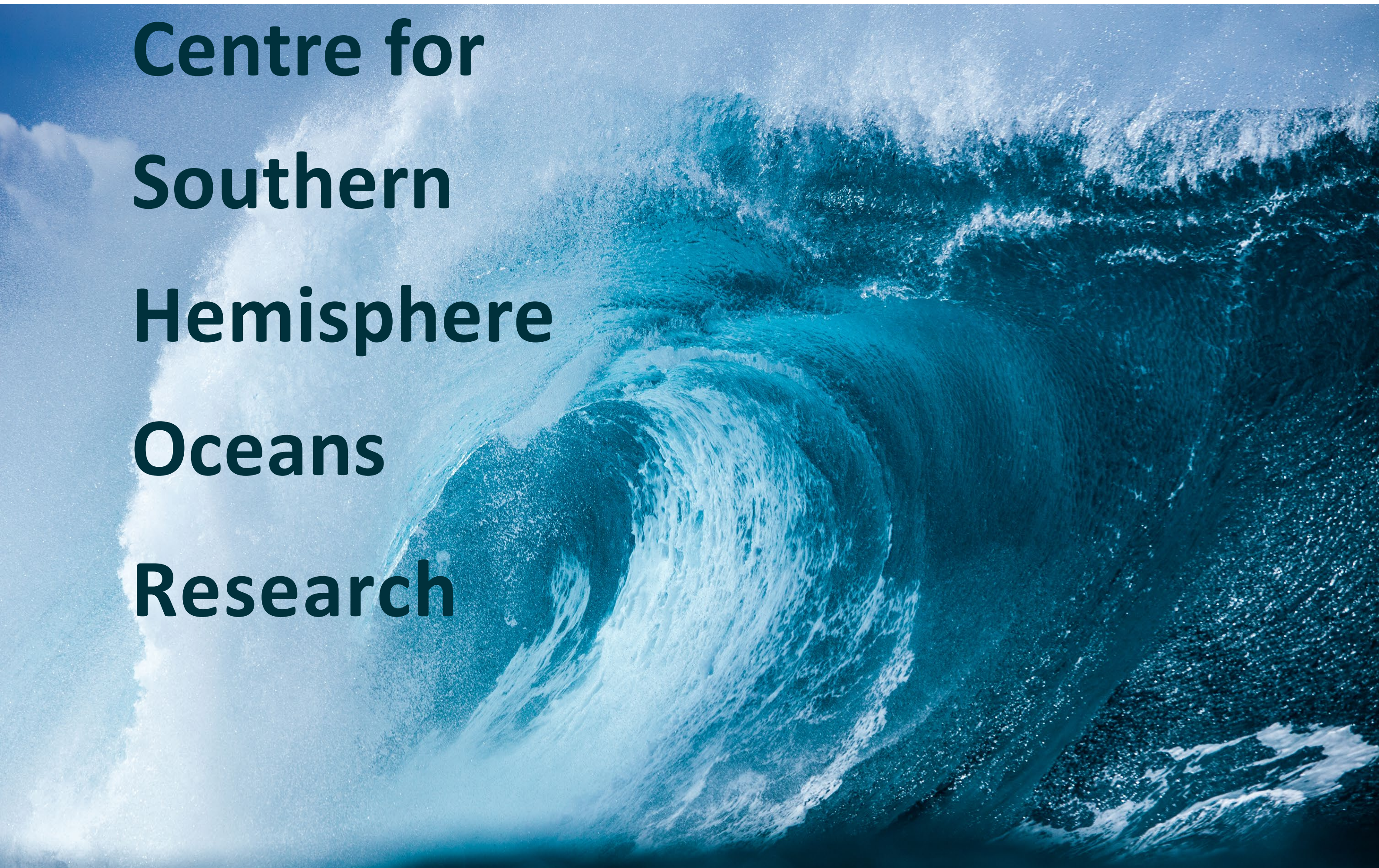
www.csiro.au

2021-22 Annual Report

Centre for Southern Hemisphere Oceans Research



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

CSIRO

UNSW SYDNEY

UNIVERSITY of TASMANIA

Published: 8 August 2022

Foreword

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

From a purely scientific perspective, CSHOR has been an immense success as demonstrated by a publication rate that is greater than many international high-quality scientific organizations. However, this partnership also enabled scientific capacity building in people who had an unusual opportunity to build careers based on international collaboration and a financial commitment to a vision that was bold and had global impact. The legacy of the impact of CSHOR has probably not yet been fully seen by the international scientific community nor by the decision-makers who will benefit immensely from the new knowledge obtained by this unique research partnership.

Key scientific advances include:

- An understanding of how ENSO events intensify with global warming and how that impacts other ocean-connected signatures of ENSO.
- Development of observational infrastructure in the Indo-Pacific to study the critical role of the air-sea interaction in the Indonesian region and its impact both regionally and globally.
- The development of machine learning approaches to advance the understanding of warm pool dynamics and the impact on weather forecasting.
- Advancement of our understanding of the tropical teleconnections to Antarctic Sea ice and the important role of melt water to the overturning circulations around Antarctica.
- New Antarctic observations that greatly enhances our understanding of the heat and carbon uptake and overturning of bottom warm processes in the deep ocean that demonstrates the vulnerability of the east Antarctic ice sheet and the critical role this will play in sea level rise projections.

This work could not have been accomplished without the support of QNLM, CSIRO, and Australian universities. And I know that partnerships can at times be challenging. But CSHOR is an unqualified success because of this partnership. The Centre Director and staff are to be highly congratulated. The financial, intellectual, and organizational support was absolutely key in enabling observational access to regions of the ocean that have been underexplored yet are so important to our understanding of ocean dynamics, climate change, and biodiversity. The vision has led to an extraordinary array of science and a deeper understanding of the critical role of the Southern Ocean not only to science but also to humanity.

CSHOR has made a difference in the following ways:

- Advanced understanding via a partnership that enabled new system thinking research on critical questions.
- Provided educational training for students in an intellectual environment that supported system methodologies.
- Enabled new ocean observing systems in Antarctica as well as in the Indonesian throughflow region.
- Improved climate projections.
- Translated this new knowledge to decision makers through climate services, targeted briefings, scientific assessments, and news releases.

I am sure CSHOR's legacy will continue well into the future.

Regards,

Dr Susan K Avery

CSHOR Steering Committee Chair

President Emerita, Woods Hole Oceanographic Institution

Professor Emeritus, University of Colorado Boulder

August, 2022

Contents

Foreword iii

Acknowledgments.....8

1 Executive summary.....11

1.1 Research achievements.....12

1.2 Communication and outreach highlights.....14

2 Project performance and highlights.....17

2.1 Understanding present and future dynamics of ENSO, the IOD, and their interactions with the southern hemisphere oceans (Project 1).....17

2.2 Indo-Pacific inter-basin exchange (Project 2).....22

2.3 Coupled warm pool dynamics in the Indo-Pacific (Project 3).....27

2.4 Southern Ocean dynamics, circulation, and water-mass formation (Project 4).....32

2.5 Southern Ocean observations and change – Antarctic observations (Project 5) 37

2.6 The role of the Southern Ocean in sea level change (Project 6).....44

3 Financial management.....50

3.1 Revenue.....50

4 Management and co-ordination.....53

Appendix A Abbreviations and acronyms.....54

Appendix B Project and support staff.....56

Appendix C PhD Students.....58

Appendix D Conference and workshop participation.....60

Appendix E Publications.....62

Figures

Figure 1 Increased future sea surface temperature (SST) variability of a, Eastern Pacific ENSO and b, Central Pacific ENSO as shown by CMIP6 and CMIP5 model ensemble. c, Nonlinear relationship between first and second modes of SST variability in the tropical Pacific for historical period (1900-1999). Orange dots indicate extreme El Nino events, blue dots extreme La Nina events, and orange stars extreme El Nino events followed by extreme La Nina event. Numbers indicate the average frequency of event type per 100 years with 90% confidence interval. d, As in c but for 2000-2099. A stronger inter-model consensus on increased ENSO SST variability emerges in CMIP6 than CMIP5 models. Only models that reasonably simulate observed ENSO nonlinearity are selected. Models are forced by historical forcing up to 2014 and, thereafter, the Shared Socioeconomic Pathway 5-8.5 (SSP5-8.5). (Cai et al. 2021, *Nat. Rev. Earth Environ*.)................18

Figure 2 (A) Schematic of the circulation in the Indonesian Seas. Black arrows illustrate the mean flow direction, including the separation of the inflow into the eastern (via Seram Sea) and western (via Makassar Strait) pathways, and the outflows into the Indian Ocean, from west to east, through Lombok, Ombai and Timor straits. Dashed lines show the two Timor throughflow sources: a direct western pathway around the eastern end of Timor and a recirculating route via Banda Sea entering Timor Passage further to the east. Red lines indicate altimeter tracks. Black circles along the eastern most altimeter track in Timor Passage show the location of the IMOS moored array. (B) Seasonal cycle of the volume transport (Sv) across Timor Passage as observed by the moored array integrated across layers. (C) Seasonal cycle of the temperature transport (°C Sv) by the Timor throughflow. Estimated from the temperature and velocity fields derived from the moorings. On the right-side axis heat transport equivalent (PW) values for an assumed return flow temperature of 3.4°C. Orange and blue shading in panels (B) and (C) illustrate the periods of the different monsoon seasons. (from Peña-Molino et al. 2022)...23

