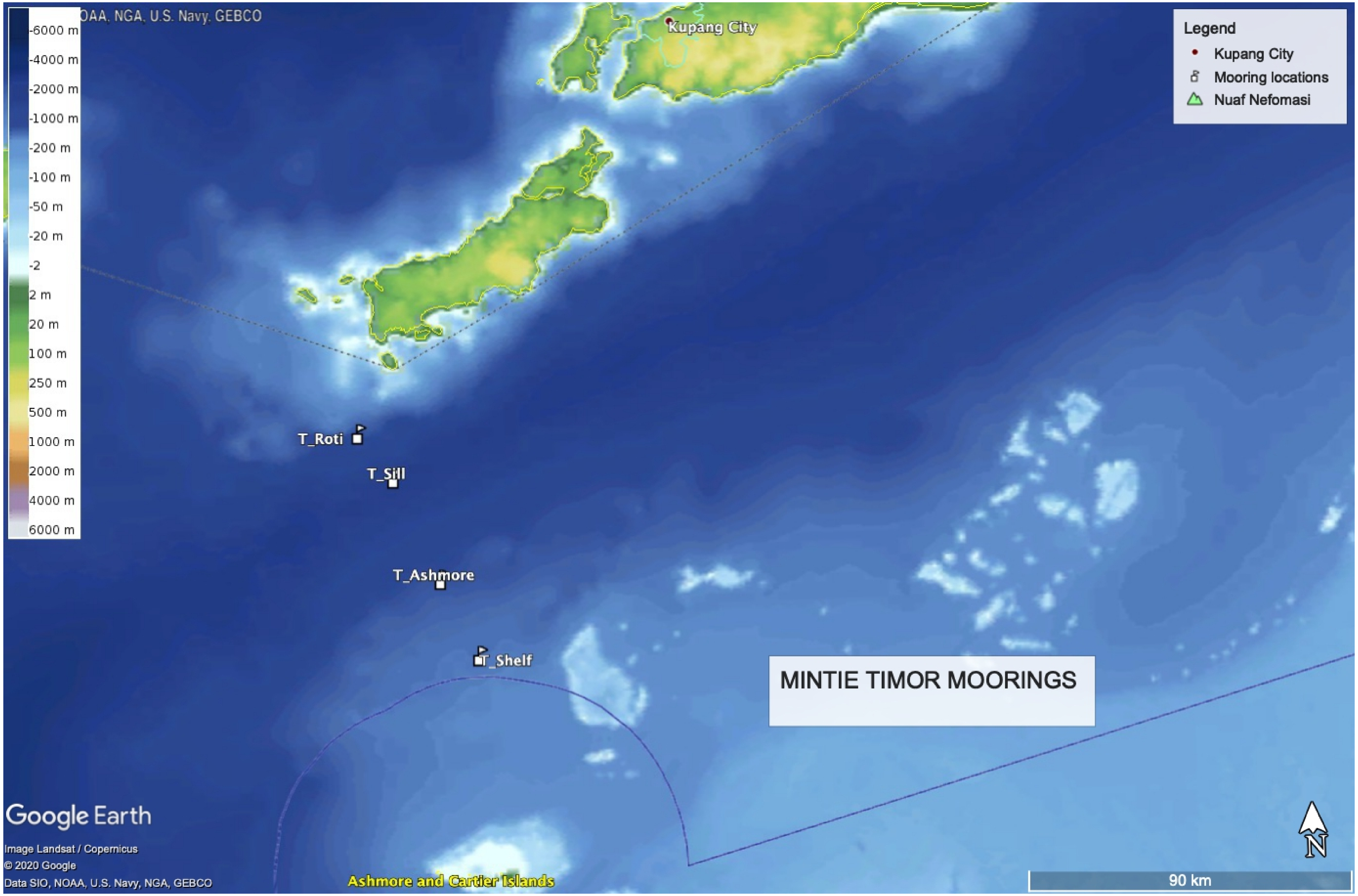

Figure 1 Planned locations of the MINTIE deep water moorings in the Timor Strait. The two CSHOR MINTIE moorings (T_Ashmore and T_Shelf) are in the southern end of the Strait. The northern moorings (T_Roti and T_Sill) will be supplied by WHOI.

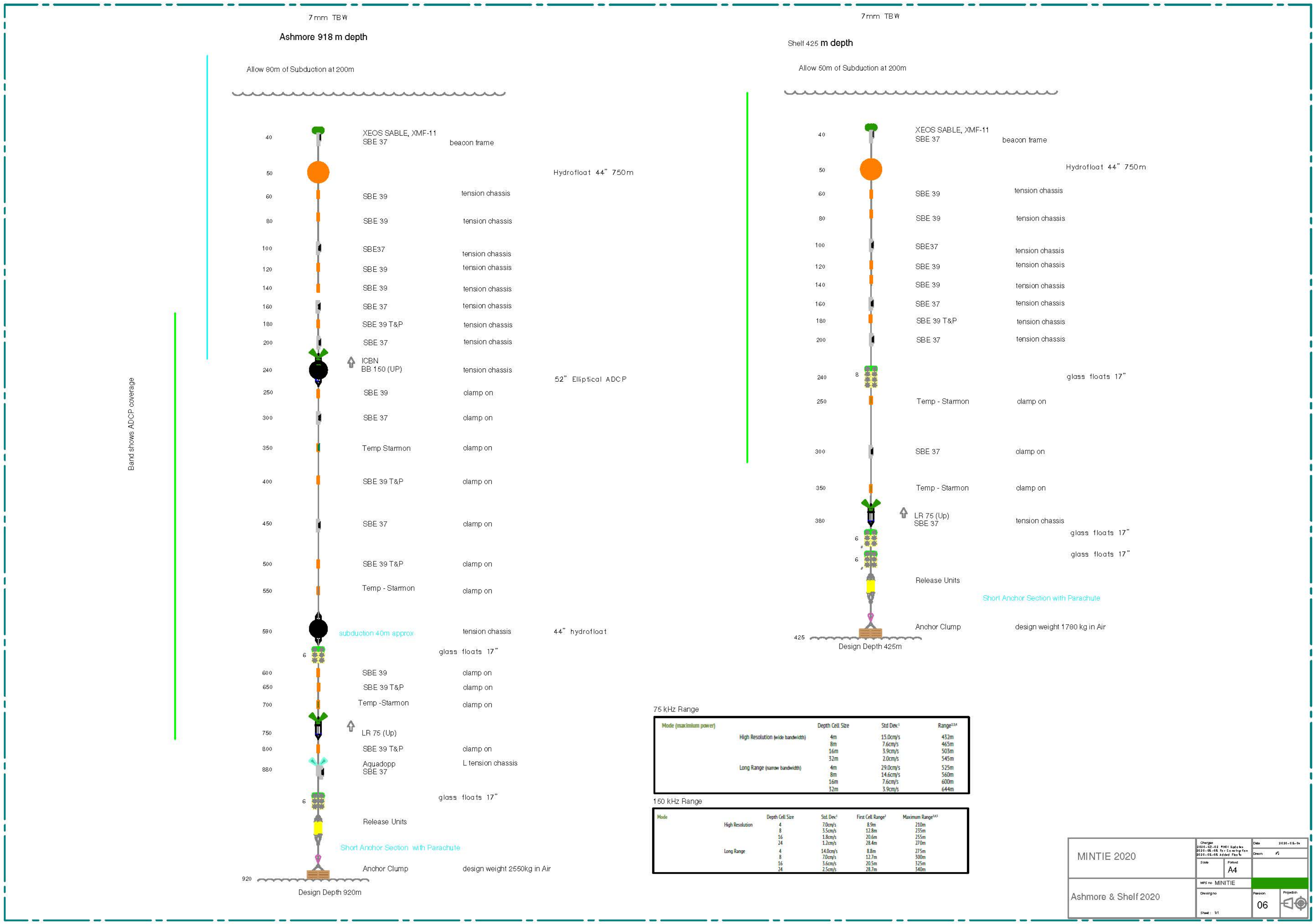

Figure 2 Design of the Timor Ashmore and Shelf moorings for MINTIE. An impressive array of oceanographic instruments will be deployed on the moorings providing velocity observations for the entire water column and high-resolution temperature and salinity observations.

Milestone 2: Include tidal forcing in the high-resolution region MITgcm (Massachusetts Institute of Technology numerical model designed for the study of the atmosphere, ocean, and climate) model

In the previous year, the MITgcm regional model was set up and ran using sea surface temperature and sea surface salinity relaxation to mimic the air-sea interactions. While surface property relaxation is appropriate for analysis of most interior ocean processes, it is not the optimum arrangement for studies targeting the modulation of surface temperature and salinity by ocean interior mixing. A strategic decision was made to move to surface bulk forcing of the MITgcm regional model. A significant amount of effort was required to move to this arrangement of the model.

The project team established equilibrium runs of the 10 km model (12 years) and the 4 km model (3 years). The tidal forcing (4 major constituents applied at the boundaries) has been implemented in the 10 km model. When the tidal model is stable, the team will move to the implementation of tides in the 4k m model.

During the year, the Australian National Computing Infrastructure (NCI) upgraded the high-performance computing centre to a new computing architecture titled, ‘Gadi’. This required the porting of and testing of our MITgcm configuration, resulting in a short delay in the implementation of the tide resolving model.

Milestone 3: Develop targeted model studies investigating the influence tidal mixing on the seasonal and mean properties of the Indonesian Sea.

In parallel to implementing the significant change to the surface ocean boundary condition, the project team developed the science plans and required model to enable an investigation of the influence of tides on the properties of the Indonesian Seas.

An initial study is planned for four major tide constituents in the 10 km model to examine the impact of the horizontal mixing induced by the tides on volume, heat and salt transport. The team will examine the seasonal variations and the time mean and the vertical structure by comparison with the previous seasonal simulation without the tides.

A second study will consider the impact of tides on the vertical mixing and property changes through the seasonal evolution of the thermocline and boundary forcing of the four major tide constituents in the 4 km model.

With these plans and the bulk forced model running, the team is ready to begin the target model runs. Comparing the non-tidally and tidally forced models will enable us to determine the impact of tides on the ITF and Indonesian Seas.

Milestone 4: Analysis of observation and model data investigating the intra and interannual variability of the ITF transport and properties

The analysis of the IMOS Ombai and Timor moorings and comparison to other moorings is complete. The IMOS ITF mooring data is a challenging data set for several reasons, one being the analysis of the IMOS moorings shows a significant reduced transport to that from the International Nusantara Stratification and Transport (INSTANT) moorings. We have spent considerable time assessing the reason for this difference. For various reasons the IMOS and INSTANT mooring in Timor Passage were in different locations, eastern and western end of the passage, respectively. The current at the eastern and western ends has a very different dynamical balance. At the eastern end the current is actively readjusting after flowing through numerous passages upstream and the nearly 180^{o} turn around the eastern tip of Timor Island (Peña Molino et al., 2020a and Peña Molino et al., 2020b). It appears, at the eastern end of the passage, that the narrow current core meanders between the IMOS ITF moorings. This meandering resulted in the need to develop a careful extrapolation scheme across the passage. This analysis was presented at the Ocean Sciences Meeting in February 2020 (Wijffels, S. et al., 2020). Dr Beatriz Peña Molino plans to prepare a manuscript in 2020-21 presenting these results.

Ms Ana Berger was awarded a PhD from the University of Tasmania for her study of the dynamics of ITF outflows. This study investigated the determinants of the amount of western pathway water exiting Lombok Strait. Experiments testing boundary conditions and vorticity equation terms were used to investigate the ITF dynamics. The study illustrates the effects of current width on the transport through Lombok Strait (Berger, A., 2020).

A study of the response of the background state of the Indonesian Seas to seasonally variable forcing was completed. Using a high-resolution regional model, the study examined the contribution of the remote and local forcing to this background state. The model results show that the main impact of the seasonal variability of the forcing is isolated to the upper ocean (0-300 m). The seasonality of the forcing induces an increase of the kinetic energy of 30% which impacts the circulation in the inflow and outflow straits. The remote forcing sets the volume transport and the energy entering in the Indonesian Seas while the local forcing redistributes the energy in the interior seas. Thus, the circulation of the region and inflow and outflow passages is a complex interplay between local and remote forcing. In addition, the local forcing controls the mixed layer temperature and salinity through the Ekman circulation, the horizontal advection and the turbulent vertical mixing. A manuscript is ready for submission to an international journal (Richet, O. et al., 2020).

Milestone 5: Appropriate and timely guidance to International Laboratory for High-Resolution Earth System Prediction (iHESP)

In February 2020, Dr Sloyan attended the iHESP Science Advisory Committee Meeting in Boulder, USA. She contributed to the meeting report. The Committee recommended CSHOR and iHESP consider holding a joint CSHOR-iHESP science meeting.

During her visit to Boulder, Dr Sloyan attended several meetings with iHESP principle investigators in which she was hoping to secure the use of the iHESP high-resolution coupled model in the CSHOR project. As a result of these meetings, the CSHOR project team can access the iHESP model data.

Milestone 6: Participate in development of a sustained observing system for the ITF/Indonesian Seas

Project members were first and contributing authors on several OceanObs'19 community white papers and active participants in the September 2019 meeting (Sloyan, B. et al., 2019, Hermes J., et al., 2019, Sprintall, J., et al., 2019, Palmer, M., et al., 2019).

Team members provided significant input to the Indian Ocean Observing System review and associated publications (Beal et al., 2020, Beal et al., 2019a, Beal et al., 2019b).

2.2.3 Project publications[2]

Beal, L.M., Vialard, J., Roxy, M.K., Li, J., Andres, M., Annamalai, H., Feng, M., Han, W., Hood, R., Lee, T., Lengaigne, M., Lumpkin, R., Masumoto, Y., McPhaden, M.J., Ravichandran, M., Shinoda, T., Sloyan, B.M., Strutton, P.G., Subramanian, A.C., Tozuka, T., Ummenhofer, C.C., Unnikrishnan, A.S., Wiggert, J., Yu, L., Cheng, L., Desbruyères, D.G., Parvathi, V. (2020). A roadmap to IndOOS-2: Better observations of the rapidly warming Indian Ocean. *Bulletin of the American Meteorological Society*. doi: 10.1175/BAMS-D-19-0209.1.

Beal, L. M., Vialard, J., Roxy, M. K. et al. (Including Feng, M., Sloyan, B.) (2019a). Full Report. IndOOS-2: A roadmap to sustained observations of the Indian Ocean for 2020-2030. CLIVAR-4/2019, GOOS-237, 206 pp. doi.org/10.36071/clivar.rp.4.2019.

Beal, L. M., Vialard, J., Roxy, M. K. et al. (Including Feng, M., Sloyan B.) (2019b). Executive Summary. IndOOS-2: A roadmap to sustained observations of the Indian Ocean for 2020-2030. CLIVAR-4/2019, GOOS-237, 8 pp. doi.org/10.36071/clivar.rp.4-1.2019.