Figure 3 Detection of rapid restratification of ocean surface boundary layer during CSHOR field campaign. Float trajectories from 29 November to 5 December 2018 (colour lines with dots in (a); labelled on the right of (b)–(g)), the measured buoyance frequency N2 normalised by a constant N_0^2 of 1.0 × 10−4 s−2 at six floats (b)–(g). The interval between each colour dot (the position of floats at 12 am each day) in (a) is one day. In (b)–(g), the green colour marks the near zero or negative N2 due to density inversions, and the magenta lines are the reference depth z0 for estimating the surface mixed layer depth (MLD; yellow lines), which is computed as the bottom of the diurnal thermocline during diurnal warming. Only z0 > 5 m at the ALAMO floats and z0 > 15 m at the EM-APEX floats are shown. Missing measurements are indicated by white areas bounded by black lines in (c), (d), and at the right of the black line in (b), (f) (Hsu et al. 2022). 28

Figure 4 Past and present Warm Circumpolar Deep Water temperature. Map: potential temperature at the neutral surface 28.05 kg m-3, between 2010 and 2018. CDW upwells from the deep ocean to <500 dbar on this density surface. The rate of ice shelf thickness change (1994-2012) is also shown (Paolo et al. 2014). The 400, 700, 1000, 3000 dbars are shown as grey contours. Pannels: potential temperature change on the neutral density surface since 1930 (green) and since 1990 (blue). All the trends (degrees per decade) are significant to the 95% confidence (estimated using a bootstrap analysis with 10,000 repetitions). From Herraiz-Borreguero and Naveira-Garabato (2022). 38

Figure 5 Changes in (upper panels) full-depth integrated ocean heat content and (lower panels) global zonal mean ocean temperature by the time of CO_2 doubling from CMIP5 models and various perturbation experiments using a global ocean sea-ice model (ACCESS-OM2): (a) Multi-model average from CMIP5 1pctCO2 experiment; (b) FAFMIP all-forcing experiment; (c) heat flux forcing experiment; (d) passive transport of surface heat uptake from a passive tracer; (e) wind stress forcing experiment; (f) freshwater flux forcing experiment. 46

Figure 6 Revenue 2021-22 Budget vs Actual $ 50

Figure 7 Revenue: Cumulative budgets to 2021-22 ($m) 50

Figure 8 Expenditure: Cumulative budgets to 2021-22 ($m) 52

Tables

Table 1 Total expenditure in 2020-21 ....**Error! Bookmark not defined.**

Table 2 Expenditure breakdown by category: 2020-21 budget vs actual**Error! Bookmark not defined.**

Acknowledgments

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

Partners

Qingdao National Laboratory for Marine Science and Technology (QNLM)

Commonwealth Scientific and Industrial Research Organisation (CSIRO)

University of New South Wales (UNSW)

University of Tasmania (UTAS)

CSHOR Steering Committee

Dr Susan Avery, Committee Chair, Woods Hole Oceanographic Institute, USA (WHOI)

Prof Kehou PAN, Secretary-General of Academic Committee, QNLM and

Professor, Ocean University of China

Madam Ning WANG, Head of the Department of International Affairs, QNLM

Dr Dan Metcalfe, Director, CSIRO Oceans and Atmosphere

Dr Jaci Brown, Director, CSIRO Climate Science Centre

CSHOR Advisory Committee

Prof AN Zhiseng, Chinese Academy of Sciences (CAS)

Dr Paul Hardisty, Australian Institute of Marine Science (AIMS)

Dr Debbie Hudson, Australian Bureau of Meteorology (BoM)

Dr Michael McPhaden, US National Oceanic and Atmospheric Administration (NOAA)

Dr Tas van Ommen, Australian Antarctic Division (AAD)

Prof Martin Visbeck, GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany

Project collaborators and participants

Dr Oscar Alves, BoM

Antarctic Climate and Ecosystems Co-operative Research Centre (ACE CRC), Australia

Australian Marine National Facility (MNF)

Australian Research Council Centre of Excellence for Climate Extremes (CLEX)

Dr Jessica Benthuysan, AIMS

Prof Nathan Bindoff, UTAS

Dr Ivana Cerovečki, Scripps Institution of Oceanography, USA

Prof Xianyao Chen, Ocean University of China

Dr Zhaohui Chen, Ocean University of China

Prof John Church, UNSW

Dr Carol Clayson, US WHOI

Prof Mat Collins, University of Exeter, UK

Prof Yan Du, South China Sea Institute of Oceanology, CAS

Dr Yongliang Duan, First Institute of Oceanography, Ministry of Natural Resources, China

Dr Bolan Gan, Ocean University of China

Prof Alberto C Naveira Garabato, National Oceanographic Centre-Southampton, UK

Prof Sarah Gille, Scripps Institution of Oceanography, USA

Prof Arnold Gordon, Lamont-Doherty Earth Observatory, Columbia University, USA

Dr Sjoerd Groeskamp, UNSW

Dr Harry Hendon, BoM

Prof Andy Hogg, Australian National University

Prof Dunxin Hu, Institute of Oceanology, CAS

Dr Shijian Hu, Institute of Oceanology, CAS

Dr Zhi Huang, Geosciences Australia

Assistant Prof Je-Yuan (Andy) Hsu, Institute of Oceanography, National Taiwan University

International Laboratory for High-Resolution Earth System Prediction (iHESP), USA

Integrated Marine Observing System (IMOS), Australia

Dr Fan Jia, Institute of Oceanology, CAS

Dr Simon Josey, National Oceanography Centre, UK

Dr Matt King, UTAS

Dr Matthieu Lengaigne, Institute of Research for Development, Laboratory of Oceanography and Climate: Experiments and numerical Approaches

Dr Qian Li, Massachusetts Institute of Technology, USA

Prof. Xiaopei Lin, Ocean University of China

Dr Lin Liu, First Institute of Oceanography, Ministry of Natural Resources, China

Dr Qin-Yan Liu, South China Sea Institute of Oceanology, CAS

Dr Jie Ma, Institute of Oceanology, CAS

Prof Trevor McDougall, UNSW

Dr Michael McPhaden, NOAA

Dr Adele Morrison, ANU

National Environmental Science Program – Earth System and Climate Change Hub

New Zealand National Institute for Water and Atmosphere Research

Dr Maxim Nikurashin, UTAS

Dr Esther Portela, UTAS

Dr Helen Phillips, UTAS

Dr Steven Phipps, UTAS

Program for Climate Model Diagnosis and Intercomparison (PCMDI)

Prof Stephen Riser, University of Washington, USA

Dr Eric Schulz, BoM

Prof Kevin Speer, Florida State University, USA

Dr Janet Sprintall, Scripps Institution of Oceanography, USA

Mr Craig Steinberg, AIMS

Mr Daniel Torres, WHOI

Prof Fan Wang, Institute of Oceanology, CAS

Prof Xiao-Hua Wang, UNSW

Dr Christopher Watson, UTAS

Dr Matthew Wheeler, BoM

Dr Susan Wijffels, Woods Hole Oceanographic Institution, USA

Prof John Wilkin, Rutgers University, USA

Prof Lixin Wu, QNLM

Prof Toshio Yamagata, Japan Agency for Marine-Earth Science and Technology

Prof Sang-Wook Yeh, Hanyang University, South Korea

Dr Weidong Yu, First Institute of Oceanography, Ministry of Natural Resources, China

Prof Dongliang Yuan, Institute of Oceanology, CAS

Prof Ronghua Zhang, Institute of Oceanology, CAS

Dr Ying Zhang, China Sea Institute of Oceanology, CAS

Mr Yu Zhang, China Sea Institute of Oceanology, CAS

Dr Xiaobing Zhou, BoM

1 Executive summary

The CSHOR Annual Report is a record of the Centre's activities, achievements, and financial management during the period from 1 July 2021 to 30 June 2022.

The Centre was launched in May 2017 with the purpose of conducting fundamental research into the role of the southern hemisphere oceans in regional and global climate systems. It is a collaborative research partnership between the CSIRO, China's Qingdao National Laboratory for Marine Science and Technology (QNLM), the University of New South Wales and the University of Tasmania. Having achieved its objectives, the Centre is closing at the end of this financial year.

Notable advances in understanding the global climate system are reported this, the final year, of CSHOR. A few highlights from the detailed project reports provided in Section 2 follow.

Project researchers discovered that the mixing in the Indonesian Seas, which plays a pivotal role in the climate system, is substantially powered by remotely generated planetary (Rossby and Kelvin) waves from the Indian Ocean and the Pacific Ocean. Likewise, ocean temperature variability in the western-central Pacific is important for variability of Ningaloo Niño, which is characterised by devastating marine heatwaves.