Berger, Ana Paula (2020). Mean circulation of the Indonesian Throughflow and a mechanism of its partitioning between outflow passages: A regional model study. PhD thesis. University of Tasmania. (Supervisors; B. M. Sloyan, M. Nikurashin, B. Peña Molino, S. Wijffels).

Hermes, J. C., Y. Masumoto, L. Beal, et al. (2019). A sustained ocean observing system in the Indian Ocean for climate related scientific knowledge and societal need. *Frontiers in Marine Science*, 6(355). doi.org/10.3389/fmars.2019.00355.

Kiss, A. E., Hogg, A. M., Hannah, N. et al. (Including Richet, O. and Zhang, X.) (2020). ACCESS-OM2 v1.0: a global ocean–sea ice model at three resolutions. *Geosci. Model Dev.*, 13(2), 401-442. doi:10.5194/gmd-13-401-2020.

Palmer, M. D., Durack, P. J., Chidichimo, M. P. et al. (Including Church, J., Sloyan, B., and Wijffels, S.) (2019). Adequacy of the Ocean Observation System for Quantifying Regional Heat and

[2] 2019-20 publications are shown in bold text.

Freshwater Storage and Change. *Frontiers in Marine Science*, 6(416). doi:10.3389/fmars.2019.00416.

Peña Molino, B., Wijffels, S. E., Sloyan, B. M., Richet, O. and Nikurashin, M. (2020a). Revisiting the seasonal cycle of the Timor Throughflow: volume, heat and freshwater transports. *Journal of Geophysical Research-Oceans*, in preparation.

Peña Molino, B., Wijffels, S. E., and Sloyan, B. M., Richet, O. and Nikurashin, M. (2020b). Structure and Variability of the Indonesian Throughflow in the Timor Passage. *Journal of Physical Oceanography*, in preparation.

Richet, O., Nikurashin, M., Peña Molino, B., Sloyan, B. M., Wijffels, S. E. (2020). The role of the seasonal variability on the background state of the Indonesian Seas. *Journal of Geophysical Research: Oceans*, to be submitted.

Sloyan, B. M., Wilkin, J., Hill, K. L., Chidichimo, M. P., Cronin, M. F., Johannessen, J. A., . . . Yu, W. (2019). Evolving the Physical Global Ocean Observing System for Research and Application Services Through International Coordination. *Frontiers in Marine Science*, 6(449). doi:10.3389/fmars.2019.00449.

Sprintall, J., A. Gordon, S. Wijffels, et al. (2019). Detecting change in the Indonesian Seas. *Frontiers in Marine Science*, 6(257). doi.org/10.3389/fmars.2019.00257.

Wijffels, S. E., Peña Molino, B., Sloyan, B. M., and Steinberg, C. (2020). Direct observations of the Indonesian Throughflow in Timor and Ombai Straits 2011-2015. Invited Talk, 2020 Ocean Sciences. https://agu.confex.com/agu/osm20/meetingapp.cgi/Paper/653606.

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

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

The Indo-Pacific warm pool hosts the largest global centre of deep convection, the dominant source of latent heating and moisture for the global atmosphere. The warm pool enables important coupled climate modes, such as El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden-Julian Oscillation (MJO). These 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/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 planning papers 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 3 highlights and progress against project objectives

After the retrieval of the Bailong buoy off northwest Australia in January 2020, the CSHOR field campaign, in collaboration with the First Institute of Oceanography (FIO), in the Indo-Pacific warm pool has concluded. A journal publication outlining the campaign has been accepted in the *Bulletin of the American Meteorological Society.* The paper summarises the achievement and promotes the CSHOR campaign (Feng et al., 2020). Two MJO convective phases propagated eastward across the region in mid-December 2018 and late-January 2019 and the second MJO was in conjunction with a tropical cyclone development. Observations showed that sea surface temperature (SST) in the region was rather sensitive to the MJO forcing. Air-sea heat fluxes warmed the SST up throughout the 2018-19 austral summer, punctuated by the MJO activities, with 2-3°C drop in SST during the two MJO events. Substantial diurnal SST variations during the suppressed phases of the MJOs were observed, and the near-surface thermal stratifications provided positive feedback for the peak diurnal SST amplitude, which may be a mechanism to influence the MJO evolution.

Figure 3 below indicates the location of the field campaign. The successful deployment of the Bailong buoy has attracted attention from the Indian Ocean Observing System (IndOOS) community. In the revised IndOOS decadal plan, an air-sea flux buoy in the Indonesian-Australian Basin has been proposed as an addition to the existing Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) array of the Indian Ocean. If enacted, the proposal will maintain the sustained monitoring of the roles of the Indian Ocean in the monsoon systems (Beal et al., 2019).

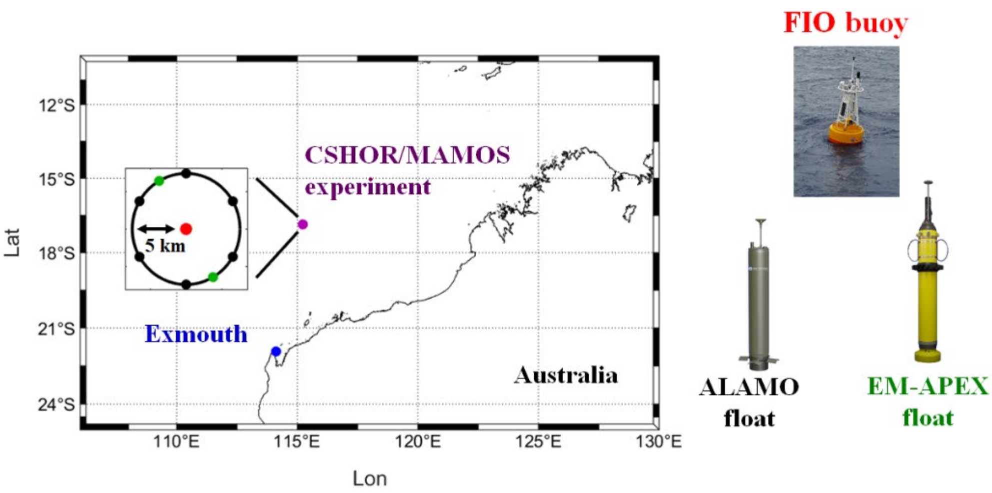

Figure 3 CSHOR field campaign diagram (From Feng et al., 2020)

In a parallel effort, Drs Susan Wijffels and Andy Hsu and Ms Anna Maggiorano participated in the 2019 RV *Investigator* Years of the Maritime Continent voyage, along with collaborators from China.

They worked with RBR Electronic to successfully deploy a wire walker to measure the upper ocean variability in the warm pool of the Australian-Indonesian Basin, in conjunction with other oceanography and atmosphere shipboard measurements. The new data stream will further our understanding of the coupled ocean-atmospheric variability in the Indo-Pacific warm pool during pre-monsoon onset.

In collaboration with scientists from the Institute of Oceanology, Chinese Academy of Sciences (IOCAS), the CSHOR project team investigated how the variability of the Indonesian Throughflow can transmit a low-frequency salinity signal into the Indian Ocean and affect the salinity balance in the basin (Hu et al., 2019). In another collaborative work, the downscaled future projection of the Indian Ocean heat balance and meridional heat transport under the influences of anthropogenic global warming was investigated (Ma et al., 2020). The slowdown of the meridional heat transport can enhance the warming of the Indian Ocean.

Knowledge of how anthropogenic heat is redistributed in the world oceans has advanced. A research paper published in *Nature Communications*, led by PhD student, Mr Saurabh Rathore, and co-supervised by Dr Ming Feng, quantified the asymmetric pattern of the global ocean warming in the past decade, when the southern hemisphere oceans absorbed more than 90% of the anthropogenic heating of the ocean. Whereas the greenhouse gas effect drove the overall warming trend of the ocean, the asymmetric warming pattern was most likely due to natural climate variability on the decadal time scale (Rathore et al., 2020). The asymmetry was most observed in the upper 700 m, strongly influenced by an asymmetric mode of climate variability, whereas the deep ocean warming (below 700 m) is more uniform, which can be unambiguously attributed to anthropogenic warming (Figure 4).

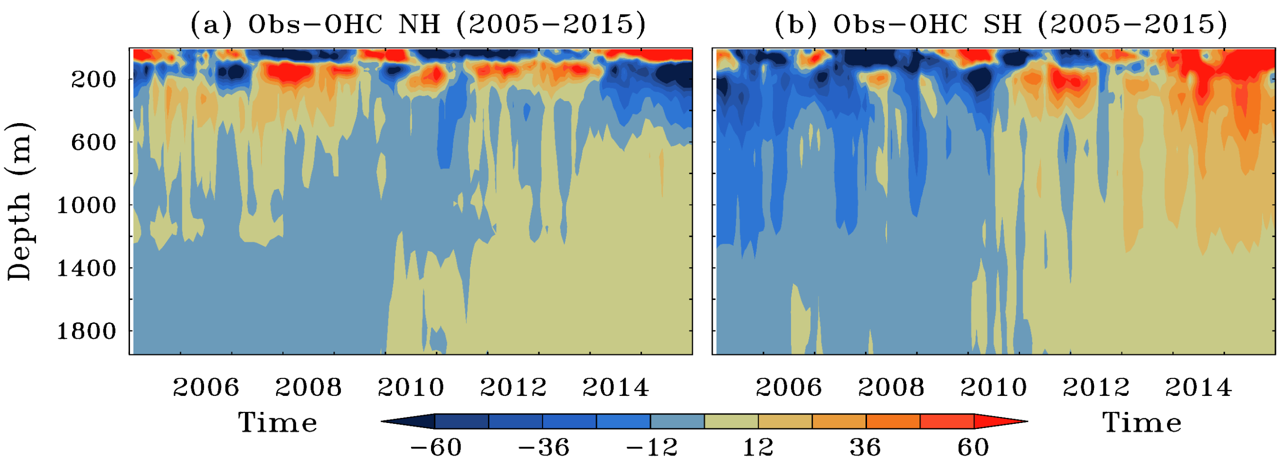

Figure 4 Hemisphere asymmetry of decadal warming of the global ocean (From Rathore et al., 2020). Left panel: ocean temperature anomalies averaged in the northern hemisphere; right panel: temperature anomalies averaged in the southern hemisphere.

2.3.2 Project performance against milestones

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

Milestone 1: Analyse 2018-19 field campaign data to improve our understanding of air-sea heat and moisture fluxes and upper ocean responses to different phases of the MJO

The field campaign data, after data quality control, has been analysed. An introductory paper on the 2018-19 CSHOR/FIO field campaign is now available in the *Bulletin of the American Meteorological Society* (Feng et al., 2020). The paper presented the time series data collected from the Bailong buoy and ocean profiling autonomous floats and analysed air-sea fluxes during different phases of the MJO. The paper highlighted the Indonesian-Australia Basin's higher sensitivity to the MJO forcing compared to other tropical regions of the Indian Ocean. The data have shown significant diurnal ocean temperature variations before the arrival of the MJOs and substantial ocean temperature cooling during the onset of the MJO convective phase, which often occur in conjunction of tropical cyclones.

Research is being carried out to understand the barrier layer structures in the upper ocean that influence the diurnal sea surface temperature variations in the warm pool. Data obtained during the 2018-19 field campaign is used to explore the effects of both temperature and salinity stratifications on the diurnal sea surface temperature variations.

Milestone 2: Participate in the RV *Investigator* cruise for the Years of Maritime Continent program during October-November 2019 to collect upper ocean mixing and air-sea flux data for process study and model validation

In October and November 2019, Drs Wijffels (Principal Investigator) and Hsu and Ms Maggiorano participated in the first leg of the RV *Investigator* Years of the Maritime Continent voyage, along with collaborators from China. Working with RBR, they successfully deployed a wire walker for a two-week period sampling the interaction between the semidiurnal internal tides and surface ocean mixed layer processes. However, the deployment of the replacement ALAMO floats failed. The wire walker data have been archived, along with other shipboard data.

Dr Feng has engaged with scientists from CAS to develop internal tide model simulations for the Indonesian-Australian Basin to better understand the mixing regime in the basin.

Milestone 3: Analyse ACCESS S1 model simulations of the 2018-19 field campaign period and improve our understanding of the role of diurnal/multi-day warming in the onset of the MJO

A research paper led by CSHOR Postdoctoral Fellow, Dr Hsu, was published in the *Journal Geophysical Research: Oceans*. In the study, he carried a suite of ACCESS coupled model simulations to understand the model's ability to capture the diurnal variations of sea surface temperature and its sensitivity to vertical model resolution and air-sea coupling frequency. One of the key results of the study is to identify the importance of the vertical resolution of less than 1 metre in the near surface layer of ocean models, in order for the coupled model to properly capture the diurnal variation of sea surface temperature in the warm pool region (Hsu et al., 2019).

Milestone 4: Contribute to Indian Ocean observation review publications

The Indian Ocean Observing System (IndOOS) review chapters and the summary report are published (Beal et al., 2019). A recommendation to enhance the RAMA mooring array with an air-sea flux mooring off northwest Australia in the Indonesian-Australian Basin has been broadly supported. A manuscript by Beal, Vialard, and Roxy, the co-chairs of the CLIVAR Indian Ocean Panel, summarising the key finding of the review reports, is published. (Beal et al., 2020).

In a research paper led by PhD student, Mr Saurabh Rathore (Rathore et al., 2020; published in *Nature Communications*), we quantified the asymmetric pattern of the global warming in the past decade and pointed out that both the greenhouse gas effect and natural climate variability worked together to drive this asymmetric warming pattern. Most of the asymmetry was observed in the upper 700 m, and the warming in the 700-2000 m layer was more uniform and can be attributed to anthropogenic warming.

A paper published in the *Journal Geophysical Research: Oceans* analysed air-sea flux data from one of the RAMA moorings in the southeast Indian Ocean – a key component of the Indian Ocean Observing System, along with upper ocean observations, to better understand the air-sea exchanges and upper ocean heat balance in the region (Cyriac et al., 2019).

In a collaboration with IOCAS and the Ocean University of China, we have used downscaling ocean model results to assess the future changes of poleward heat transport and heat balance of the Indian Ocean, under the influences of anthropogenic climate change forcing (Ma et al., 2020). The key results suggest that with a reduction of the Indonesian Throughflow and the spin-down of the subtropical gyre of the southern Indian Ocean, the poleward heat transport of the Agulhas Current will reduce. More heat is retained in the Indian Ocean to drive a faster warming trend of the Indian Ocean under the anthropogenic forcing.

Dr Feng has participated in an overview paper discussion on the Indian Ocean circulation and climate led by the International Indian Ocean Expedition-2 community. He has also collaborated with Chinese colleagues on the upper ocean variability in the Indian Ocean (Sun et al., 2019; Zhang et al., 2020).

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

A modelling study of the upper ocean heat budget has been carried out for the 2013 marine heatwave off the northwest coast of Australia. Based on the results, Ms Maggiorano has submitted a manuscript of the 2013 northwest shelf marine heatwave for journal publication. It has been identified that both air-sea exchange and horizontal advection anomalies contributed to the peak of the 2013 marine heatwave. In another effort, PhD student, Mr Gang Yang, from UNSW, has studied the sediment dynamics of the Darwin Harbour under the monsoonal forcing.

2.3.3 Project publications[3]

Beal, L.M., Vialard, J., Roxy, M.K., Li, J., Andres, M., Annamalai, H., Feng, M., Han, W., Hood, R., Lee, T., Lengaigne, M., Lumpkin, R., Masumoto, Y., McPhaden, M.J., Ravichandran, M., Shinoda, T., Sloyan, B.M., Strutton, P.G., Subramanian, A.C., Tozuka, T., Ummenhofer, C.C., Unnikrishnan, A.S., Wiggert, J., Yu, L., Cheng, L., Desbruyères, D.G., Parvathi, V. (2020). A roadmap to IndOOS-2: Better observations of the rapidly warming Indian Ocean. *Bulletin of the American Meteorological Society*. doi: 10.1175/BAMS-D-19-0209.1.

Beal, L. M., Vialard, J., Roxy, M. K. et al. (Including Feng, M., Sloyan, B.) (2019). Full Report. IndOOS-2: A roadmap to sustained observations of the Indian Ocean for 2020-2030. CLIVAR-4/2019, GOOS-237, 206 pp. doi.org/10.36071/clivar.rp.4.2019.

Beal, L. M., Vialard, J., Roxy, M. K. et al. (Including Feng, M., Sloyan B.) (2019). Executive Summary. IndOOS-2: A roadmap to sustained observations of the Indian Ocean for 2020-2030. CLIVAR-4/2019, GOOS-237, 8 pp. doi.org/10.36071/clivar.rp.4-1.2019.

Cyriac, A., McPhaden, M. J., Phillips, H. E., Bindoff, N. L., & Feng, M. (2019). Seasonal evolution of the surface layer heat balance in the eastern subtropical Indian Ocean. *Journal of Geophysical Research: Oceans*, 124(9), 6459–6477. doi.org/10.1029/2018JC014559.

Feng, M., Duan, Y., Wijffels, S., Hsu, J.Y., Li, C., Wang, H., Yang, Y., Shen, H., Liu, J., Ning, C. and Yu, W. (2020). Tracking air-sea exchange and upper ocean variability in the Indonesian-Australian Basin during the onset of the 2018-19 Australian summer monsoon. *Bulletin of the American Meteorological Society*. doi: 10.1175/bams-d-19-0278.1.

Hsu, J.Y. Hendon H., Feng M., Zhou, X. (2019). Magnitude and Phase of Diurnal SST Variations in the ACCESS-S1 model during the Suppressed Phase of the MJOs. *Journal of Geophysical Research: Oceans*, 124(12), 9553-9571. doi:10.1029/2019jc015458.

Hu, S., Zhang, Y., Feng, M., Du, Y., Sprintall, J., Wang, F., Hu, D., Xie, Q., Chai, F. (2019). Interanual to decadal variability of upper ocean salinity in the southern Indian Ocean and the role of the Indonesian Throughflow. *Journal of Climate*, 32(19), 6403-6421. doi/full/10.1175/JCLI-D-19-0056.1.

[3] 2019-20 publications are shown in bold text.

Ma, J., Feng, M., Lan, J. and Hu, D. (2020). Projected future changes of meridional heat transport and heat balance of the Indian Ocean. *Geophysical Research Letters*, *47*(4), e2019GL086803. doi: 10.1029/2019gl086803

Rathore, S., N. L. Bindoff, H. E. Phillips, M. Feng (2020). Recent hemispheric asymmetry in global ocean warming induced by climate change and internal variability. *Nature Communications*, 11(1), 1-8. doi: 10.1038/s41467-020-15754-3.

Sun, Q., Du, Y., Zhang, Y., Feng, M., Chowdary, J.S., Chi, J., Qiu, S. and Yu, W. (2019). Evolution of Sea Surface Salinity Anomalies in the Southwestern Tropical Indian Ocean During 2010–2011 Influenced by a Negative IOD Event. *Journal of Geophysical Research: Oceans*, 124(5), 3428-3445. doi.org/10.1029/2018JC014580.

Zhang, Y., Du, Y., Jayarathna, W.S., Sun, Q., Zhang, Y., Yao, F. and Feng, M. (2020). A Prolonged High-Salinity Event in the Northern Arabian Sea during 2014–17. *Journal of Physical Oceanography*, *50*(4), pp.849-865. doi: 10.1175/jpo-d-19-0220.1.

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

Project leader – Prof Matthew England (UNSW)

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

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

2.4.1 Year 3 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 specific project objectives are outlined below.

The first intercomparison of observations of air-sea heat fluxes at two Subantarctic Mode Water (SAMW) formation sites is completed. This comparison has led to a better understanding of the processes controlling SAMW formation and heat loss regimes in two distinct regions of the Southern

Ocean; the southeast Pacific and south of Tasmania (Figure 5). The study led to a deeper understanding of the processes controlling interannual variability in mixed layer and SAMW formation at these regions. The work has been published in *Journal of Climate;* “Mooring observations of air-sea heat fluxes in two Subantarctic Mode Water formation regions.”

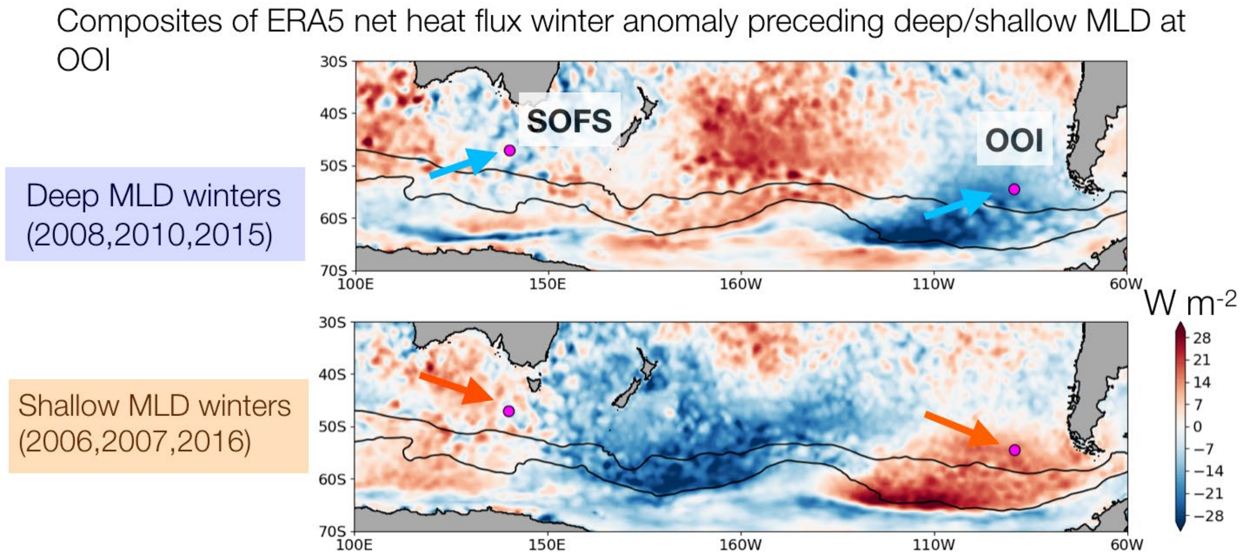

Figure 5 Co-variability of wintertime air-sea heat flux in the Southeast Indian and Southeast Pacific Subantarctic Mode Water formation regions (From Tamsitt et al. 2020a). Composites of ERA5 wintertime (June, July, August) anomaly of net air-sea heat flux (positive is anomalous ocean heat gain) for years with anomalously deep September mixed layer depths at the OOI mooring and surrounding region (top panel; 2010 and 2015) and years with anomalously shallow September mixed layer depths at the OOI mooring and surrounding region (lower panel; 2006, 2007, and 2016). Black lines indicate the boundaries of the Antarctic Circumpolar Current.

The biogeochemical structure of observed long-lived cold core mesoscale eddies in the Southern Ocean, south of Australia, has been characterised for the first time (Patel, Lenton et al., in press). This work showed that the distribution of nutrients in cold-core eddies is dominated by eddy dynamics below the mixed layer and by biological processes in the mixed layer. These eddies influence the concentration of nutrients exported from the Southern Ocean via mode waters. This water re-emerges at lower latitudes, driving productivity outside the Southern Ocean.

Regional variations of the eddy-induced overturning along the East Antarctic slope have been estimated using available hydrographic data collected by CTD-tagged seals (Foppert et al., *GRL*, 2019). Hot spots of eddy-driven transport of relatively warm, saline Circumpolar Deep Water were identified across the Antarctic slope that influenced the reservoirs of heat and salt available at the shelf break. The spatial and temporal variability of deep-water properties and pathways from the slope to the abyssal ocean, as well as the dynamics of major jets/fronts of the Antarctic Circumpolar Current, were also analysed.

The formation rate of Subantarctic Mode Water has been quantified using Argo data and atmospheric reanalysis fields. Multiple methods were tested, including Lagrangian and Eulerian approaches, as well as a water-mass transformation approach. Consistent year-to-year variations were found. Seasonal-to-interannual variability in Southern Ocean surface mixed layer depth were also analysed and linked to both the Southern Annular Mode (Li et al., 2019) and ENSO (Li and England, 2020).

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

Dr Tamsitt has designed and executed multiple Lagrangian particle release experiments using output from a 1/10 degree ocean-sea ice model to investigate the spatial variation in pathways and residence time of warm Circumpolar Deep Water crossing the Antarctic continental shelf break. The results show a clear circumpolar structure in transformation and residence time of warm water on the Antarctic shelf. This work was presented at the 2020 Ocean Sciences Meeting in San Diego. A manuscript (Tamsitt et al., 2020b) is in preparation for submission in the second half of 2020.

Dr Foppert carried out an observational investigation of cross-slope exchange using available data collected by seals and found hot spots of eddy-driven transport of Circumpolar Deep Water to the shelf break and eddy-induced overturning. This work was published in the *Geophysical Research Letters* in July (Foppert et al., 2019) and highlighted on the MEOP website in February 2020 (link).

Preparation for a voyage to the slope/shelf region near Prydz Bay, led by Australian Antarctic Division scientists, is well underway. Dr Foppert helped design the CTD (conductivity-temperature-depth mooring), which has been submitted to Marine National Facility as part of the voyage plan. The voyage will survey the regional hydrography and characterise the physical environment between 55-80°E with a suite of shallow and full-depth CTDs to compare with a similar survey done in 2006.

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

Dr Tamsitt supervised a University of Tasmania Honours student, Ms Kai Wang, who has completed her Honours thesis using data from RV *Investigator* voyage. The thesis is titled, "Characterising upwelling of Circumpolar Deep Water at the Polar Front and investigating submesoscale processes associated with upwelling of CDW." The results characterise upwelling of CDW south of the Polar Front and investigate the submesoscale dynamics, and the theses is being modified for submission to a journal in late 2020 (Wang et al., 2020, in prep.). Dr Tamsitt has also worked with collaborators Dr Vidhi Bharti, Professor Helen Phillips, and Professor Nathan Bindoff to study the imprint of the Polar Front on air-sea heat fluxes, showing a complex air-sea interaction process resulting in upwelling and cooling along the core of the front. A manuscript on this work is almost complete and will be submitted to a special collection of *Frontiers in Marine Science,* "Energy, Water, and Carbon Dioxide Fluxes at the Earth's Surface," before September 2020 (Bharti et al., 2020, in prep.).

Dr Foppert is using data from the 2018 RV *Investigator* voyage to study the dynamics of the Polar Front by quantifying its velocity and density structure and characterise its instability properties. This analysis combines data from the lowered acoustic Doppler current profiler (ADCP) and CTD to calculate the total transport of the jet and its potential vorticity structure. The latter enables the project team to infer the jet's stability properties and reveals which mechanism(s) are at work to generate large eddies and mixing across the front.

Milestone 3: Analyse Subantarctic Mode Water formation and variability at two mooring sites in the Southeast Indian and Southeast Pacific oceans

Dr Tamsitt has completed a comparison of air-sea heat fluxes and mixed layers from moorings in the Southeast Indian and Southeast Pacific Oceans along with collaborators, Dr Ivana Cerovečki, Professor Sarah Gille, Professor Simon Josey and Dr Eric Schulz. The comparison has yielded insight into different heat loss regimes in the two regions and interannual variability in the region. This work was published in the *Journal of Climate* in January 2020, and Dr Tamsitt was a co-author on related work led by Dr Andrew Meijers published in *GRL* in December 2019.

Milestone 4: Quantify subduction rates of Subantarctic Mode Water and Antarctic Intermediate Water using Argo data in combination with both Lagrangian and Eulerian approaches

The formation rates of both Subantarctic Mode Water and Antarctic Intermediate Water have been quantified. Several methods have been tested, including both Lagrangian and Eulerian approaches, and using a water-mass transformation method. Using a gridded Argo product and the ERA-Interim[4] reanalysis for years 2004-2018, seasonal evolution of the SAMW volume was analysed using a kinematic estimate of subduction combined with the thermodynamic estimate using the air-sea formation rate. The seasonal SAMW volume changes were separately estimated within the monthly mixed layer and in the interior below it. The seasonal volume variability of the mixed-layer SAMW is governed by air-sea formation (50%, lasting from April to September), obduction of low potential vorticity (PV) water either from upstream or below the mixed layer below (15%), and the northward Ekman transport across the Subantarctic Front (20%). The interior SAMW volume is almost entirely controlled by exchange with the mixed layer. The strongest exchange between the mixed layer and the interior occurs from August to October by subduction through the wintertime mixed-layer base. A paper on this work is being submitted to *Journal of Physical Oceanography* (Li, et al., 2020).

Milestone 5: Document mixed layer depth variations over the Southern Ocean linked to both ENSO variability as well as variations in the westerly winds

A study was completed (Li, England, et al., 2019; *J. Climate*) detailing the seasonal-to-interannual response of the Southern Ocean surface layer to variations in the Southern Annular Mode, using a global 1/10° ocean model. Follow up work then explored what controls interannual to multi-decadal Southern Ocean mixed layer depth (MLD) variations, which are closely tied to the formation of

[4] ERA-Interim is a global atmospheric reanalysis that is available from 1 January 1979 to 31 August 2019. Available via European Centre for Medium-Range Weather Forecasts.