On a larger scale, in addition to showing increased variability Niño-Southern Oscillation and the Indian Ocean Dipole under greenhouse warming, CSHOR scientists have found that the response of tropical variability has a substantial impact in the projected Southern Ocean circulation change, with an increase in El Niño-Southern Oscillation (ENSO) variability slowing the Southern Ocean warming.

Further, our scientists discovered that Southern Ocean warming-induced meltwater input is likely to drive a contraction of Antarctic Bottom Water, facilitating a greater access of warm Circumpolar Deep Water to the continental shelf. Our observation team has found a warming signal along the Australian East Antarctic sector induced in part by a southward migration of the westerlies/easterlies, which is likely behind the recent acceleration in the ice mass loss from the East Antarctic Ice Sheet. Such observations are essential for understanding how southern oceans are changing, and for constraining projection of future changes. For example, using Argo array observations since 2005 to constrain projected thermosteric sea level rise suggests that without dramatic reductions in greenhouse gas emissions, by the end of this century, the upper 2,000 metres of the ocean is likely to warm by 11-15 times the amount of warming observed during 2005-19.

There are many other exciting results in the pipeline, which will appear in the press after CSHOR's closure.

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 2021-22 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 published 52 research articles, including ten in the *Nature* group of journals, one each in *Science* and *Science Advances,* and one in *Proceedings of the National Academy of Sciences*. Approximately 20 publications, several in review with high-profile journals, remain in the pipeline for completion next financial year. Publications are listed in Appendix E .

The Indo-Pacific and tropical variability

The El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) project synthesised advances in observed and projected changes of multiple aspects of ENSO, including the processes behind such changes (Cai et al. 2021, *Nature Reviews Earth & Environment*). A paper published in *Nature Climate Change* found that the North Pacific Meridional Mode contributes to an increased frequency of future extreme ENSO events and becomes a more influential precursor for their predictability (Jia et al. 2021). Another, published in *Nature Climate Change,* find increased sea surface temperature (SST) variability in commonly used ENSO indices under all likely emission pathways, in contrast to the Intergovernmental Panel on Climate Change (IPCC) report which finds no systematic change in ENSO SST over the 21st century in any scenarios considered (Cai et al. 2022). In addition, Yang et al. (2021) published in *Science Advances* reveals a robust intensification of tropical North Atlantic SST variability under greenhouse warming.

The Indo-Pacific inter-basin exchange project focused on the analysis of existing data sets and expanding modelling capacity. The team's work has shown that the impact of small-scale motions in the Indonesian Seas controls circulation pathways, water mass transformation, surface properties and inter-basin property exchange (Peña-Molino et al. 2022). A study estimating wave and eddy energy fluxes in the Indonesian Seas, is the first showing that the remotely generated planetary (Rossby and Kelvin) waves and eddies can power mixing in the Indonesian Seas (Pang et al., under review). This is a significant finding as the Indonesian Seas are one of the most intense mixing regions in the ocean and play a pivotal role in the climate system. As well as its regional and global climate implications, the project team's results bear directly on the problem of constructing physically-based mixing parameterisations for climate models. Models in this region exhibit systematic biases that have been attributed to poor representation of mixing. Thus, having an accurate representation of the various processes that maintain mixing will be critical to improving climate projections. Profiling floats deployed in the internal seas combined with our suite of high-resolution numerical models, will reveal critical information about those processes in years to come.

The warm pool dynamics project identified a rapid re-stratification of the ocean surface boundary layer in the Indonesian-Australian Basin, which corresponds with extremely low surface winds during the calm phase of the Madden-Julian Oscillations (MJOs) (Hsu et al. 2022). Knowledge of marine heatwaves and their drivers in the Indo-Pacific region has greatly improved. It is now understood that ocean temperature variability in the western-central Pacific is important for the Ningaloo Niño variability (Feng et al. 2021; Marin et al. 2022). The project has also made breakthroughs in applying machine learning and data mining techniques in characterisation and predictions of sea surface temperatures in the Indo-Pacific region (Taylor and Feng 2022; Chapman et al. 2022; Feng et al. 2022).

The Southern Ocean

The Southern Ocean observation project discovered a warming signal along the Australian East Antarctic sector. This warming is explained by a southward migration of the southernmost fronts of the Southern Ocean as well as a southward migration of the westerlies/easterlies. The change in the location of the winds is likely behind the recent acceleration in the ice mass loss from the East Antarctic Ice Sheet: more upwelling-favouring winds are located near the continental shelf, allowing warmer Circumpolar Deep Water to reach the ice shelves. The work has recently beed accepted by *Nature Climate Change.*

The first in depth analysis of Deep Argo float data in an Antarctic Basin was published in the *Journal of Geophysical Research: Oceans* (Foppert et al. 2021). The float data reveal the pathways and variability of Antarctic Bottom Water (AABW) supplied by the Ross Sea and Adélie Land coast with unprecedented detail. The work was selected as a Research Highlight by the editors of EOS, published by the American Geophysical Union.

Complementing the work of the Southern Ocean observations team, CSHOR modellers analysed recent and future projected abyssal ocean temperature trends using a global high-resolution ocean model. The numerical experiments separately consider wind-driven changes, meltwater anomalies, and warming of the ocean surface to disentangle the driving mechanisms at play. The results indicate that meltwater change is driving modern-day bottom water warming, with projections indicating that this is set to accelerate in the coming decades. The CSHOR modelling team also produced new Lagrangian estimates of the pathways and time-scales of ocean connectivity around the Antarctic continental shelf, which is critical for understanding pathways of meltwater transport as well as advection of marine biota around the Antarctic margin.

For the first time the Argo array observations since 2005 were used to constrain climate model projections of ocean warming and thermosteric sea level rise by the end of this century based on the Emergent Constraints methodology (Lyu et al. 2021, *Nature Climate Change*). The Southern Ocean and sea level rise project team's analysis shows that without dramatic reductions in greenhouse gas emissions, by the end of this century, the upper 2,000 metres of the ocean is likely to warm by 11-15 times the amount of warming observed during 2005-19. Water expands as it gets warmer, so this warming will cause sea levels to rise by 17-26 centimetres.

The project team also contributed to an international collaboration reported in *Nature Climate Change* examining ozone forcing on Southern Ocean warming over the historical period (1955-2000). The study found that tropospheric ozone increases, not considered much before, played a comparable role as stratospheric ozone depletion (Liu et al. 2022).

1.2 Communication and outreach highlights

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

Media and communication

The prevailing La Niña event through late 2021 and into 2022 have contributed to significant interest in the ENSO modes of variability from media and the public. As wet weather conditions prevailed across eastern states of Australia during summer and autumn months CSHOR science and expertise was reported on regularly.

The Nature Earth & Environment review paper Cai et al. 2021 was published in August 2021 and received coverage in COSMOS magazine & WSWS.org. This paper coincided with the publication of the Intergovernmental Panel on Climate Change's (IPCC) Working Group I 2021 climate change assessment. There was syndicated media coverage in The Age and Sydney Morning Herald about how results differed between IPCC findings and this paper. Scientists and communications team worked together during this time to ensure consistent scientific messaging and demonstrating support for the IPCC process and climate science community.

The *Science Advances* paper by Yang et al. also in August 2021 received news coverage in the Mirage News. And again in August CSHOR Director was called upon by The Age for an expert opinion on a scientific publication from the *Journal of Climate*.

CSHOR leaders were called upon to give expert explainers about La Niña (announced in November 2021) and ENSO cycles through the reporting year.

- **Dr Wenju Cai**: insurancenews.com.au in November 2021; Mongabay in November 2021; The Age and SMH in January 2021 (during a humid heatwave on Australia's east coast); Inside Climate News (with Matthew England) in March 2021
- **Dr Agus Santoso**: ABC News, COSMOS in February 2022; Parts of NSW could be in for fifth flood in The Canberra Times, July 2022; live interview with Studio 10 and ABC Adelaide radio in June 2022; The Guardian in June, 2022; Threat of third straight La Nina summer threatens to flood Brisbane, Daily Telegraph in May 2022; ABC Weekend Breakfast (live TV interview) April 2022, Wet autumn outlook for parts of eastern Australia as the BOM predicts above average rainfall; ABC News, April 2022; BOM indicates drenching La Nina is set to hang around until late autumn, ABC News, March, 2022.
- **Prof Matthew England**: ABC TV News, Reuters and Channel 9 TV Perth, Triple JJJ Hack, SBS TV news on east coast flooding (9 March 2022), Prime News 7 regarding La Nina and flooding rains (25 February, 2022), ABC Radio (AM program) about a new study examining ocean salinity changes (24 February), ABC Radio – Mornings with Cassie McCullagh

regarding Sydney's wet summer (21st January 2022), ABC TV News24 regarding ocean warming (13th January, 2022)

Phys.org covered the Foppert et al. (2021) paper on Deep Argo in the Antarctic Basin.

Drs Kewei Lyu, Xuebin Zhang and Prof John Church received some media coverage of their *Nature Climate Change* paper (Lyu et al. 2021). Their article in The Conversation was read by over 26,000 readers, and Dr Lyu was invited to participate in The Conversation's weekly podcast which was listened to by over 10,000 listeners. Science Daily also covered this paper.