Subantarctic Mode Water. Atmospheric observations were combined with a global 1/10° ocean–sea-ice model. Tropical teleconnections from the Indo-Pacific to the Amundsen Sea Low via ENSO and the Indian Ocean Dipole were found to control mixed layer variability along the path of a Rossby wave train across the South Pacific during early winter. This suggests recent multi-decadal variations in mixed layer properties are likely to have been significantly impacted by transitions in the Interdecadal Pacific Oscillation. This second paper (Li and England, 2020; *GRL*) is now in press.

Milestone 6: Analyse the dynamics of topographic upwelling hotspots in the Antarctic Circumpolar Current

Dr Tamsitt worked with collaborator Dr Adele Morrison, from Australian National University, to develop an analysis of topographic upwelling hotspots in the ACC using a two-pronged approach in a 1/10 degree ocean-sea-ice model. We have successfully diagnosed energy budget terms in the model and conducted targeted Lagrangian particle release experiments in topographic upwelling hotspot regions. Analysis of experiment results is ongoing.

Dr Foppert is contributing to this (see Milestone 2 above) as the RV *Investigator* voyage was to an upwelling hot spot and the instability analysis will reveal the dynamic processes driving cross-frontal exchange and upwelling of Circumpolar Deep Water. Additionally, Drs Foppert and Rintoul are helping to supervise a PhD student, Mr Jan Jaap Meijer, along with collaborators at the University of Tasmania, Profs Helen Phillips and Nathan Bindoff, looking at the drivers of along-stream water-mass changes using shipboard data from a previous voyage to a standing meander of the Subantarctic Front (Meijer et al., 2020, in prep). The terms in the vorticity budget have elucidated some of the dynamics driving the evolution of water masses in the meander (with standing meanders being closely linked to upwelling hot spots).

Milestone 7: Investigation of deep-water properties, including quantifying the spatial and temporal variability of Antarctic Bottom Water.

In conjunction with Project 5, Dr Foppert has worked on the novel deep Argo pilot array in the Australian Antarctic Basin to characterise and quantify the spatial and temporal variability of properties of Antarctic Bottom Water (AABW). Extending the work of Silvano et al., 2020 (*Nature Geoscience*, under review) and Thomas et al., 2020 (*GRL*, under review), both of which Drs Foppert and Rintoul are co-authors, we perform a more detailed investigation of the pathways of the two sources of AABW in the basin. Analysis of the most recent profiles, before several of the floats went under the sea ice for the winter, are being added to the study for the most up-to-date view of the region. With many floats profiling for two full years, a characterisation of the seasonality of AABW properties can be done with greater statistical confidence. A manuscript, in preparation, will be submitted for publication in the upcoming months (Foppert et al, 2020, in prep,).

Milestone 8: Presentations at national and international conferences

Results were presented at multiple domestic and international meetings and conferences, including the 2020 Ocean Sciences Meeting in San Diego (Drs Foppert and Tamsitt and Prof England), where Drs Foppert and Tamsitt and Prof England all convened conference sessions. Dr Tamsitt and Prof

England where both invited speakers at the Ocean Gateways Symposium in honour of Arnold Gordon at Scripps Institution of Oceanography. Dr Foppert attended the AMOS Annual Meeting in Fremantle. Dr Tamsitt was invited to present her work on air-sea interactions at an International Workshop of Ocean Mesoscale-to-Submesoscale Variability at QNLM in Qingdao in July 2020, however, the event is postponed.

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

2.4.3 Project publications[5]

Bharti, V., V. Tamsitt, H. E. Phillips, and N. L. Bindoff (2020). The imprint of the Southern Ocean Polar Front on air-sea fluxes. *Frontiers in Marine Science*, in preparation.

Belkin, I., Foppert, A., Rossby, T., Fontana, S., & Kincaid, C. (2020). A Double-Thermostad Warm-Core Ring of the Gulf Stream. *Journal of Physical Oceanography*, 50(2), 489-507. doi:10.1175/jpo-d-18-0275.1.

Foppert, A., Rintoul, S. R., & England, M. H. (2019). Along-Slope Variability of Cross-Slope Eddy Transport in East Antarctica. *Geophysical Research Letters*, 46(14), 8224-8233. doi:10.1029/2019gl082999.

Foppert, A., et al. (2020). Variability of bottom water properties in the Australian Antarctic Basin: A perspective from Deep Argo. *Journal of Geophysical Research: Oceans,* in preparation.

Holmes, R. M., Zika, J. D., Ferrari, R., Thompson, A. F., Newsom, E. R., & England, M. H. (2019). Atlantic Ocean Heat Transport Enabled by Indo-Pacific Heat Uptake and Mixing. *Geophysical Research Letters, 46*(23), 13939-13949. doi:10.1029/2019gl085160.

Lago, V., & England, M. H. (2019). Projected Slowdown of Antarctic Bottom Water Formation in Response to Amplified Meltwater Contributions. *Journal of Climate*, 32(19), 6319-6335. doi:10.1175/jcli-d-18-0622.1.

Li, Z., M. H. England, S. Groeskamp, I. Cerovečki, and Y. Luo (2020). The Origin and fate of Subantarctic Mode Water in the Southern Ocean. *Journal of Physical Oceanography*, in preparation.

Li, Q., and England, M. H. (2020). Tropical Indo-Pacific teleconnections to Southern Ocean mixed layer variability. *Geophysical Research Letters*, in press.

Li, Q., Lee, S., England, M. H., & McClean, J. L. (2019). Seasonal-to-Interannual Response of Southern Ocean Mixed Layer Depth to the Southern Annular Mode from a Global 1/10° Ocean Model. *Journal of Climate*, 32(18), 6177-6195. doi:10.1175/jcli-d-19-0159.1.

[5] 2019-20 publications are shown in bold text.

Meijer, J. J., H. E. Phillips, N. L. Bindoff, S. R. Rintoul, and A. Foppert (2020). Changing water masses and their mechanisms in a standing meander of the Antarctic Circumpolar Current. *Journal of Geophysical Research: Oceans*, in preparation.

Meijers, A. J. S., Cerovečki, I., King, B. A., & Tamsitt, V. (2019). A See-Saw in Pacific Subantarctic Mode Water Formation Driven by Atmospheric Modes. *Geophysical Research Letters*, 46(22), 13152-13160. doi:10.1029/2019gl085280.

Patel, R, Llort, J, Strutton, P. G., Moreau S., Pardo P. C., Phillips. H. E., Lenton A. (2020) The biogeochemical structure of Southern Ocean mesoscale eddies. *Journal of Geophysical Research: Oceans*, in press.

Silvano, A., A. Foppert, S. R. Rintoul, et al. (2020). Recovery of Antarctic Bottom Water formation driven by anomalous climate forcing. *Nature Geoscience*, in review.

Tamsitt, V., Cerovečki, I., Josey, S. A., Gille, S. T., & Schulz, E. (2020a). Mooring Observations of Air–Sea Heat Fluxes in Two Subantarctic Mode Water Formation Regions. *Journal of Climate*, 33(7), 2757-2777. doi:10.1175/jcli-d-19-0653.1.

Tamsitt, V. et al. (2020b) Lagrangian pathways and residence time of warm Circumpolar Deep Water on the Antarctic continental shelf, *Geophysical Research Letters*, in preparation.

Thomas, G., Purkey, S. G., Roemmich, D., Foppert, A, and Rintoul S. R. (2020) Spatial variability of Antarctic Bottom Water in the Australian Antarctic Basin from 2018-2020 captured by Deep Argo. *Geophysical Research Letters*, in review.

Wang, K., V. Tamsitt, H. E. Phillips, and N. L. Bindoff (2020). A detailed submesoscale survey of the Polar Front. *Journal of Geophysical Research: Oceans,* in preparation.

Wei, Y., Gille, S. T., Mazloff, M. R., Tamsitt, V., Swart, S., Chen, D., & Newman, L. (2020). Optimizing mooring placement to constrain Southern Ocean air-sea fluxes. *Journal of Atmospheric and Oceanic Technology.* doi: 10.1175/jtech-d-19-0203.1.

2.5 Project 5: Southern Ocean observations and change – Antarctic observations

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 3 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.

Analysis of Southern Ocean change in the past year has focused on Antarctic Bottom Water (AABW). A unique long time-series of hydrographic observations was used to document a surprising rebound in the salinity and density of dense water formed on the Ross Sea continental shelf, after nearly 50 years of freshening (Castagno et al., 2019). A follow-up paper under review at *Nature Geoscience* uses repeat hydrography, deep Argo data, and reanalyses to identify the physical mechanisms responsible for the recovery of AABW formation (Silvano et al., 2020). The results show that an unusual combination of tropical and Southern Ocean forcing led to a temporary reversal in the long-term freshening trend driven by melt of Antarctic ice shelves.

As part of a collaborative project with New Zealand and the USA, profiling floats were used to obtain the first comprehensive, year-round measurements of the Ross Gyre and quantify the circulation. New floats were deployed in the Ross Gyre from an Italian research vessel and a new collaboration with France was initiated, which will allow a novel satellite altimeter data set to be used to quantify the structure and transport of the gyre.

The deep Argo floats continue to operate well and have survived winters under sea ice (this array is the first to demonstrate the feasibility of deep Argo operation under ice). Early data from the deep float array has been used in the Silvano et al. (2020) paper mentioned above, in a submitted paper using the deep float data to quantify pathways and changes in AABW (Thomas et al., 2020) and work to be submitted soon led by Annie Foppert (see Project 4, Section 2.4). A novel method to navigate floats under sea ice will increase the value of winter measurements made by deep floats (Wallace et al., 2020).

Two papers, including CSHOR researcher Laura Herraiz-Borreguero, provide important new insights into the physical processes that regulate the delivery of warm water to the base of floating ice shelves. A paper published in *Nature* by Wåhlin et al., shows how the sharp change in water column thickness at the front of the ice shelf provides a dynamical barrier. This barrier restricts inflow of heat to the sub-ice shelf cavity by depth-independent (barotropic) motions. A paper submitted to *Journal of Geophysical Research: Oceans* shows that the oceanic heat content into the western Amundsen Sea is controlled by the Amundsen Sea Low. Although this research focused on West Antarctica, it shows that atmospheric variability should not be disregarded in favour of oceanic processes in other regions of Antarctica, such as East Antarctica.

2.5.2 Project performance against milestones

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

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

A paper published in *Nature Communications* used a unique long time series of observations in the Ross Sea to document a rebound in salinity and density of dense shelf waters after 50 years of freshening (Castagno et al., 2019).

A follow-up paper under review at *Nature Geoscience* showed that the increase in salinity and density of shelf waters led to a recovery of AABW formation. More importantly, the authors identified the physical mechanism responsible for renewed bottom water formation. An unusual combination of positive SAM and El Niño produced anomalous winds that contributed to enhanced sea ice formation and a recovery of AABW formation, reversing a multi-decadal freshening trend (Silvano et al., 2020).

Ice-capable Argo profiling floats were deployed by a Japanese ship on the continental shelf near the Totten Glacier. The floats will provide year-round, full-depth water profiles from beneath the sea ice in this poorly observed region. Despite extremely heavy sea ice conditions this season, all floats reported back and are working well. They reveal persistent onshore flow of warm water in deep troughs of the continental shelf, providing a source of heat to drive melt of the Totten Ice Shelf.

A paper submitted to the *Journal of Geophysical Research: Oceans* documents the existence of a "continental shelf pump" transporting carbon dioxide to the abyssal ocean (Arroyo et al., 2020). Carbon dioxide transported onto the shelf in Circumpolar Deep Water is transferred to the deep ocean by the formation and export of AABW.

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

New floats from the USA and Australia were deployed from an Italian research vessel in January 2020. The combined float and altimeter data set is being used to quantify the circulation of the Ross Gyre and its interactions with the ACC to the north and the slope regime to the south. A new collaboration with French researchers will allow us to use a new multi-satellite estimate of ocean circulation under sea ice in winter.

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 heavily instrumented tall mooring was deployed in a standing meander of the Antarctic Circumpolar Current in 2018, with an expected recovery in early 2020. The recovery voyage was delayed by COVID-19. In March 2020, the top 450 m of the mooring broke free. With help from the CSIRO Marine National Facility, we arranged a charter of a fishing boat to recover the drifting instruments. All instruments were returned in good shape with full data records, despite a month drifting at the surface of the Southern Ocean. The remainder of the mooring will be recovered on a voyage scheduled for August 2020 on RV *Investigator*.

The meander experiment is a collaborative effort between CSHOR, Australian Antarctic Program Partnership (AAPP) and a project funded by the Australian Research Council. The project team is making good progress on several aspects, including air-sea interaction (see Project 4, Section 2.4, for Tamsitt contribution), velocity structure and dynamics (see Project 4, Section 2.4, for Foppert contribution), high resolution modelling, and analysis of EM-APEX float data.

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

The deep Argo floats continue to perform well, and analysis of the deep Argo array is progressing. Two papers have been submitted recently (Thomas et al., 2020; Silvano et al., 2020) that use early data from the deep floats. A more comprehensive analysis of the float data is being led by Dr Foppert for a paper expected to be submitted later this year. The focus of this paper is using the deep floats to identify the pathways of AABW with unprecedented detail. A paper published in *Geophysical Research Letters* proposes a new approach for geolocation of floats (including deep floats) under sea ice (Wallace et al., 2020). The method uses depths measured by the floats in combination with known bathymetry to constrain the trajectory of the floats under ice.

Milestone 5: Publication of a study showing how movement of ACC fronts influences heat delivery to the Antarctica ice sheet

The Antarctic Ice Sheet is losing mass at a troubling speed. This ice mass loss is believed to be driven by an increase in the delivery of ocean heat to the underside of the Antarctic ice shelves. However, the exact physical process behind this increased ocean heat delivery is not completely understood. A *Nature* paper by Wåhlin et al. (2020) represents a significant step towards a more complete physical understanding of the processes that regulate heat delivery to ice shelves. Work done by Dr Laura Herraiz-Borreguero shows that a southward migration of the strong Westerly winds over the Southern Ocean has allowed Warm Circumpolar Deep Water to migrate closer to the Antarctic continental slope. Moreover, Antarctic coastal easterly winds have weakened (and migrated south) during the austral summer, making warm Circumpolar Deep Water shallower, thus, exposing East Antarctic ice shelves to warmer ocean than occurred 20 years ago. A paper is expected to be submitted in the next 3 months (Herraiz-Borreguero, L. and Naveira-Garabato A., 2020).

Humpback whales tagged with satellite transmitters showed that the whales target specific frontal regions of the Southern Ocean (Bestley et al., 2019). In particular, the study showed that the rapidly increasing population of humpbacks off the west coast of Australia migrate to the eastern side of the Kerguelen Plateau to forage in a consistent meander of the Antarctic Circumpolar Current.

A paper under review (Dotto et al., 2020) reported on a reduced ocean heat supply to the West Antarctic Ice Sheet. This reduced heat supply was controlled by local wind forcing of a shelf-break undercurrent, which determines the hydrographic properties of inflowing warm waters via tilting of density surfaces above the continental slope. Local wind is coupled to the Amundsen Sea Low (ASL) low-pressure system, which is modulated by large-scale climatic modes via atmospheric teleconnections. The present work suggests that the fate of the West Antarctic ice shelves is closely tied to the future evolution of that low-pressure system.

Milestone 6: Develop plan for future observations in CSHOR, in collaboration with other groups in Australia and overseas

A new paper published in *One Earth* presents a roadmap of future research imperatives in Antarctic and the Southern Ocean (Kennicutt et al., 2019). The volume of the journal was timed to coincide with the Climate Action Summit in New York. The paper provides a comprehensive summary of progress made on 80 high priority science questions identified in a “horizon scan” carried out in 2014 and outlines priorities for the future.

A paper published in *Frontiers in Marine Science* presents a pathway to deliver sustained, coordinated, and integrated observations of the Southern Ocean for global impact (Newman et al., 2019).

Joint fieldwork has been carried out this summer with the Italian, USA, Korean and Japanese programs (mostly float and Autonomous Underwater Vehicle (AUV) deployments). This included the first deployment of the CSIRO-UTAS AUV near the Thwaites glacier ice shelf in West Antarctica as part of a joint project with Korean researchers, float deployments in the Ross Gyre from an Italian vessel, and float deployments near Totten Glacier from a Japanese vessel.

A collaborative study of polynyas, water mass formation and circulation in Prydz Bay is underway with Chinese researchers, including PhD student, Mr Saisai Hou.

Several proposals for collaborative fieldwork were submitted this year, including:

- A proposal submitted to National Science Foundation (USA) by collaborators at Woods Hole Oceanographic Institution for support for a spar buoy to measure air-sea fluxes in the Southern Ocean, to be deployed by CSHOR south of Tasmania. (not successful first time, will try again).
- A Chinese proposal investigating ocean – ice shelf interaction in East Antarctica.
- A proposal was submitted to the Schmidt Foundation in collaboration with USA investigators, to address the grand challenge of better representation of the physics of the ocean surface mixed layer.
- Discussions on collaboration with the new Australian Antarctic Program Partnership (AAPP) and the Australian Centre for Excellence in Antarctic Science (ACEAS) are underway, including joint voyages on the new Australian icebreaker RSV *Nuyina*.
- A proposal is under development for submission in late 2020 for a joint physical oceanography – biogeochemistry voyage on RV *Investigator*, including a re-seeding of the deep Argo float array in the Australian – Antarctic Basin.

2.5.3 Project publications[6]

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*, submitted.

Bestley, S., Andrews-Goff, V., van Wijk, E., Rintoul, S. R., Double, M. C., & How, J. (2019). New insights into prime Southern Ocean forage grounds for thriving Western Australian humpback whales. *Scientific Reports*, 9(1), 13988. doi:10.1038/s41598-019-50497-2.

Castagno, P. V. Capozzi, G. R. DiTullio, P. Falco, G. Fusco, S. R. Rintoul, and G. Budillon (2019). Rebound of shelf water salinity in the Ross Sea. *Nature Communications*, 10, 1-6. doi.org/10.1038/s41467-019-13083-8.

Dotto, T.S., A. C. Naveira Garabato, A. K. Wåhlin, S. Bacon, P. R. Holland, S. Kimura, M. Tsamados, L. Herraiz-Borreguero, O. Kalén and A. Jenkins, T.S. (2020). Control of the oceanic heat content of the Getz-Dotson Trough, Antarctica, by the Amundsen Sea Low. *Journal of Geophysical Research: Oceans,* under review.

L. Herraiz-Borreguero and Naveira-Garabato A. (2020). Increased ocean heat supply to the East Antarctic Ice Sheet during 21st century, in preparation for submission to *Nature.*

Kennicutt II, M. C., D. Bromwich, D. Liggett, B. Njåstad, L. Peck, S. R. Rintoul, C. Ritz, M. J. Siegert, A. Aitken, C. M. Brooks, J. Cassano, S. Chaturvedi, D. Chen, K. Dodds, N. R. Golledge, C. Le Bohec, M. Leppe, A. Murray, P. C. Nath, M. N. Raphael, M. Rogan-Finnemore, D. M. Schroeder, L. Talley, T. Travouillon, D. G. Vaughan, L. Wang, A. T. Weatherwax, H. Yang, and S. L. Chown (2019). Sustained Antarctic Research: a 21st Century Imperative. *One Earth*, 1(1), 95-113. doi.org/10.1016/j.oneear.2019.08.014.

Newman, L., P. Heil, R. Trebilco, K. Katsumata, A. Constable, E. van Wijk, K. Assmann, J. Beja, P. Bricher, R.Coleman, Daniel Costa, S. Diggs, R. Farneti, S. Fawcett, S.T Gille, Katharine R Hendry, S. Henley, E. Hofmann, Ted Maksym, Matthew Mazloff, A. Meijers, M. M Meredith, S. Moreau, B. Ozsoy, R. Robertson, I. Schloss, O. Schofield, J. Shi, E. Sikes, I. J Smith, S. Swart, A. Wahlin, Guy Williams, Michael JM Williams, L. Herraiz-Borreguero, Stefan Kern, J. Lieser, R. A Massom, J. Melbourne-Thomas, P.Miloslavich, G.Spreen (2019). Delivering sustained, coordinated, and integrated observations of the Southern Ocean for global impact. *Frontiers in Marine Science* 6(433). doi.org/10.3389/fmars.2019.00433.

[6] 2019-20 publications are shown in bold text.

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. Climate anomalies drive recovery of Antarctic Bottom Water formation in the Ross Sea. *Nature Geoscience*, under review.

Thomas, G., S. G. Purkey, D. Roemmich, A. Foppert, S. R. Rintoul, 2020. Spatial Variability of Antarctic Bottom Water in the Australian Antarctic Basin from 2018-2020 captured by Deep Argo. *Geophysical Research Letters*, submitted.

Wåhlin, A. K., N. Steiger, E. Darelius, K. M. Assmann, M. S. Glessmer, H. K. Ha, L. C. Herraiz-Borreguero, C. Heuzé, A. Jenkins, T. W. Kim, A. K. Mazur, J. Sommeria, and S. Viboud. (2020) Ice front blocking of ocean heat transport to an Antarctic ice shelf. *Nature,* 578, 568–571. doi.org/10.1038/s41586-020-2014-5.

Wallace, L.O., E.M. van Wijk, S.R. Rintoul and B. Hally (2020). Bathymetry-constrained navigation of Argo floats under sea ice on the Antarctic continental shelf. *Geophysical Research Letters*, 47, e2020GL087019. doi.org/10.1029/2020GL087019.

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

Project leader – Dr Xuebin Zhang (CSIRO)

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

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

The project team has made significant progress towards addressing the key objectives. In the past three years, the team has been mainly working on: 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; tuning up a suite of ocean models and carrying out carefully-designed numerical experiments with certain forcing being turned on or off; quantifying uncertainty in Antarctic surface mass balance and carrying ice sheet modelling to project future contribution of Antarctic Ice Sheet to sea-level rise; analysing sea level and related climate variables in the latest CMIP6 ensemble; and producing high-resolution sea-level fingerprints due to land ice mass changes using the NASA/JPL's ISSM sea-level module on unstructured mesh grid.

In the next two years, 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 new CMIP6 models, refined sea-level fingerprints and new projections of Antarctic Ice Sheet mass loss.

2.6.1 Year 3 highlights and progress against project objectives

It has been another successful year for the sea-level project. Fourteen journal manuscripts and one book chapter have been published, five manuscripts have been submitted 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 buoyance and momentum forcing on heat and sea-level distributions. Results will be published in one community ocean-only FAFMIP paper (Todd et al., 2020), and another manuscript to focus on comparison between model perturbation experiments and a theoretical framework (Lyu et al., 2020c, in preparation).

Sea-level output from CMIP5/6 ensembles were analysed and compared, and two manuscripts were published (Lyu et al., 2020b; Grose et al., 2020), one was submitted (Wu et al., 2020). Lyu et al., 2020b focused on a novel aspect of CMIP5/6 model analysis by making linkage between mean state biases and future projection uncertainties. Grose et al. (2020) discussed all new insights from CMIP6 for Australia's future Climate, which is highlighted by *American Geophysical Union (AGU) EOS Research Spotlight*. Wu et al. (2020) discussed different sea-level patterns, unknown before, in response to transient and stabilisation emission pathways.

The Ice Sheet System Model (ISSM) sea-level module with unstructured mesh grid developed by NASA/JPL was installed and tested extensively to various resolutions and underlying Earth models, based on which high-resolution sea-level fingerprints in response to polar ice sheet mass change projections were produced. 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.

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 submitted to *Nature Communications* (Wang et al., 2020), which is under the second review since early February (delayed due to COVID-19).

Natural variability in Antarctic surface mass balance (net snow accumulation) was examined, focusing on testing the sensitivity to different noise models. This work was published in *Geophysical Research Letters* (King and Watson 2020).

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 (Phipps et al., 2020, in preparation).

The project team (Drs Zhang and Lyu) has also contributed to three review papers published in *Surveys in Geophysics* (Carson et al., 2020; Han et al., 2020; Van de Wal et al., 2020. These papers were the result of a working group on Coastal Sea level and Ocean Circulation, sponsored by the International Space Science Institute (Bern, Switzerland). The project team (Drs Church and Zhang) has also contributed to three Oceanobs'19 community papers (Meyssignac et al., 2019; Palmer et al., 2019; Ponte et al., 2019) aimed at better quantifying ocean heat uptake, and observing and modelling coastal sea levels. Several papers authored by students under our supervision, or a result of collaboration, have been published or submitted (Holbrook et al., 2020; Li and Holbrook et al., 2020; Li and Liu, et al., 2020; Jin et al., 2020; Niphadkar et al., 2020; Savita et al., 2020).

Over the past year, our project members attended several national and international conferences, chairing sessions and delivering invited talks. In July 2019, Dr Zhang and Prof King attended the 27th International Union of Geodesy and Geophysics (IUGG) General Assembly, and Dr Zhang attended the Ocean Sciences Meeting in February 2020, to give talks based on findings from the CSHOR sea-level project. Dr Lyu delivered online presentations on FAFMIP experiments and the latest CMIP6 sea-level analysis. Dr Phipps presented his Antarctic Ice Sheet modelling results at several workshops and conferences.

In early-2020, supported by his CSIRO Julius Career Award, Dr Zhang visited Scripps Institution of Oceanography (San Diego, USA) for an external placement and collaboration with Drs Bruce Cornuelle and Matt Mazloff. The group worked on Southern Ocean modelling, adjoint modelling technique and dynamical downscaling, all of which are closely related to the CSHOR sea-level project.

With several other CSHOR scientists, Dr Zhang co-convened the third CSHOR session at the 2020 Australian Meteorological and Oceanographic Society (AMOS) conference in Perth, Australia. The CSHOR sea-level project team presented four abstracts at this conference.

CSHOR researchers, Drs Zhang, Lyu, Foppert and Tamsitt, hosted the online annual Consortium for Ocean-Sea Ice Modelling in Australia (COSIMA) workshop in May, which was converted from a physical to virtual workshop due to COVID-19. Three sessions, CSHOR, sea level, and Southern Ocean dynamics, were co-convened by the project team for 2020 Asia Oceania Geosciences Society (AOGS) annual conference, which was eventually cancelled due to COVID-19.

2.6.2 Project performance against milestones

Apart from the sixth milestone, which experienced a slight delay, all the 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 to separate various forcings (e.g, atmospheric momentum and buoyancy forcing, freshwater discharge from Antarctica), to study the impacts on ocean heat uptake and sea level in the Southern Ocean

A suite of perturbation experiments to separate impacts from atmospheric forcing (wind stress, heat and freshwater fluxes) have been carried out with a global ocean-sea ice model, following the FAFMIP protocol. Our project contributed to a community paper focusing on ocean-only FAFMIP experiments, which was recently accepted by *Journal of Advances in Modeling Earth Systems* (Todd et al., 2020). Another work led by CSIRO team focusing on comparison between FAFMIP experiments and a theoretical framework has been finished and is being written into a manuscript (Lyu et al., 2020c, in preparation), to be submitted to *Journal of Physical Oceanography* soon.

Milestone 2: Examination of sea-level change and variability in historical and future simulations of available CMIP6 models, with a focus on the Southern Ocean. Preparing dynamical sea-level component for the next generation of total sea-level projection

A manuscript describing the novel aspect of CMIP6 sea-level analysis by examining the linkage between mean state biases and future projection uncertainties was submitted to *Journal of Climate* in December and was accepted shortly after minor revision (Lyu et al., 2020b). The project team also contributed to a community paper describing new insights of Australian future climate based on CMIP6 simulations, which was published by *Earth's Future* (Grose et al., 2020), and highlighted by *AGU EOS Research Spotlight.* A manuscript focusing on distinct sea-level patterns between transient and stabilisation emission pathways based on global climate model simulations was submitted to *Climate Dynamics* (Wu et al., 2020). Another manuscript examining gyre circulation and sea-level changes based on CMIP5/6 models will be submitted soon (Zhang et al., 2020).

Milestone 3: Developing refined regional sea-level fingerprints associated with melting of land ice, in particular Antarctica Ice Sheet using high-resolution unstructured mesh grid based on updated Antarctic Ice Sheet melting contribution, including that coming from UTAS's group (#6). Preparing updated & refined fingerprint component for next generation of total sea-level projection

Ice Sheet System Model (ISSM) sea-level module developed by NASA/JPL has been installed at CSIRO and extensively tested. Refined regional sea-level fingerprints associated with melting of polar ice sheets were produced using ISSM sea-level module with high-resolution unstructured mesh grid (e.g., resolving melting sources at 10 km resolution), which provides refined global sea-level fingerprint component for next generation of total sea-level projection.

Milestone 4: Finishing the study of sensitivity of multi-decadal Southern Ocean heat uptake estimates to vertical interpolation schemes. Examination of historical regional sea-level budget (UNSW)

Estimates of ocean heat content are sensitive to several factors. We have contributed to several papers better quantifying this uncertainty (Meyssignac et al., 2019; Palmer et al., 2019; Savita et al., 2020). These papers focus on Expendable Bathythermograph (XBT) correction and mapping uncertainties. Also, different vertical interpolation schemes for ocean temperature have been tested and compared and a new vertical interpolation scheme has been used to quantify uncertainties in ocean heat content estimates. Encouraging results are being incorporated in a manuscript still under preparation. Significant progress has been made in regional sea-level budget for both historical and future periods, with one manuscript published (Richter et al., 2020) demonstrating the detection of anthropogenic sea-level change, one submitted and under second review with *Nature Communications* (Wang et al., 2020). An additional paper is currently being developed and will focus on the historical local (at coastal tide gauges) sea-level budget closure over 1958-current using improved component datasets and methodology, which is currently being developed into a manuscript.