The Liu et al. 2022 *Nature Climate Change* paper on ozone forcing Southern Ocean warming also received some media coverage, including by SciTechDaily which was re-published by other online publications.

At the end of the previous annual reporting period (June 2021) Dr Steve Rintoul was made an Officer of the Order of Australia for his service to climate science, chiefly in oceanographic and Antarctic research. This was reported in the Launceston Examiner, Hobart Mercury, Tasmanian Examiner, and on ABC Radio. In 2021 Dr Rintoul was also made a Fellow of the American Geophysical Union which was shared by some media outlets.

In another acknowledgment of CSHOR staff expertise Prof Matthew England was named as a Green Power Player in The Australian newspaper's list produced in Feb 2022. Whilst CSHOR was not mentioned specifically, this publication reached 495,000 potential audience. This is not included in total CSHOR reach below.

The csiro.au web page for CSHOR has been viewed around 530 times during the reporting period, with a significant peak in late September 2021.

Across 54 media articles measured by media monitoring, the estimated audience size was **over 214,000**. This does not consider outlets with no data on average audience size, stories from non-CSIRO CSHOR staff members, and international news stories. Therefore, the audience estimate of 214,000 is considered to be low for this reporting period.

Outreach – workshops and conferences

CSHOR research was presented at a host of national and international meetings during 2021-22. Meetings were held online due to the physical distancing requirements and travel restrictions associated the COVID-19 pandemic. CSHOR staff convened sessions at several meetings. Major conferences and workshops attended by CSHOR staff are listed in Appendix D .

In February 2022, CSHOR convened a session at the 13th International Conference on Southern Hemisphere Meteorology and Oceanography (ICSHMO). Prof England convened a session at AGU Ocean Sciences in March 2022.

Awards and special mentions

Dr Steve Rintoul was appointed to an Officer of the Order of Australia (AO), elected as a Fellow of the American Geophysical Union (AGU), and received a CSIRO Lifetime Achievement Award.

Prof John Church was also appointed to an Officer of the Order of Australia (AO). Prof

Church is a Professor at UNSW's Climate Change Research Centre (CCRC), and collaborates with CSHOR's Southern Ocean and sea-level change project team.

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. A full list of 2021-22 publications is in Appendix E Abbreviations and acronyms are explained in Appendix A .

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

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

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

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

2.1.1 Year 5 highlights and progress against project objectives

A paper published in *Nature Reviews Earth & Environment* (Cai et al. 2021) synthesised advances in observed and projected changes of multiple aspects of ENSO (see Figure 1 below), including the processes behind such changes. One paper published in *Nature Climate Change* (Jia et al. 2021) found that the North Pacific Meridional Mode contributes to an increased frequency of future extreme ENSO events and becomes a more influential precursor for their predictability. Cai et al. (2022) also published in *Nature Climate Change* find increased sea surface temperature variability in commonly used ENSO indices under all likely emission pathways, in contrast to IPCC report which finds no systematic change in ENSO SST over the 21st century in any scenarios considered. In addition, Yang et al. (2021) published in *Science Advances* reveals a robust intensification of North Tropical Atlantic sea surface temperature variability under greenhouse warming. Wang et al. (2022), also in *Nature Climate Change,* found that Southern Ocean warming during the 21st century is influenced by change in amplitude of El Niño-Southern Oscillation.

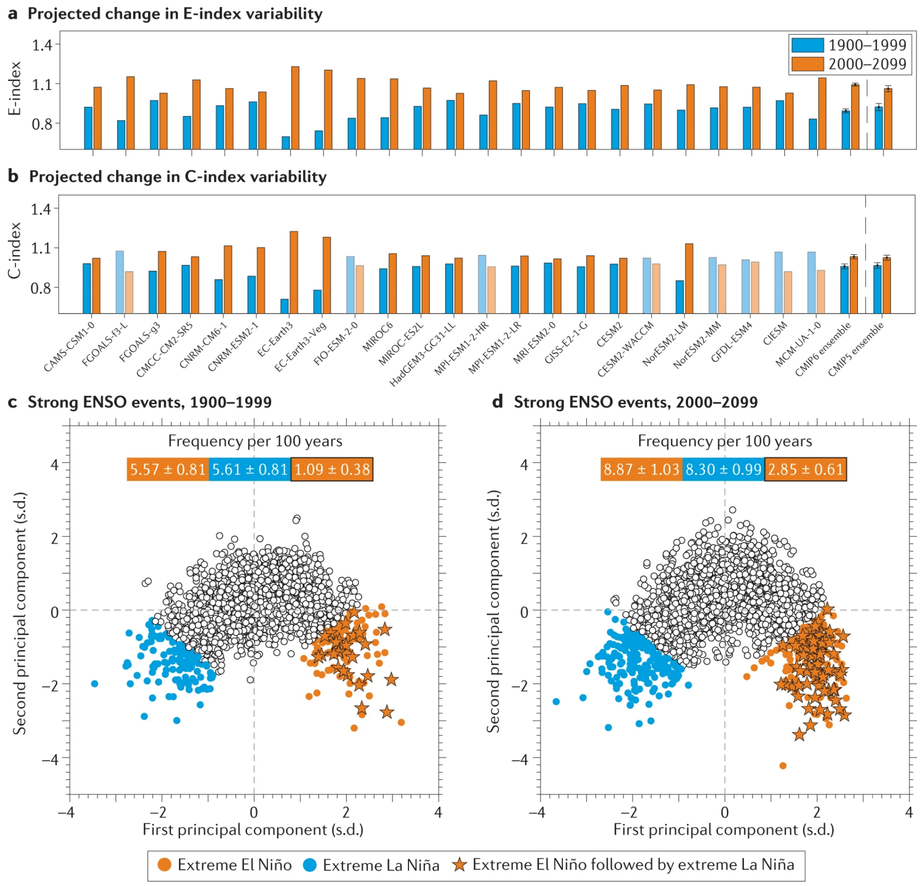


Figure 1 Increased future sea surface temperature (SST) variability of a, Eastern Pacific ENSO and b, Central Pacific ENSO as shown by CMIP6 and CMIP5 model ensemble. c, Nonlinear relationship between first and second modes of SST variability in the tropical Pacific for historical period (1900-1999). Orange dots indicate extreme El Nino events, blue dots extreme La Nina events, and orange stars extreme El Nino events followed by extreme La Nina event. Numbers indicate the average frequency of event type per 100 years with 90% confidence interval. d, As in c but for 2000-2099. A stronger inter-model consensus on increased ENSO SST variability emerges in CMIP6 than CMIP5 models. Only models that reasonably simulate observed ENSO nonlinearity are selected. Models are forced by historical forcing up to 2014 and, thereafter, the Shared Socioeconomic Pathway 5-8.5 (SSP5-8.5). (Cai et al. 2021, *Nat. Rev. Earth Environ*.)

2.1.2 Project performance against milestones

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

Milestone 1: Investigating link between Southern Hemisphere climate and tropical climate variability, in particular, possible influences by the tropical Pacific Ocean on response of the Southern Ocean to greenhouse warming:

Study influence of tropical variability in Southern Ocean and Antarctic climate change in observation

Li et al. (2021) synthesised understanding of tropical teleconnections to the southern hemisphere extratropics arising from the El Niño–Southern Oscillation, Interdecadal Pacific Oscillation and Atlantic Multidecadal Oscillation, focusing on the mechanisms and long-term climatic impacts. It is now published with *Nature Reviews Earth & Environment.*

Examine impact of ENSO response to greenhouse warming on Southern Ocean heat uptake

The Southern Ocean is a primary heat sink that buffers atmospheric warming, and has warmed substantially, accounting for an outsized portion of global warming-induced excess heat in the climate system. However, the projected Southern Ocean warming is highly uncertain and varies substantially across climate models, affected by climate sensitivity, parametrisation of mesoscale ocean eddies, and relative importance of increasing carbon dioxide, Antarctic ozone recovery, and decreasing aerosols. Using outputs from models participating in the sixth phase of Coupled Model Inter-comparison Project, Wang et al. (2022) show that Southern Ocean warming during the 21st century is influenced by change in amplitude of El Niño-Southern Oscillation (ENSO). Models simulating a larger increase in ENSO amplitude systematically produce a slower Southern Ocean warming, and vice versa. This is accepted by *Nature Climate Change*.

Examine Indo-Pacific tropical variability in response to Southern Hemisphere climate changes

Pontes et al. (2022), accepted in *Nature Geoscience*, examine PlioMIP ensemble and found that ENSO weakening in response to global-scale warming in the mid Pliocene is due to off-equatorial mean state changes in the Pacific. Further analysis is being conducted to investigate changes in Indo-Pacific climate variability.

In addition, Yang et al. (2022) found that there is an increased variability of western Pacific Subtropical high in response to greenhouse warming. Using outputs from 32 latest climate models, Yang et al. (2022) shows an increase in western Pacific subtropical high (WPSH) variability translating into a 73% increase in frequency of strong WPSH events under a business-as-usual emission scenario, supported by a strong inter-model consensus. Under greenhouse warming, response of tropical atmosphere convection to Central Pacific sea surface temperature anomalies increases, as does the response of the northwestern Pacific anticyclonic circulation. Thus, climate extremes such as floods in Yangtze River Valley of East China associated with WPSH variability are likely to be more frequent and more severe. This is accepted by *PNAS*.