Milestone 5: Publication of natural variability of trends in Antarctic Surface Mass Balance considering realistic noise models (UTAS)

A manuscript drafted by the UTAS team titled, “Antarctic Surface Mass Balance: Natural Variability, Noise, and Detecting New Trends,” was published by *Geophysical Research Letters* (King and Watson, 2020). It was also presented at the 27th IUGG General Assembly.

Milestone 6: Analysis of large ensemble ice sheet modelling over the next 5000 years taking into account uncertainty due to model physics (UTAS). Collaborate on sea-level fingerprint analysis and meltwater discharge effects on ocean circulation

The PISM has been set up to simulate the entire Antarctic Ice Sheet with large ensemble modelling approach, from the Last Glacial Maximum to present, and present to 2500 under different emission scenarios. This works estimates the Antarctic contribution to global sea-level rise and has been designed to drive future sea-level fingerprint ensemble projections (see Milestone 3). The main modelling work has been done, although submission of the manuscript (Phipps et al., 2020, in preparation) summarising this work was slightly delayed.

2.6.3 Project publications[7]

Abhishek Savita, Catia M. Domingues, Tim Boyer, Viktor Gouretski, Masayoshi Ishii, Gregory C. Johnson, John M. Lyman, Josh K. Willis, Simon J. Marsland, William Hobbs, John A. Church, Didier P. Monselesan, Peter Dobrohotoff, Rebecca Cowley and Susan E. Wijffels (2020). Quantifying uncertainty in spatio-temporal changes of upper-ocean heat content estimates: an internationally coordinated comparison. *Journal of Climate*, submitted.

Carson, M., Lyu, K., Richter, K., Becker, M., Domingues, C. M., Han, W., & Zanna, L. (2019). Climate Model Uncertainty and Trend Detection in Regional Sea Level Projections: A Review. *Surveys in Geophysics*. doi.org/10.1007/s10712-019-09559-3.

Grose, M., S. Narsey, F. Delage, A. Dowdy, M. Bador, G. Boschat, C. Chung, J. Kajtar, S. Rauniyar, M. Freund, K. Lyu, H. Rashid, X. Zhang, S. Wales, C. Trenham, N. Holbrook, T. Cowan, L. Alexander, J. Arblaster and S. Power (2020). Insights from CMIP6 for Australia's future climate, *Earth's Future*, 8, e2019EF001469. doi.org/10.1029/2019EF001469.

Han, W., Stammer, D., Thompson, P., Ezer, T., Palanisamy, H., Zhang, X., Domingue, C. M., Zhang, L. and Yuan, D. (2019). Impacts of Basin-Scale Climate Modes on Coastal Sea Level: a Review. *Surveys in Geophysics*. 40, 1493–1541. doi.org/10.1007/s10712-019-09562-8.

Holbrook, N.J., D.C. Claar, A.J. Hobday, K.L. McInnes, E.C. Oliver, A. Sen Gupta, M.J. Widlansky, and X. Zhang (2020). Chapter 18: ENSO-Driven Ocean Extremes and Ecosystem Impacts. AGU Monograph: ENSO in a Changing Climate. McPhaden, M., A. Santoso, W. Cai (Eds.), Wiley, in press.

Jin, Y., X. Zhang, J. A. Church and X. Bao (2020). Projected sea level changes in the China marginal seas based on dynamical downscaling. *Journal of Climate*, to be submitted.

King, M. A., and C. S. Watson (2020). Antarctic Surface Mass Balance: natural variability, noise and detecting new trends. *Geophysical Research Letters*, 47, e2020GL087493. doi.org/10.1029/2020GL087493.

Li, Z., N. J. Holbrook, X. Zhang, E. C. J. Oliver, and E. A. Cougnon (2020). Remote Forcing of Tasman Sea Marine Heatwaves. *Journal of Climate*, 33, 5337–5354. doi.org/10.1175/JCLI-D-19-0641.1.

Li, S., W. Liu, K. Lyu and X. Zhang (2020). The effect of stratospheric ozone depletion on Southern Ocean heat uptake and storage. *Climate Dynamics*, submitted.

Lyu, K., Zhang, X., Church, J. A., & Wu, Q. (2020a). Processes Responsible for the Southern Hemisphere Ocean Heat Uptake and Redistribution under Anthropogenic Warming. *Journal of Climate, 33*(9), 3787-3807. doi:10.1175/jcli-d-19-0478.1.

[7] 2019-20 publications are shown in bold text.

Lyu, K., X. Zhang, and J. A. Church (2020b). Regional Dynamic Sea Level Simulated in the CMIP5 and CMIP6 Models: Mean Biases, Future Projections, and Their Linkages. *Journal of Climate*, 33, 6377–6398. doi.org/10.1175/JCLI-D-19-1029.1.

Lyu, K., X. Zhang, J. A. Church, et al. (2020c) Drivers of the Southern Ocean heat and salt redistribution: revisiting a theoretical framework based on model perturbation experiments. *Journal of Physical Oceanography,* in preparation.

Meyssignac, B., Boyer, T., Zhao, Z., Hakuba, M. Z., Landerer, F. W., Stammer, D., . . . Zilberman, N. (Including Church, J. and Wijffels, S.) (2019). Measuring Global Ocean Heat Content to Estimate the Earth Energy Imbalance. *Frontiers in Marine Science*, 6(432). doi:10.3389/fmars.2019.00432

Niphadkar, P., M. Bowen, **X. Zhang** (2020). Sea level around the New Zealand coast: trends, variability and future projections. *Frontiers in Marine Science*, submitted.

Palmer, M. D., Durack, P. J., Chidichimo, M. P., Church, J. A., Cravatte, S., Hill, K., . . . Wijffels, S. (2019). Adequacy of the Ocean Observation System for Quantifying Regional Heat and Freshwater Storage and Change. *Frontiers in Marine Science*, 6(416). doi:10.3389/fmars.2019.00416

Ponte, R. M., Carson, M., Cirano, M., Domingues, C. M., Jevrejeva, S., Marcos, M., . . . Zhang, X. (2019). Towards Comprehensive Observing and Modeling Systems for Monitoring and Predicting Regional to Coastal Sea Level. *Frontiers in Marine Science*, 6(437). doi:10.3389/fmars.2019.00437

Richter, Kristin; Meyssignac, Benoit; Slangen, Aimee; Melet, Angélique; Church, John; Fettweis, Xavier; Marzeion, Ben; Agosta, Cecile; Ligtenberg, Stefan; Spada, Giorgio; Palmer, Matthew; Roberts, Christopher; Champollion, Nicolas (2020). Detecting a forced signal in satellite-era sea level change. *Environmental Research Letters*, doi.org/10.1088/1748-9326/ab986e.

Stammer, D., van de Wal, R. S. W., Nicholls, R. J., Church, J. A., Le Cozannet, G., Lowe, J. A., . . . Hinkel, J. (2019). Framework for High-End Estimates of Sea Level Rise for Stakeholder Applications. *Earth's Future*, 7(8), 923-938. doi:10.1029/2019ef001163.

Todd, A., L. Zanna, M. Couldrey, J. Gregory, Q. Wu, J. 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*. doi: 10.1029/2019ms002027.

van de Wal, R.S.W., X. Zhang, S. Minobe, S. Jevrejeva, R.E.M. Riva, C. Little, K. Richter and M. Palmer (2019). Uncertainties in long-term process-based coastal sea-level projections. *Surveys in Geophysics*, 40, 1655-1671. doi.org/10.1007/s10712-019-09575-3.

Wang, J., J.A. Church, X. Zhang and X. Chen (2020). Comparing global and regional sea level changes between observations and IPCC projections. *Nature Communications*, submitted.

Wu, Q., X. Zhang, J.A. Church, J. Hu, J. Gregory (2020). Evolving patterns of sterodynamic sea-level rise under mitigation scenarios and insights from linear system theory. *Climate Dynamics*, submitted.

Zhang, X., K. Lyu and J. Church (2020). Projected changes of ocean gyre circulation and associated sea level changes based on CMIP5/6 models. *Geophysical Research Letters*, in preparation.

3 Financial management

The Centre's revenue over a 5-year period to 2021-22 is AU$20m. An overview of the Centre's finances in 2019-20 is provided below.

3.1 Revenue

Total Revenue was $3,350m comprising contributions of $2m from QNLM funds and $1,350m from CSIRO funds (Figure 6).

Since the Centre's inception, CSIRO has contributed $4,143m (50% of Agreement funds) and QNLM $8m (80% of Agreement funds) (Figure 7). CSIRO currently holds $2,750m funds in trust to be rolled over to 2020-21 operations.

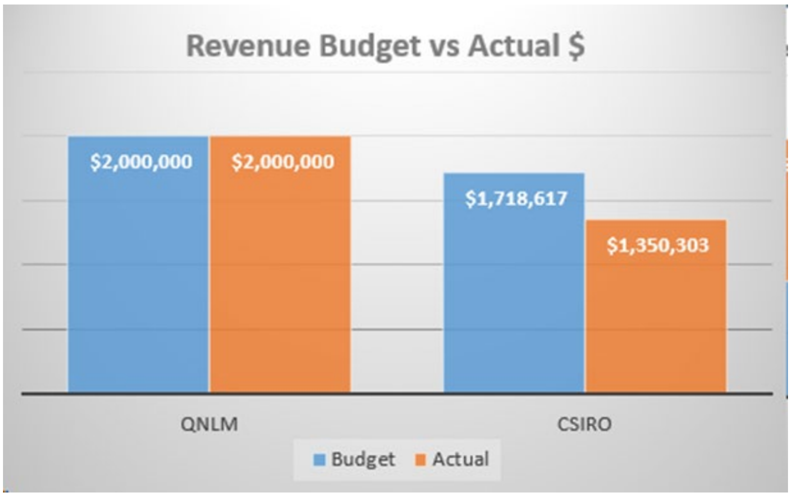

Figure 6 Revenue 2019-20: budget vs actual $

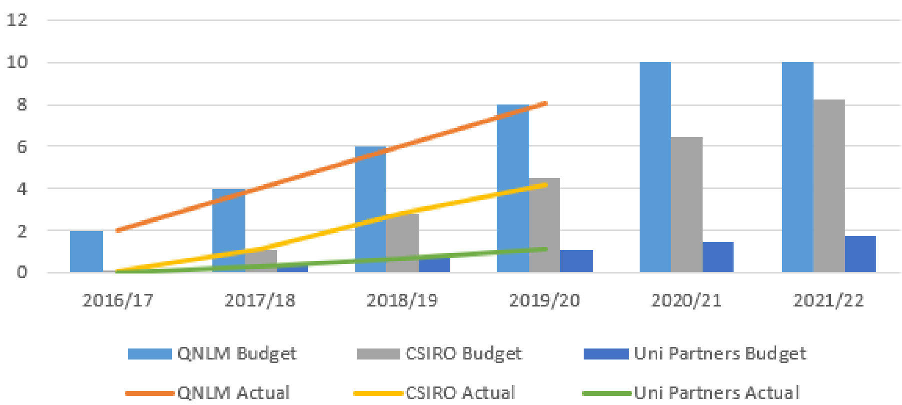

Figure 7 Revenue: cumulative budgets to 2021-22 ($m)

3.2 Expenditure

The total 2019-20 expenditure incurred was $3,410,008 acquitted to each partner as shown in Table 1.

Table 1 Total expenditure in 2019-20

Fund Source	2019-20 Budget	2019-20 Actuals	Variance
QNLM	$2,296,188	$1,635,283	-$660,905
CSIRO	$1,718,617	$1,350,303	-$368,314
UNSW (In-kind)	$290,000	$261,069	-$28,931
UTAS (In-kind)	$100,00	$163,353	+$63,353

The underspent variance on QNLM/CSIRO funds was -$1,029,219 which reflects a movement of $292,146 QNLM funded capital deferred to 2020-21; UTAS partner payment of $25,000 held over to August 2020 as final 2019-20 milestone not fully completed; and $712,073 underspend in normal operations, particularly in the fourth quarter due to COVID-19 business lockdowns and domestic and international travel restrictions/bans. Labour expenditure was down on budget due to staff taking leave (Table 2). These funds will be carried forward to 2020-21.

Total expenditure since the Centre commenced is $9,393m, which is approximately fifty one percent of the Centre's budget (Figure 8).

Table 2 Expenditure breakdown by category: 2019-20 budget vs actual

Expenditure by Category	19/20 Budget	19/20 Actual	WOL Budget	WOL Actual
Labour	1,871,306	1,658,771	9,296,243	4,647,124
Overheads	1,270,949	1,039,131	6,050,372	3,046,140
Travel	311,944	152,396	1,248,508	642,115
Operating	258,460	184,710	1,054,877	763,008
Payments to Partners	400,000	375,000	1,750,000	1,125,000
Capital	292,146	-	550,000	257,854
Total Expenditure	**4,404,805**	**3,410,008**	**19,950,000**	**10,481,241**

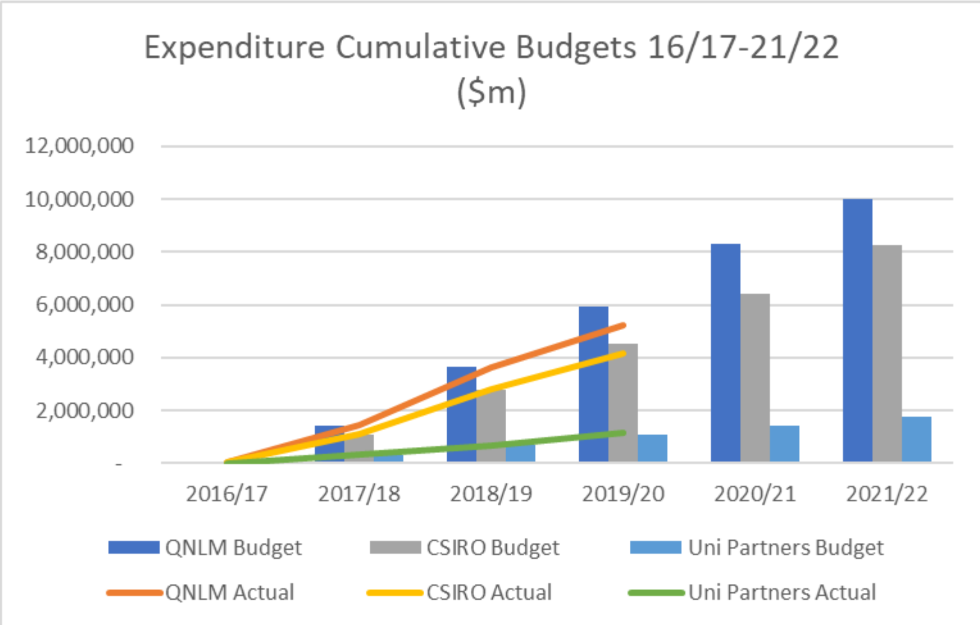

Figure 8 Expenditure: cumulative budgets to 2021-22 ($m)

3.3 Partner in-kind contribution

UNSW 2019-20 in-kind contribution was $261,069, -$28,931 under budget. UTAS 2019-20 in-kind contribution was $163,353, +$63,353 above budget. In-kind contributions since the Centre commenced are UNSW 63% at $782,899 and UTAS 61% at $305,163 (Figure 9).

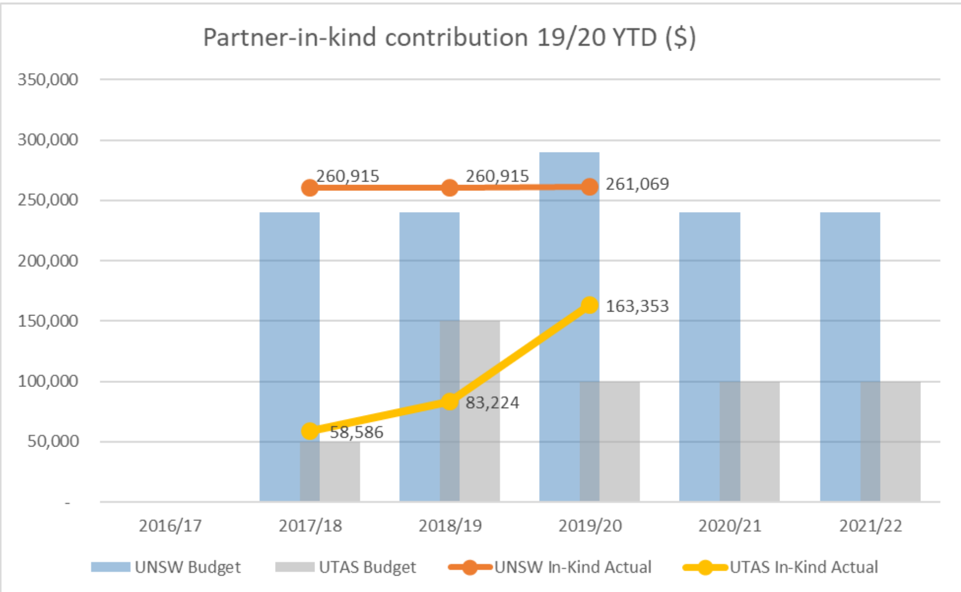

Figure 9 University partners in-kind contribution: 2019-20 year-to-date ($)

4 Management and co-ordination

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

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

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

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

The **CSHOR Steering Committee** convened via video conference on 28 November 2019 and on 23 and 24 July 2020. Due to international travel restrictions associated with the COVID-19 pandemic it was not possible for the Committee to meet face-to-face 2020.

The **CSHOR Research Leadership Team** met on 28 April, 20 May and 28 May 2020 and with the Steering Committee on 23 and 24 July 2020.

The **CSHOR Management Team**, comprising the Director, Project Support Officer and representatives from CSIRO Finance, Contracts, Communications and Business Development, joined the Leadership Team Meeting on the dates listed above and met separately on 24 June 2019 and on 27 February 2020.

The Director also attended various meetings at QNLM in Qingdao including CSHOR budget review and planning meetings in November and December 2019, and the QNLM Annual Meeting in January 2020.

Appendix A Project and support staff

Wenju Cai	Director
Rebecca Cowley	Scientific Programmer & Ocean Data Analyst - project 2 Indo-Pacific inter-basin exchange
Matthew England[8]	Project Leader - project 4 Southern Ocean dynamics
Ming Feng	Project Co-leader - project 3 Coupled warm pool dynamics in the Indo-Pacific
Annie Foppert	Postdoctoral Fellow - project 4 Southern Ocean dynamics
Laura Herraiz-Borreguero	Research Scientist – project 5 Southern Ocean observations
Je-Yuan (Andy) Hsu	Postdoctoral Fellow - project 3 Coupled warm pool dynamics in the Indo-Pacific
Andrew Lenton	Principal Research Scientist - project 4 Southern Ocean dynamics
Yuehua (Veronica) Li[9]	Research Associate - project 6 Southern Ocean sea-level change
Kewei Lyu	Postdoctoral Fellow - project 6 Southern Ocean sea-level change
Ben Ng	Postdoctoral Fellow – project 1 Understanding ENSO/IOD dynamics
Beatriz Peña-Molino	Research Scientist – project 2 Indo-Pacific inter-basin exchange
Océane Richet	Postdoctoral Fellow - project 2 Indo-Pacific inter-basin exchange
Steve Rintoul	Project Leader - project 5 Southern Ocean observations
Agus Santoso[10]	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[11]	Postdoctoral Fellow - project 4 Southern Ocean dynamics
Guojian Wang	Project Co-leader - project 1 Understanding ENSO/IOD dynamics
Susan Wijffels	Project Co-leader - project 3 Coupled warm pool dynamics in the Indo-Pacific
Leonie Wyld	Project Support Officer
Xuebin Zhang	Project Leader - project 6 Southern Ocean sea-level change

[8] UNSW Scientia Professor of Climate Dynamics

[9] UNSW Research Associate

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

[11] UNSW staff based at CSHOR Hobart

SUPPORT STAFF[12]	
Fiona Brown	Communication Advisor, CSIRO Oceans and Atmosphere
Sandy Farnworth	Legal and Contracts Advisor, CSIRO Oceans and Atmosphere
Chris Gerbing	Communication Manager, CSIRO Oceans and Atmosphere
Hugh Kater	Business Development Manager, CSIRO Oceans and Atmosphere
Sophie Schmidt	Communication Advisor, CSIRO Oceans and Atmosphere
Brenda Tuckwood	Finance and Projects Advisor, CSIRO Oceans and Atmosphere

[12] Provided by CSIRO

Appendix B PhD Students

Ana Berger	University of Tasmania, Aust Project 2 Indo-Pacific inter-basin exchange
Gauthier Gacoin	Ecole Normale Superieure of Lyon (ENS Lyon), France Project 5 Southern Ocean observations and change team member
Saisai Hou[13]	Ocean University of China Project 5 Southern Ocean observations and change team member
Zhi Li[14]	UNSW, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Jie Ma	Ocean University of China Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
Anna Maggiorano	UNSW Canberra, Australia Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
Jinping Wang[15]	Ocean University of China Project 6 Southern Ocean sea-level change project team
Ying Zhang	University of Chinese Academy of Sciences Project 3 Coupled warm pool dynamics in the Indo-Pacific team member

[13] Sponsored by the China Scholarship Council.

[14] Sponsored by the China Scholarship Council.

[15] Sponsored by the China Scholarship Council.

Appendix C Conference and workshop participation

C.1 First Quarter (July to September)

AMSA 2019 Annual Symposium, Fremantle, Perth, 7 to 11 July: Drs Feng and Huang attended. Dr Feng, presented, 'The Indonesian Throughflow, its variability, and influences on the Indian Ocean' and Dr Huang, in collaboration with Ming Feng, presented, 'Using Himawari-8 SST data for the investigation of highly dynamic oceanographic phenomena.'

The 27th IUGG General Assembly in Montreal, Canada, 8 to 18 July: Drs Sloyan, Richet, Zhang and Prof King attended. Dr Sloyan was invited to present to the Ocean Boundary Current session. The presentation focussed on the seasonal and higher frequency variability of the East Australian Current, based on observations and models.

Carbon Down Under Workshop, Sydney University, 24 to 25 July: Dr Santoso was invited to present a talk titled, 'El Niño Southern Oscillation under greenhouse warming'.

The 20th International Union for Quaternary Research (INQUA) Congress, Dublin, Ireland, 25 to 31 July: Dr Phipps (UTAS) presented a paper titled, 'Using the history of the Antarctic Ice Sheet to reduce uncertainties in projections of global sea-level rise'.

Asia Oceania Geosciences Society (AOGS) Annual Meeting in Singapore, 28 July to 2 August: Drs Cai, Wang and Hsu attended. Dr Cai gave the Ocean Sciences Distinguished Lecture. His presentation titled, 'Response of El Niño/La Niña to Greenhouse Warming', presented recent findings showing that the frequency of extreme La Niña and variability of eastern Pacific El Niño SST are expected to increase in response to unabated greenhouse gas emissions. Dr Hsu presented, 'Simulations of Diurnal Variability SST and Upper Ocean Structure in the Access-S1 Model During the Suppressed Phase of MJO.'

CLIVAR South American Monsoon Workshop in Brazil from 19 to 21 August**:** Dr Cai attended and gave a talk on 'ENSO under greenhouse warming'.

The 4th Annual Consortium of Ocean-Sea Ice Modelling in Australia (COSIMA) Workshop at ANU, Canberra, 3 to 4 September. Dr Tamsitt presented a talk on Lagrangian pathways and residence time of Circumpolar Deep Water on the Antarctic continental shelf. Dr Zhang and Lyu presented talks on numerical perturbation experiments and dynamical downscaling.

Australasian Coasts and Ports 2019, Hobart, Tasmania, 10 to 13 September: Dr Phipps (UTAS) presented a paper titled, 'The commitment to global sea-level rise over the next 500 years: exploring the threat of the Antarctic Ice Sheet to coastal infrastructure'.

OceanObs'19, Hawaii in 16 to 20 September: Dr Cai, Wang and Tilbrook attended. QNLM and CSIRO hosted a special session focused on building an international transparent ocean community by encouraging nations to share data, develop innovative observing technologies, and build a cost-effective global observing system.

World Marine Science and Technology Conference in Qingdao from 24 to 25 September: Dr Cai and Wang attended. Dr Cai chaired the plenary session in which Prof Ian Allison gave an invited talk.

Southern Ocean and Climate Change Workshop held in Qingdao from 25 to 27 September: Dr Cai and Wang attended.

C.2 Second Quarter (October to December)

The 3rd workshop of ENSO impacts on South America, São Paulo, Brazil from 6 to 13 October: Drs Cai, Santoso, Ng and Wang.

CLIVAR Pacific Regional Panel (PRP) meeting and a joint workshop between CLIVAR PRP and PICES WG-40 on Climate and Ecosystem Predictability in the Pacific, Victoria, Canada from 19 to 20 October: Dr Zhang.

South China Sea Conference 2019, Sanya, China from 24 to 25 October: Dr Feng presented an invited talk on 'The Indonesian Throughflow, its variability, and influences on the Indian Ocean.'

International Ocean Science Biennial Conference, Sanya, China on 26 October: Dr Feng presented a keynote talk titled, 'Argo data detect fast warming trend in the southern hemisphere oceans.'

CLIVAR-IOC Joint Meeting, Orléans, France from 26 October to 1 November: Dr Cai.

The Workshop on Future Climate Change, Nanjing, China from 15 to 16 November: Drs Cai and Wang.

The international symposium on Climate Variation, Prediction and Application: 20-year Anniversary of IOD Research, Nanjing, China from 17 to 19 November: Drs Cai and Wang.

The 10th International Workshop on Tropical Marine Environmental Changes (MEC 2019): The Oceans and Climate, Guangzhou from 24 to 25 November: Drs Cai, Feng, Lyu, Santoso and Wang. Ming Feng presented an invited talk on 'Recent hemispheric asymmetry in global ocean warming induced by climate change and internal variability.'

AGU 2019, San Francisco, United States from 9 to 13 December: Drs Cai and Hsu. Dr Hsu presented 'Rapid foundation SST Warming Captured by ALAMO Floats during the Suppressed Phase of the MJO.'

UNSW Sea-level Workshop, Sydney from 2 to 3 December: Prof Church, Drs Lyu and Zhang and Ms Wang.

C.3 Third Quarter (January to March)[16]

100th American Meteorological Society Annual Meeting 2020, 12 to 16 January, Boston, Mass., USA: Dr Santoso attended and received the AMS Editor's award for his reviews in the *Journal of Climate*, "For consistently high-quality reviews on various topics in tropical climate dynamics."

Australian Meteorological and Oceanographic Society (AMOS) 2020, 10 to 14 February, Fremantle, Western Australia: Drs Cai, Wang, Santoso, Feng, Lyu, Foppert, Ng and Ms Jinping Wang attended. Drs Santoso, Wang, Ng, and Feng chaired the CSHOR session consisting of 20 presentations. Dr Cai gave an AMOS plenary talk.

Gateways to the Ocean Symposium, 13 to 14 February 2020, Scripps, San Diego, USA: Drs Tamsitt and Wijffels.

Ocean Sciences Meeting 2020, 16 to 21 February, San Diego, California, USA: Drs Cai, Wang, Wijffels, Nikurashin, Phillips, Foppert, Tamsitt and Zhang and Prof England attended. Dr Cai, as CLIVAR SSG Co-chair, hosted the CLIVAR Town Hall Meeting. Although they were unable to attend the Ocean Sciences Meeting, Dr Laura Herraiz-Borreguero was a lead author on a presentation and a co-author on a second and Dr Steve Rintoul was a co-author on five presentations.

C.4 Fourth Quarter (April to June)

None to report this quarter. Most meetings were postponed or cancelled due to the physical distancing requirements and travel restrictions resulting from the COVID-19 pandemic.

[16] None to report in March. Meetings were postponed or cancelled due to the physical distancing requirements and travel restrictions resulting from the COVID-19 pandemic.

Appendix D Datasets

One dataset was produced in 2019-20:

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

October-November 2019, wire walker profiling data will be publicly available 3 years after data validation at Australian Ocean Data Network (AODN).