Other recently published results contribute to understanding how Indo-Pacific climate variability is linked to the southern hemisphere climate system. These include investigations on how ENSO, IOD, and their interactions influence moisture sources for southeastern Australian rainfall (Holgate et al. 2022), and Indonesian Throughflow (Santoso et al. 2022). Climate models exhibit biases in ENSO and IOD that impact on the representation of Indonesian Throughflow variability. One of the solutions in improving these biases requires increased model resolution. Wang S. et al. (2022) showed using a high-resolution climate model that oceanic eddies damp El Niño and La Niña, suggesting that resolving eddies in climate models can lead to more realistic ENSO amplitude.

Milestone 2: Investigating tropical - extratropical and interbasin interactions and their response to changes in ENSO teleconnections:

Study ENSO response to greenhouse warming in the new CMIP6 models

Cai et al. (2021) synthesised advances in observed and projected changes of multiple aspects of ENSO, including the processes behind such changes. As in previous syntheses, there is an inter-model consensus of an increase in future ENSO rainfall variability. Now, however, it is apparent that models that best capture key ENSO dynamics also tend to project an increase in future ENSO sea surface temperature variability and, thereby, ENSO magnitude under greenhouse warming, as well as an eastward shift and intensification of ENSO-related atmospheric teleconnections — the Pacific–North American and Pacific–South American patterns. It is now published in *Nature Reviews Earth & Environment.*

Examine changing influence of tropical North Pacific variability on ENSO

Most ENSO events are preceded by the North Pacific Meridional Mode (NPMM), a dominant coupled ocean–atmospheric mode of variability. How the precursory NPMM forcing on ENSO responds to greenhouse warming remains unknown. Here, using climate model ensembles under high-emissions warming scenarios, Jia et al. (2021) find an enhanced future impact on ENSO by the NPMM. This is manifested by increased sensitivity of boreal-winter equatorial Pacific winds and sea surface temperature (SST) anomalies to the NPMM three seasons before. The enhanced NPMM impact translates into an increased frequency of NPMM that leads to an extreme El Niño or La Niña. Under greenhouse warming, higher background SSTs cause a nonlinear evaporation–SST relationship to induce surface wind anomalies more effectively in the equatorial western Pacific, conducive to ENSO development. Thus, NPMM contributes to an increased frequency of future extreme ENSO events and becomes a more influential precursor for their predictability. This is published in *Nature Climate Change.*

In addition, Cai et al. (2022) considered the recent IPCC report which finds no systematic change in ENSO SST over the 21st century in any scenarios considered. In contrast to IPCC report, comparing ENSO in the 20th and 21st century Cai et al. find increased SST variability in commonly used ENSO indices under all likely emission pathways. This has been published in *Nature Climate Change*.

Ng et al. (in preparation) is examining extreme positive Indian Ocean Dipole events defined by either SST or rainfall in the CMIP6 ensemble and their different response to greenhouse warming. Analysis for this study is in its preliminary stages.

Examine changing ENSO teleconnections over the tropical North Atlantic and the associated impact

Variability of North Tropical Atlantic (NTA) sea surface temperature (SST), characterised by a near-uniform warming at its positive phase, is a consequential mode of climate variability. Modulated by El Niño–Southern Oscillation (ENSO) and the North Atlantic Oscillation, NTA warm anomalies tend to induce La Niña events, droughts in Northeast Brazil, increased frequency of extreme hurricanes, and phytoplankton blooms in the Guinea Dome. Future changes of NTA variability could have profound socioeconomic impacts yet remain unknown.

Yang et al. (2021) reveal a robust intensification of NTA variability under greenhouse warming. This intensification mainly arises from strengthening of ENSO-forced Pacific-North American pattern and tropospheric temperature anomalies, as a consequence of an eastward shift of ENSO-induced equatorial Pacific convection and of increased ENSO variability, which enhances ENSO influence by reinforcing the associated wind and moist convection anomalies. The intensification of NTA SST variability suggests increased occurrences of extreme NTA events, with far-reaching ramifications. This is published in *Science Advances.*

2.1.3 Project publications

Journal articles

Cai, W., Ng, B., Wang, G., Santoso, A., Wu, L., and Yang, Kai (2022). Increased ENSO sea surface temperature variability under four IPCC emission scenarios. *Nature Climate Change*. https://doi.org/10.1038/s41558-022-01282-z.

Cai, W., Santoso, A., Collins, M. et al. (Including Wang, G. and Ng, B.) (2021). Changing El Niño–Southern Oscillation in a warming climate. *Nature Reviews Earth and Environment*. https://doi.org/10.1038/s43017-021-00199-z.

Holgate, C.; Evans, J. P.; Taschetto, A. S; Sen Gupta, A.; Santoso, A. (2022). The impact of interacting climate modes on east Australian precipitation moisture sources. *Journal of Climate*, pp. 1 - 31, https://doi.org/10.1175/JCLI-D-21-0750.1.

Jeong, YC., Yeh, SW., Lim, YK. Santoso, A, Wang, G. (July 2022). Indian Ocean warming as key driver of long-term positive trend of Arctic Oscillation. *npj Climate and Atmospheric Science* 5, 56. https://doi.org/10.1038/s41612-022-00279-x.

Jia, F., Cai, W., Gan, B. Di Lorenzo, E. (2021). Enhanced North Pacific impact on El Niño/Southern Oscillation under greenhouse warming. *Nature Climate Change.* https://doi.org/10.1038/s41558-021-01139-x.

Li, X., Cai, W., Meehl, G. A., et al. (Including Wang, G.) (2021). Tropical teleconnection impacts on Antarctic climate changes. *Nature Reviews Earth and Environment.* https://doi.org/10.1038/s43017-021-00204-5.

Ng, B., Cai, W., Wang, G., et al. Different response of extreme positive Indian Ocean Dipole events from rainfall and SST definitions. In preparation.

Pontes, G. M., A. Taschetto, A. Sen Gupta, A. Santoso, I. Wainer, A. Haywood, W.-L. Chan, A. Abe-Ouchi, et al. Northward ITCZ shift suppresses ENSO activity in the Mid-Pliocene Warm Period. *Nature Geoscience*, accepted (2022).

Power. S., Lengaigne, M., Capotondi, A. et al. (Including Cai, W., Zhang, X. and Wang G.) (2021). Decadal climate variability in the tropical Pacific: Characteristics, causes, predictability, and prospects. *Science* 374 (6563), eaay9165. https://doi.org/10.1126/science.aay9165.

Santoso, A.; England, M. H.; Kajtar, J. B.; Cai, W. (2022). Indonesian Throughflow Variability and Linkage to ENSO and IOD in an Ensemble of CMIP5 Models. *Journal of Climate*, pp. 1 - 46, https://doi.org/10.1175/JCLI-D-21-0485.1.

Wang, G., Cai, W., Santoso, A., Wu, L., Fyfe, J. C., Yeh, S.-W., Ng, B., Yang, K., McPhaden, M. J. (2022). Future Southern Ocean warming linked to projected ENSO variability. *Nature Climate Change*.

https://doi.org/10.1038/s41558-022-01398-2.
Wang, S., Jing, Z., Wu, L. et al. (2022). El Niño/Southern Oscillation inhibited by submesoscale ocean eddies. Nature Geoscience 15,112-117. https://doi.org/10.1038/s41561-021-00890-2.
Yang, K., Cai, W., Huang, G., Hu, K., Ng, B., & Wang, G. (2022). Increased variability of the western Pacific subtropical high under greenhouse warming. *Proceedings of the National Academy of Sciences*, 119(23), e2120335119. https://doi.org/10.1073/pnas.2120335119.
Yang, Y., Wu, L., Guo, Y., Gan, B., Cai, W., Huang, G., Li, X., Geng, T., Jing, Z., Li, S., Liang, X., and Xie, S.-P. (2021). Greenhouse warming intensifies north tropical Atlantic climate variability. *Science Advances*. https://www.science.org/doi/abs/10.1126/sciadv.abg9690.

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

Project leaders – Drs Bernadette Sloyan and Beatriz Peña-Molino (CSIRO)

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

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

2.2.1 Year 5 highlights and progress against project objectives

Despite the various delays in field work due to COVID-19 the team made significant progress this year focusing on the analysis of existing data sets and expanding our modelling capacity. Collectively our work has shown that the impact of small-scale motions in the Indonesian Seas controls circulation pathways, water mass transformation, surface properties and inter-basin property exchange (Peña-Molino et al. 2022) (Figure 2). Our study estimating wave and eddy energy fluxes in the Indonesian Seas, is the first showing that the remotely generated planetary (Rossby and Kelvin) waves and eddies can power mixing in the Indonesian Seas (Pang et al., under review). This is an important finding because the Indonesian Seas are one of the most intense mixing regions in the ocean and play a pivotal role in the climate system. As well as its regional and global climate implications, our results bear directly on the problem of constructing physically-based mixing parameterisations for climate models. Models in this region exhibit systematic biases that have been attributed to poor representation of mixing. Thus, having an accurate representation of the various processes that maintain mixing will be critical to improving climate projections. Profiling floats deployed in the internal seas combined with our suite of high-resolution numerical models, will reveal critical information about those processes in years to come.