Appendix E Publications

Journal Articles

1. Beal, L. M., Vialard, J., Roxy, M. K., Li, J., Andres, M., Annamalai, H., . . . Parvathi, V. (Including Feng, M., Sloyan, B.) (2020). A roadmap to IndOOS-2: Better observations of the rapidly-warming Indian Ocean. *Bulletin of the American Meteorological Society*. doi:10.1175/bams-d-19-0209.1
2. Belkin, I., Foppert, A., Rossby, T., Fontana, S., & Kincaid, C. (2020). A Double-Thermostad Warm-Core Ring of the Gulf Stream. *Journal of Physical Oceanography, 50*(2), 489-507. doi:10.1175/jpo-d-18-0275.1
3. Bestley, S., Andrews-Goff, V., van Wijk, E., Rintoul, S. R., Double, M. C., & How, J. (2019). New insights into prime Southern Ocean forage grounds for thriving Western Australian humpback whales. *Scientific Reports, 9*(1), 13988. doi:10.1038/s41598-019-50497-2
4. Bordbar, M. H., England, M. H., Sen Gupta, A., Santoso, A., Taschetto, A. S., Martin, T., . . . Latif, M. (2019). Uncertainty in near-term global surface warming linked to tropical Pacific climate variability. *Nature Communications, 10*(1), 1990. doi:10.1038/s41467-019-09761-2
5. Cai, W., McPhaden, M. J., Grimm, A. M., Rodrigues, R. R., Taschetto, A. S., Garreaud, R. D., . . . Vera, C. (2020). Climate impacts of the El Niño–Southern Oscillation on South America. *Nature Reviews Earth & Environment, 1*(4), 215-231. doi:10.1038/s43017-020-0040-3
6. Carson, M., Lyu, K., Richter, K., Becker, M., Domingues, C. M., Han, W., & Zanna, L. (2019). Climate Model Uncertainty and Trend Detection in Regional Sea Level Projections: A Review. *Surveys in Geophysics*. doi:10.1007/s10712-019-09559-3
7. Castagno, P., Capozzi, V., DiTullio, G. R., Falco, P., Fusco, G., Rintoul, S. R., . . . Budillon, G. (2019). Rebound of shelf water salinity in the Ross Sea. *Nature Communications, 10*(1), 5441. doi:10.1038/s41467-019-13083-8
8. Cyriac, A., McPhaden, M. J., Phillips, H. E., Bindoff, N. L., & Feng, M. (2019). Seasonal Evolution of the Surface Layer Heat Balance in the Eastern Subtropical Indian Ocean. *Journal of Geophysical Research: Oceans, 124*(9), 6459-6477. doi:10.1029/2018jc014559
9. Feng, M., Duan, Y., Wijffels, S., Hsu, J.-Y., Li, C., Wang, H., . . . Yu, W. (2020). Tracking air-sea exchange and upper ocean variability in the Indonesian-Australian Basin during the onset of the 2018-19 Australian summer monsoon. *Bulletin of the American Meteorological Society*. doi:10.1175/bams-d-19-0278.1
10. Foppert, A., Rintoul, S. R., & England, M. H. (2019). Along-Slope Variability of Cross-Slope Eddy Transport in East Antarctica. *Geophysical Research Letters, 46*(14), 8224-8233. doi:10.1029/2019gl082999

11. Grose, M. R., Narsey, S., Delage, F. P., Dowdy, A. J., Bador, M., Boschat, G., . . . Power, S. (2020). Insights From CMIP6 for Australia's Future Climate. *Earth's Future, 8*(5), e2019EF001469. doi:10.1029/2019ef001469

12. Han, W., Stammer, D., Thompson, P., Ezer, T., Palanisamy, H., Zhang, X., . . . Yuan, D. (2019). Impacts of Basin-Scale Climate Modes on Coastal Sea Level: a Review. *Surveys in Geophysics*. doi:10.1007/s10712-019-09562-8

13. Holmes, R. M., Zika, J. D., Ferrari, R., Thompson, A. F., Newsom, E. R., & England, M. H. (2019). Atlantic Ocean Heat Transport Enabled by Indo-Pacific Heat Uptake and Mixing. *Geophysical Research Letters, 46*(23), 13939-13949. doi:10.1029/2019gl085160

14. Hsu, J.-Y., Hendon, H., Feng, M., & Zhou, X. (2019). Magnitude and Phase of Diurnal SST Variations in the ACCESS-S1 Model During the Suppressed Phase of the MJOs. *Journal of Geophysical Research: Oceans, 124*(12), 9553-9571. doi:10.1029/2019jc015458

15. Hu, S., Sprintall, J., Guan, C., McPhaden, M. J., Wang, F., Hu, D., & Cai, W. (2020). Deep-reaching acceleration of global mean ocean circulation over the past two decades. *Science Advances, 6*(6), eaax7727. doi:10.1126/sciadv.aax7727

16. Hu, S., Zhang, Y., Feng, M., Du, Y., Sprintall, J., Wang, F., . . . Chai, F. (2019). Interannual to Decadal Variability of Upper-Ocean Salinity in the Southern Indian Ocean and the Role of the Indonesian Throughflow. *Journal of Climate, 32*(19), 6403-6421. doi:10.1175/jcli-d-19-0056.1

17. Jia, F., Cai, W., Wu, L., Gan, B., Wang, G., Kucharski, F., . . . Keenlyside, N. (2019). Weakening Atlantic Niño–Pacific connection under greenhouse warming. *Science Advances, 5*(8), eaax4111. doi:10.1126/sciadv.aax4111

18. Kennicutt II, M. C., D. B., Daniela Liggett, Birgit Njåstad, Lloyd Peck, Stephen R. Rintoul, Catherine Ritz, Martin J. Siegert, Alan Aitken, Cassandra M. Brooks, John Cassano, Sanjay Chaturvedi, Dake Chen, Klaus Dodds, Nicholas R. Golledge, Céline Le Bohec, Marcelo Leppe, Alison Murray, P. Chandrika Nath, Marilyn N. Raphael, Michelle Rogan-Finnemore, Dustin M. Schroeder, Lynne Talley, Tony Travouillon, David G. Vaughan, Lifan Wang, Allan T. Weatherwax, Huigen Yang, Steven L. Chown,. (2019). Sustained Antarctic Research: A 21st Century Imperative. *One Earth, 1*(1), 95-113. doi:doi.org/10.1016/j.oneear.2019.08.014

19. King, M. A., & Watson, C. S. (2020). Antarctic Surface Mass Balance: Natural Variability, Noise, and Detecting New Trends. *Geophysical Research Letters, 47*(12), e2020GL087493. doi:10.1029/2020gl087493

20. Kiss, A. E., Hogg, A. M., Hannah, N., Boeira Dias, F., Brassington, G. B., Chamberlain, M. A., . . . Zhang, X. (2020). ACCESS-OM2 v1.0: a global ocean–sea ice model at three resolutions. *Geosci. Model Dev., 13*(2), 401-442. doi:10.5194/gmd-13-401-2020

21. Lago, V., & England, M. H. (2019). Projected Slowdown of Antarctic Bottom Water Formation in Response to Amplified Meltwater Contributions. *Journal of Climate, 32*(19), 6319-6335. doi:10.1175/jcli-d-18-0622.1

22. Li, Q., Lee, S., England, M. H., & McClean, J. L. (2019). Seasonal-to-Interannual Response of Southern Ocean Mixed Layer Depth to the Southern Annular Mode from a Global 1/10° Ocean Model. *Journal of Climate, 32*(18), 6177-6195. doi:10.1175/jcli-d-19-0159.1

23. Li, S., Wu, L., Yang, Y., Geng, T., Cai, W., Gan, B., . . . Ma, X. (2020). The Pacific Decadal Oscillation less predictable under greenhouse warming. *Nature Climate Change, 10*(1), 30-34. doi:10.1038/s41558-019-0663-x

24. Li, Z., Holbrook, N. J., Zhang, X., Oliver, E. C. J., & Cougnon, E. A. (2020). Remote Forcing of Tasman Sea Marine Heatwaves. *Journal of Climate, 33*(12), 5337-5354. doi:10.1175/jcli-d-19-0641.1

25. Lyu, K., Zhang, X., & Church, J. A. (2020). Regional Dynamic Sea Level Simulated in the CMIP5 and CMIP6 Models: Mean Biases, Future Projections, and Their Linkages. *Journal of Climate, 33*(15), 6377-6398. doi:10.1175/jcli-d-19-1029.1

26. Lyu, K., Zhang, X., Church, J. A., & Wu, Q. (2020). Processes Responsible for the Southern Hemisphere Ocean Heat Uptake and Redistribution under Anthropogenic Warming. *Journal of Climate, 33*(9), 3787-3807. doi:10.1175/jcli-d-19-0478.1

27. Ma, J., Feng, M., Lan, J., & Hu, D. (2020). Projected Future Changes of Meridional Heat Transport and Heat Balance of the Indian Ocean. *Geophysical Research Letters, 47*(4), e2019GL086803. doi:10.1029/2019gl086803.

28. McKenna, S., A. Santoso, A. Sen Gupta, A. Taschetto, W. Cai (2020). Indian Ocean Dipole in CMIP5 and CMIP6: Characteristics, biases, and links to ENSO. *Scientific Reports,* 10(1), 11500. doi.org/10.1038/s41598-020-68268-9.

29. Meijers, A. J. S., Cerovečki, I., King, B. A., & Tamsitt, V. (2019). A See-Saw in Pacific Subantarctic Mode Water Formation Driven by Atmospheric Modes. *Geophysical Research Letters, 46*(22), 13152-13160. doi:10.1029/2019gl085280

30. Meyssignac, B., Boyer, T., Zhao, Z., Hakuba, M. Z., Landerer, F. W., Stammer, D., . . . Zilberman, N. (2019). Measuring Global Ocean Heat Content to Estimate the Earth Energy Imbalance. *Frontiers in Marine Science, 6*(432). doi:10.3389/fmars.2019.00432.

31. Newman, L., Heil, P., Trebilco, R., Katsumata, K., Constable, A., van Wijk, E., . . . Spreen, G. (2019). Delivering Sustained, Coordinated, and Integrated Observations of the Southern Ocean for Global Impact. *Frontiers in Marine Science, 6*(433). doi:10.3389/fmars.2019.00433.

32. Palmer, M. D., Durack, P. J., Chidichimo, M. P., Church, J. A., Cravatte, S., Hill, K., . . . Wijffels, S. (2019). Adequacy of the Ocean Observation System for Quantifying Regional Heat and Freshwater Storage and Change. *Frontiers in Marine Science, 6*(416). doi:10.3389/fmars.2019.00416

33. Ponte, R. M., Carson, M., Cirano, M., Domingues, C. M., Jevrejeva, S., Marcos, M., . . . Zhang, X. (2019). Towards Comprehensive Observing and Modeling Systems for Monitoring and

Predicting Regional to Coastal Sea Level. *Frontiers in Marine Science, 6*(437). doi:10.3389/fmars.2019.00437

34. Rathore, S., Bindoff, N. L., Phillips, H. E., & Feng, M. (2020). Recent hemispheric asymmetry in global ocean warming induced by climate change and internal variability. *Nature Communications, 11*(1), 2008. doi:10.1038/s41467-020-15754-3
35. Richter, K., Benoit, M., Aimée, B. A. S., Angélique, M., John, A. C., Xavier, F., . . . Nicolas, C. (2020). Detecting a forced signal in satellite-era sea-level change. *Environmental Research Letters*.
36. Sloyan, B. M., Wilkin, J., Hill, K. L., Chidichimo, M. P., Cronin, M. F., Johannessen, J. A., . . . Yu, W. (2019). Evolving the Physical Global Ocean Observing System for Research and Application Services Through International Coordination. *Frontiers in Marine Science, 6*(449). doi:10.3389/fmars.2019.00449
37. Stammer, D., van de Wal, R. S. W., Nicholls, R. J., Church, J. A., Le Cozannet, G., Lowe, J. A., . . . Hinkel, J. (2019). Framework for High-End Estimates of Sea Level Rise for Stakeholder Applications. *Earth's Future, 7*(8), 923-938. doi:10.1029/2019ef001163
38. Sun, Q., Du, Y., Zhang, Y., Feng, M., Chowdary, J. S., Chi, J., . . . Yu, W. (2019). Evolution of Sea Surface Salinity Anomalies in the Southwestern Tropical Indian Ocean During 2010–2011 Influenced by a Negative IOD Event. *Journal of Geophysical Research: Oceans, 124*(5), 3428-3445. doi:10.1029/2018jc014580
39. Tamsitt, V., Cerovečki, I., Josey, S. A., Gille, S. T., & Schulz, E. (2020). Mooring Observations of Air–Sea Heat Fluxes in Two Subantarctic Mode Water Formation Regions. *Journal of Climate, 33*(7), 2757-2777. doi:10.1175/jcli-d-19-0653.1
40. van de Wal, R. S. W., Zhang, X., Minobe, S., Jevrejeva, S., Riva, R. E. M., Little, C., . . . Palmer, M. D. (2019). Uncertainties in Long-Term Twenty-First Century Process-Based Coastal Sea-Level Projections. *Surveys in Geophysics, 40*(6), 1655-1671. doi:10.1007/s10712-019-09575-3
41. Wåhlin, A. K., Steiger, N., Darelius, E., Assmann, K. M., Glessmer, M. S., Ha, H. K., . . . Viboud, S. (2020). Ice front blocking of ocean heat transport to an Antarctic ice shelf. *Nature, 578*(7796), 568-571. doi:10.1038/s41586-020-2014-5
42. Wallace, L. O., van Wijk, E. M., Rintoul, S. R., & Hally, B. (2020). Bathymetry-Constrained Navigation of Argo Floats Under Sea Ice on the Antarctic Continental Shelf. *Geophysical Research Letters, 47*(11), e2020GL087019. doi:10.1029/2020gl087019
43. Wang, G., Cai, W., & Santoso, A. (2020). Stronger Increase in the Frequency of Extreme Convective than Extreme Warm El Niño Events under Greenhouse Warming. *Journal of Climate, 33*(2), 675-690. doi:10.1175/jcli-d-19-0376.1

44. Wei, Y., Gille, S. T., Mazloff, M. R., Tamsitt, V., Swart, S., Chen, D., & Newman, L. (2020). Optimizing mooring placement to constrain Southern Ocean air-sea fluxes. *Journal of Atmospheric and Oceanic Technology*. doi:10.1175/jtech-d-19-0203.1

45. Zhang, Y., Du, Y., Jayarathna, W. N. D. S., Sun, Q., Zhang, Y., Yao, F., & Feng, M. (2020). A Prolonged High-Salinity Event in the Northern Arabian Sea during 2014–17. *Journal of Physical Oceanography, 50*(4), 849-865. doi:10.1175/jpo-d-19-0220.1

Reports

1. Beal, L. M., Vialard, J., Roxy, M. K. et al. (Including Feng, M., Sloyan, B.) (2019a). Full Report. IndOOS-2: A roadmap to sustained observations of the Indian Ocean for 2020-2030. CLIVAR-4/2019, GOOS-237, 206 pp. doi.org/10.36071/clivar.rp.4.2019.

2. Beal, L. M., Vialard, J., Roxy, M. K. et al. (Including Feng, M., Sloyan B.) (2019b). Executive Summary. IndOOS-2: A roadmap to sustained observations of the Indian Ocean for 2020-2030. CLIVAR-4/2019, GOOS-237, 8 pp. doi.org/10.36071/clivar.rp.4-1.2019.

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