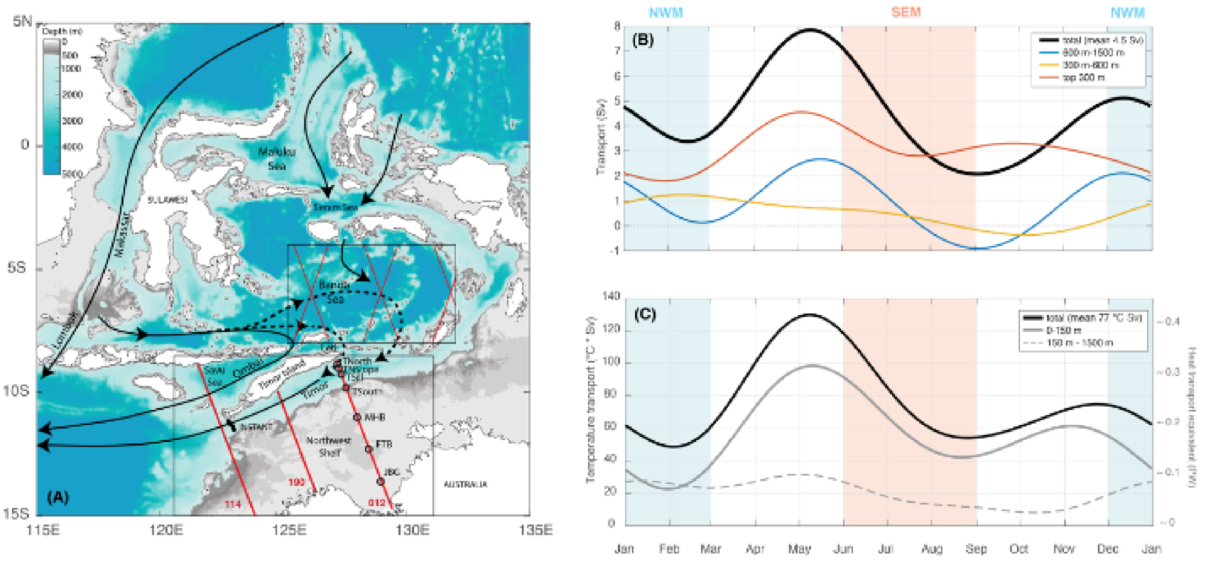


Figure 2 (A) Schematic of the circulation in the Indonesian Seas. Black arrows illustrate the mean flow direction, including the separation of the inflow into the eastern (via Seram Sea) and western (via Makassar Strait) pathways, and the outflows into the Indian Ocean, from west to east, through Lombok, Ombai and Timor straits. Dashed lines show the two Timor throughflow sources: a direct western pathway around the eastern end of Timor and a recirculating route via Banda Sea entering Timor Passage further to the east. Red lines indicate altimeter tracks. Black circles along the eastern most altimeter track in Timor Passage show the location of the IMOS moored array. (B) Seasonal cycle of the volume transport (Sv) across Timor Passage as observed by the moored array integrated across layers. (C) Seasonal cycle of the temperature transport (°C Sv) by the Timor throughflow. Estimated from the temperature and velocity fields derived from the moorings. On the right-side axis heat transport equivalent (PW) values for an assumed return flow temperature of 3.4°C. Orange and blue shading in panels (B) and (C) illustrate the periods of the different monsoon seasons. (from Peña-Molino et al. 2022).

2.2.2 Project performance against milestones

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

Milestone 1: Floats deployed as contribution to MINTIE project

CSHOR/CSIRO in collaboration with a University of Tasmania's led Australian Research Council discovery grant have worked together with our partners in the University of Washington and Indonesia through the 'Measuring and Modelling the INdonesian Throughflow International Experiment' (MINTIE) project to deploy, for the first time, profiling floats in the Indonesian Seas. All floats deployed provide return temperature, salinity and horizontal velocity shear. This information will allow us to estimate mixing. In addition, two of the floats are equipped with temperature microstructure sensors, also providing direct observations of mixing. The floats are programmed to record information over a whole seasonal cycle. Once complete, these records will be used to evaluate processes contributing to water mass transformation in the internal seas and provide critical information to validate model performance in one of the most data poor regions of the tropical ocean.

Milestone 2: Ship MINTIE mooring to USA for deployment in early 2023

CSHOR/CSIRO in partnership with the Australian Integrated Marine Observing System (IMOS) is contributing two tall moorings to the MINTIE program to monitor the Timor Throughflow into the Indian Ocean. The moorings have been shipped to Scripps to be consolidated with gear from international partners. This will be the second time, since 2004-2006, that inflow and outflow straits are monitored simultaneously. USA, China, Indonesia and Australia are partners in the MINTIE program.

Milestone 3: Create MINTIE float database

Communication accounts were set up for the floats and a data base created to manage the data flow with partners in the MINTIE program.

Milestone 4: Assess the impact of model resolution on the structure and pathway of ITF

To explore the effect of resolution in the circulation and properties of the Indonesian Throughflow we designed three experiments over the same regional domain, with identical forcing but varying horizontal resolutions of 1/10° (10km), 1/25° (4km) and 1/100° (1km). Our results show that increased resolution has a large impact in the upper ocean, with both cooler temperatures at the surface and across the mixed throughout the Indonesian Seas. At 1/25° resolution small scales motions are better resolved, leading to larger vertical shear and more mixing. At the bottom of the mixed layer this mixing leads to entrainment of deeper colder waters, which results in the observed sea surface temperature (SST) reduction. Cooler SST has a direct impact on precipitation, hence parametrising this resolution induced mixing in coarser resolution models has the potential to improve interactions between the atmosphere and the ocean over the Indo-Pacific region. In addition, we find that resolution also affects the circulation pathways and subsurface properties along those pathways, which in turn lead to different volume and heat transports across the various outflow straits with potential consequences to the overall Indian Ocean heat budget. Postdoctoral Fellow, Dr Océane Richet, has led this work and results are being prepared for publication (Richet et al, in prep).

Milestone 5: Explore what controls ITF partitioning

An idealised western boundary current model and realistic regional model of the Indonesian seas were combined to derive a theory of the control on the partitioning of the Indonesian Throughflow (i.e., the ratio between the transports of the three outflow passages). The theory shows that the width of the boundary current flowing through Makassar strait determines the fraction of the transport reaching the Indian Ocean through Lombok strait, the westernmost of the outflow passages. Perturbation experiments performed with the realistic regional model further show that boundary current width is controlled by the non-linearities in the flow. In the absence of inertial terms, a linear flow results in a wider current and lower transport through Lombok. As water undergoes significant transformation in transit through the internal seas, and the vertical profiles of the flow are different at the various straits, how the flow is partitioned across the straits will determined temperature and freshwater fluxes into the Indian Ocean. This work formed part of student Ana Berger's PhD thesis, and she is currently preparing it for publication.

Milestone 6: Quantify the impact of tidal-driven mixing on the evolution of ITF characteristics

Breaking of internal tides is thought to provide the main source of mixing in the Indonesian seas. We implemented the two major tidal constituents in the Indonesian seas, M2 and K1, in a 1/10° regional model forced by seasonally varying fields. Averaged over a whole seasonal cycle, adding tides results into a deeper thermocline, lower sea surface salinity (SSS) and changes in the meridional gradients of temperature and salinity across the internal seas. However, the stratification and circulation undergo a large seasonal cycle. Postdoctoral Fellow, Dr Océane Richet's work focuses on understanding how that seasonal variability modulates tidal mixing. She will be preparing her results for publication during the remaining time of her postdoctoral appointment.

In addition to tidal mixing, a new previously unaccounted for energy source that can powered mixing in the Indonesian seas was diagnosed from our high-resolution regional models. In this study, led by student Chengyuan Pang, we show that the Indonesian Seas are a sink of the energy generated by winds in the equatorial Indian and Pacific Oceans. We estimate that up to 2 GW of the remotely generated energy enters the Indonesian Seas across all major straits. The energy flux is concentrated in the upper 100-200 m of the ocean and is characterised by a strong convergence, implying energy dissipation and mixing. Chengyuan Pang is currently reviewing the manuscript after very positive reviews in *Nature Communications*.

Milestone 7: Analyse ITF spatial and temporal variability in the Timor Passage

A study combining satellite altimetry, a high-resolution sea surface temperature atlas, in situ observations from moorings and a regional model of the Indonesian Seas, revealed the complex nature of the interactions between the different elements of the seasonal forcing in the Indonesian seas. Kelvin waves, local and remote winds, and eddy-driven recirculations modulate the Throughflow in different layers. The study, published earlier this year (Peña-Molino et al. 2022), shows that due to the surface intensified nature of the velocity and temperature profiles, processes that control the circulation in the top 150 m of the water column have a disproportionate contribution to the heat transport. Coarser resolution models that cannot represent these complex dynamics can potentially introduce temperature biases in the Indian Ocean.

Milestone 8: Explore sources of interannual variability on the ITF

Due to the complex bathymetry in the Indonesian seas, along-track altimeter data is too noisy to derive physically meaningful surface geostrophic velocities. Building on the seasonal work from Peña-Molino et al. (2022), we have derived a new method to extract surface geostrophic velocity anomalies on interannual time scales. The method uses a reduced set of empirical orthogonal functions (EOF) to filter along-track sea level anomalies. Only the first three leading modes are required to capture over 90% of the variability through most tracks crossing the internal seas. Except for in the vicinity of the coastline where contamination by land is large in the altimeter signal, the method allows us to derive along-track surface geostrophic velocities without the need to invoke proxies. In Timor passage where in situ observations are collocated with the altimeter track, the agreement between the in situ velocities in the top 150 m and altimeter track velocity anomalies is excellent. Altimeter velocities combined with in situ observations at Timor and Ombai show the outflows are often out of phase in the eastern passages, implying changes in the partitioning on interannual time scales. These results are being prepared for publication.

Milestone 9: ARC-supported postdoctoral fellow and PhD appointed

A postdoctoral fellow position has been drafted and will be approved and then advertised by the Institute for Marine and Antarctic Studies (IMAS) with a view to appointing the successful candidate in late 2022, to maximise alignment with the delayed observational program.

Chengyuan Pang, formerly an honour student, has been recruited as a PhD candidate. His thesis will build up on his previous work and use the water transformation framework to characterise the spatial and temporal distribution of transformation in the Indonesian seas, and the processes contributing to it. An additional project PhD project description will be approved within IMAS and submitted to the University of Tasmania Research Office for recruitment later in the year. This second position will combine observations from the upcoming observational program with modelling work.

2.2.3 Project publications

Berger, A., Peña-Molino, B., Sloyan, B.M., Nikurashin, M., Wijffels, S.E. Boundary current width control on the Indonesian Throughflow. In preparation.

Black, A., Monselesan, D., Risbey, J., Sloyan, B.M., Chapman, C., Hannachi, A., Moore, T., Richardson, D., Squire, D., Tozer, C., Trendafilov, N. Archetypal Analysis of Geophysical Data illustrated by Sea Surface Temperature. *Journal of Climate*, under review.

Chengyuan, P., Nikurashin, M., Peña-Molino, B., and Sloyan, B.M. Remote energy sources for mixing in the Indonesian Seas. *Nature Communications*, under review.

Cyriac, A., H. Phillips, N. Bindoff, M. Feng (2022). Characteristics of wind generated near-inertial internal waves in the southeast Indian Ocean. *Journal of Physical Oceanography*. https://doi.org/10.1175/JPO-D-21-0046.1

Marin, M., Bindoff, N. L., Feng, M., & Phillips, H. E. (2021). Slower long-term coastal warming drives dampened trends in coastal marine heatwave exposure. *Journal of Geophysical Research: Oceans*, 126, e2021JC017930. https://doi.org/10.1029/2021JC017930

Peña-Molino, B., Sloyan, B. M., Nikurashin, M., Richet, O., & Wijffels, S. E. (2022). Revisiting the Seasonal Cycle of the Timor Throughflow: Impacts of Winds, Waves and Eddies. *Journal of Geophysical*

Research: Oceans, e2021JC018133. https://doi.org/10.1029/2021JC018133

Phillips, H. E., Tandon, A., Furue, R., Hood, R., Ummenhofer, C. C., Benthuysen, J. A., ... & Wiggert, J. (2021). Progress in understanding of Indian Ocean circulation, variability, air–sea exchange, and impacts on biogeochemistry. *Ocean Science*, 17(6), 1677-1751. https://doi.org/10.5194/os-17-1677-2021.

Richet, O., Sloyan, B.M., Nikurashin, M., and Peña-Molino, B. Impact of model resolution on the Indonesian Throughflow and its property transport. In preparation.

Richet, O., Sloyan, B.M., Nikurashin, M., and Peña-Molino, B. Seasonal modulation of tidal mixing in the Indonesian Throughflow. In preparation.

Sloyan, B.M., Chapman, C., Cowley., R., Charantonis, A.A. Application of machine learning techniques to ocean mooring time-series data. *Journal of Atmospheric and Oceanic Technology*, under review.

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

Project leader – Dr Ming Feng (CSIRO)

The Indo-Pacific warm pool hosts the largest global centre of deep convection, the dominant source of latent heating and moisture for the global atmosphere. The warm pool enables important coupled climate modes, such as El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden-Julian Oscillation (MJO). These modes of climate variability are likely the most important sources of enhanced weather and climate prediction on the globe.

This project is to advance our knowledge of high-frequency air-sea coupling in the eastern Indian Ocean warm pool through new observations of MJO and diurnal variability at the air-sea interface and coupled ocean-atmosphere model simulations. We also aim to better understand the roles of the Indonesian Throughflow in transmitting the Pacific ENSO/ Pacific decadal oscillation (PDO) signals into the Indian Ocean, in affecting the warming trend of the Indian Ocean and the meridional heat transport of the Indian Ocean. We explore drivers of the upper ocean salinity balance in the Indian Ocean and their role in the warm pool dynamics.

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

2.3.1 Year 5 highlights and progress against project objectives

The project has progressed well in wrapping up publications from the 2018-19 CSHOR field campaign and marine heatwave research, with more than 10 journal publications. Hsu et al. (2022) identified a rapid restratification of the ocean surface boundary layer in the Indonesian-Australian Basin, which corresponds with extremely low surface winds during the calm phase of the MJOs (Figure 3). We have greatly improved our knowledge of the marine heatwaves in the Indo-Pacific region and their drivers (Feng et al. 2021; Marin et al. 2022), such as identifying ocean temperature variability in the western-central Pacific is important for the Ningaloo Nino variability. The project has also made breakthroughs in applying machine learning and data mining techniques in characterisation and predictions of sea surface temperatures in the Indo-Pacific region, with three manuscripts in the pipeline for publication (Taylor and Feng, 2022; Chapman et al. 2022; Feng et al. 2022). Several PhD students co-supervised under the project have successfully finished their thesis works and moved on to careers in academics and industry consultatory.

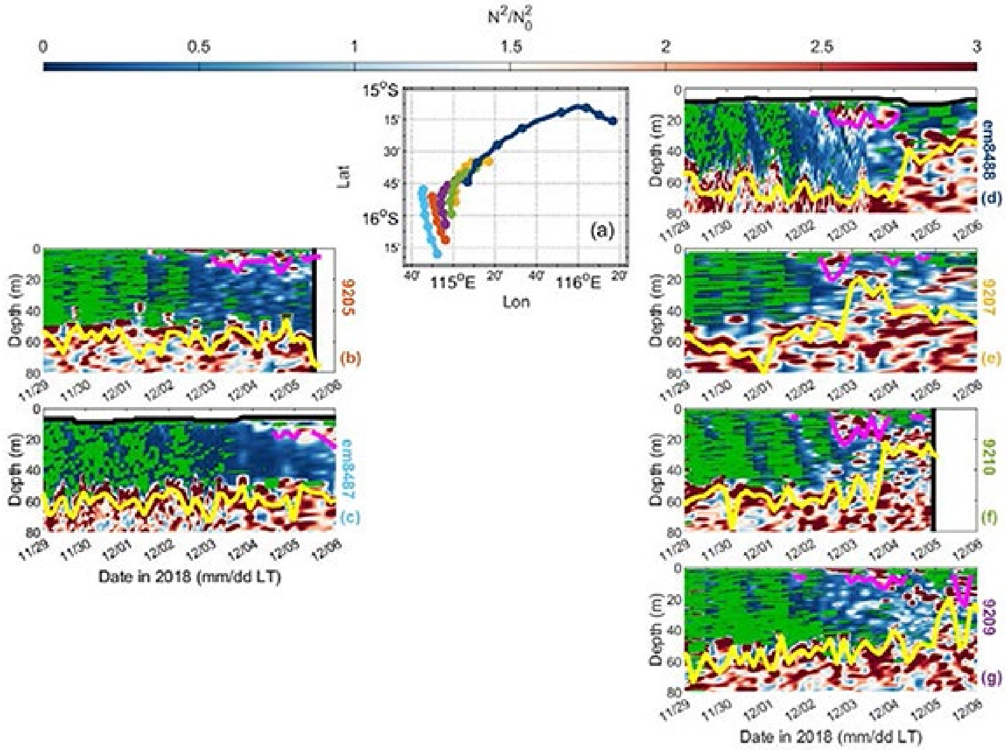


Figure 3 Detection of rapid restratification of ocean surface boundary layer during CSHOR field campaign. Float trajectories from 29 November to 5 December 2018 (colour lines with dots in (a); labelled on the right of (b)–(g)), the measured buoyance frequency N2 normalised by a constant N_0^2 of 1.0 × 10−4 s−2 at six floats (b)–(g). The interval between each colour dot (the position of floats at 12 am each day) in (a) is one day. In (b)–(g), the green colour marks the near zero or negative N2 due to density inversions, and the magenta lines are the reference depth z0 for estimating the surface mixed layer depth (MLD; yellow lines), which is computed as the bottom of the diurnal thermocline during diurnal warming. Only z0 > 5 m at the ALAMO floats and z0 > 15 m at the EM-APEX floats are shown. Missing measurements are indicated by white areas bounded by black lines in (c), (d), and at the right of the black line in (b), (f) (Hsu et al. 2022).

2.3.2 Project performance against milestones

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

Milestone 1: Improve our understanding of coupled air-sea process in the Indonesian-Australian Basin

Wrapping up the analysis of the 2018-19 CSHOR field campaign in the Indonesian-Australian Basin, Hsu et al. (2022) identified a rapid restratification of the ocean surface boundary layer in the Basin, captured in austral spring 2018, under the conditions of low wind speed and clear sky during the suppressed phase of MJOs. Despite sunny days, strong diurnal variations of sea surface temperature (SST) were not observed until the wind speed became extremely low. Combined with the horizontal advection of ocean current, the reduced upward heat loss inhibited the nighttime convective mixing and facilitated the restratification of the subsurface ocean layers.

On a broad scale in the Indo-Pacific warm pool, a detailed study of oceanic conditions associated with MJO events, including two-way fluxes and feedback process has been assessed using a synthesis of tropical moorings from the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) tropical moorings array. The oceanic conditions that trigger and sustain deep convections during the transition between the suppressed and active phase of the MJO have been identified (Chapman et al., in preparation).

Milestone 2: Continue our effort to assess the R/V Investigator cruise data for research use

The wire walker CTD data from the research voyage has been published online after quality control (Cowley and Dever, 2022). There have been ongoing discussions with principal investigators from the voyage to collaboratively work on the dataset.

Milestone 3: Carry out research on the interannual variability and predictability of key regions in the Indo-Pacific warm pool

A Journal paper on Niño-4W variability has improved our understanding of sea surface temperature (SST) variability in the western half of the Niño 4 region in the western Pacific warm pool (Feng et al. 2021). The region exhibits significant negative SST skewness, with the strong penetration of the cold tongue into the western Pacific during strong La Niñas but a more muted response during El Niños. The region can have significant influences on Ningaloo Nino development and Australian rainfall variability and may hold potential predictability.

We have also adapted and developed various machine learning techniques, such as a convolutional neural network model for SST predictions in a single region (Feng et al. 2022), a U-Net convolutional long-short term memory model for the prediction of a 2-dimensional SST field (Taylor and Feng, 2022).

Milestone 4: Carry out low-latitude western boundary currents and equatorial undercurrent study and continue efforts in Indian Ocean as well as marine heatwave research

Collaborative research with UNSW has shown that low-latitude western boundary currents and equatorial undercurrent of the Pacific are well captured in Coupled Model Intercomparison Project (CMIP) models and high-resolution ocean models. A strengthening tendency of the equatorial undercurrent in the western Pacific in the future climate can be attributed to the enhanced New Guinea Coastal Undercurrent. PhD student Annette Stellema has finalised research on the analysis of future projections of the Pacific Equatorial Undercurrent using CMIP models and ocean downscaling model. Annette has also used the particle tracking method to trace the sources of the equatorial current in terms of contributions from the Mindanao Current and the New Guinea Coastal Undercurrent, and influences of the future climate change.

Maxime Marin has successfully finished his PhD thesis. Among his research, coastal marine heatwaves around the global ocean have been assessed using multiple satellite sea surface temperature (SST) products and their increasing trends have been attributed to long-term ocean warming (Marin et al. 2020). It has also been found that coastal SST trends are less pronounced than the open ocean, which may provide refuges for marine species under the influence of global warming.

Research led by Dr Chris Chapman in the application of an advanced data mining tool (Archetype Analysis) to detect characteristics of marine heatwaves/cold spells in the Australasian region and link these events to large-scale climate drivers. Collaborative research papers on marine heatwaves in the Indo-Pacific have been published: In Zhang et al. (2021, *GRL*), it was discovered that the long-lasting marine heatwaves in three key upwelling regions in the tropical Indian Ocean were associated with persistent downwelling oceanic planetary waves linked to the ENSO/Indian Ocean Dipole events in 2015-16 and 2019-20; In Huang et al. (2021), we developed a tool to use the Himawari-8 satellite SST observations to detect marine heatwaves around Australia in high-resolution in real time; In Hu et al. (2021), subsurface marine heatwave characteristics has been described using the long-term mooring data in the western Pacific and their driving mechanism is explored.

A research paper has been published on how the SST structure off the west coast of Australia can feedback on mesoscale surface winds in the region (Wang et al. 2021). It is identified that the Leeuwin Current front, despite being much weaker compared to the western boundary current systems, can still steer surface winds and the effect has significant seasonal variations.

A review paper on the Indian Ocean circulation and climate variability research progress in the past decade has been accepted for publication (Phillip et al. 2021). In addition, Zhang et al. (2021, *JPO*) discovered a decadal change of model water formation in the southern Indian Ocean. Ajitha Cyriac, a former PhD student, published a paper on the characteristics of the near-inertial internal waves in the southeast Indian Ocean (Cyriac et al. 2022), the last chapter of her PhD thesis. Saurabh Rathore, a former PhD student, collaborated with CSHOR on the research of the Interactions between a Marine Heatwave and Tropical Cyclone Amphan in the Bay of Bengal in 2020. The research is being accepted for publication in the Frontiers in Climate.

Milestone 5: Understanding impact on estuarine physics under the influence of climate change in South-east Australia. Analysing NARCliM (NSW and ACT Regional Climate Modelling) and Global Climate Model (GCM) data to quantify temporal and spatial variability of these processes. Correlating above variability to the long-term climate pattern

The NARCliM, GCM, and historical estuarine datasets are collected and analysed. A comparison of the extreme values from observational data and datasets of GCMs and NARCliM by calculating generalised extreme value (GEV) distribution has been conducted. Daily minimum surface pressure, maximum precipitation and extreme wind speed are analysed. The prediction for minimum mean sea level pressure performs best among all variables. The GCMs and NARCliM replicate the observed decreasing trend in the 20-year average recurrence interval (ARI) of minimum sea-level pressure but under-predicts the magnitude of pressure changes with latitude. A number of publications have been finalised from this study.

2.3.3 Project publications

Journal articles

Chapman, C., Monselesan, D.P., Risbey, J.S., Feng, M., Sloyan, B.M., Large-Scale Drivers of Marine Heatwaves Revealed by Archetype Analysis, submitted to *Nature Communications*.

Cyriac, A., H. Phillips, N. Bindoff, M. Feng (2022). Characteristics of wind generated near-inertial internal waves in the southeast Indian Ocean. *Journal of Physical Oceanography*. https://doi.org/10.1175/JPO-D-21-0046.1.

Du, Y.; Feng, M.; Xu, Z.; Yin, B.; Hobday, A.J. Summer Marine Heatwaves in the Kuroshio-Oyashio Extension Region. *Remote Sens.* **2022**, *14*, 2980. https://doi.org/10.3390/rs14132980

Feng, M., Boschetti, F., Ling, F., Zhang, X., Hartog, J., Akhtar, M., Shi, L., Luo, J. J., Hobday, A., J., Predictability of sea surface temperature anomalies off Sumatra-Java in the eastern Indian Ocean – using a convolutional neural network model. *Frontiers in Climate,* accepted.

Feng, M., Lengainne, M., Sunanda, M., Sen Gupta, A., Vialard, J. (2022). Extreme events and impacts in the Indian Ocean. In *The Indian Ocean and its role in the global climate system*. Elsevier, Ed. Ummenhofer, C. C. and Hood, R. R. Published online June 2022. Print edition 1 November 2022.

Feng, M., Zhang, Y., Hendon, H. H., McPhaden, M. J., & Marshall, A. G. (2021). Niño 4 west (Niño-4W) sea surface temperature variability. *Journal of Geophysical Research: Oceans*, 126, e2021JC017591.https://doi.org/10.1029/2021JC017591.

Gang Yang, Xiao Hua Wang, Zhixin Cheng, Yi Zhong, Thomas Oliver (2021). Modelling study on estuarine circulation and its effect on turbidity maximum zone in the Yalu River Estuary, China. *Estuarine, Coastal and Shelf Science*, 263, 107634. https://doi.org/10.1016/j.ecss.2021.107634.

Hsu, J.Y., Feng, M. and Wijffels, S. (2022). Rapid restratification of the ocean surface boundary layer during the suppressed phase of the MJO in austral spring. *Environmental Research Letters*, 17(2), p.024031. https://doi.org/10.1088/1748-9326/ac4f11.

Hu, S., Li, S., Zhang, Y., Guan, C., Du, Y., Feng, M., Ando, K., Wang, F., Schiller, A. and Hu, D. (2021). Observed strong subsurface marine heatwaves in the tropical western Pacific Ocean. *Environmental Research Letters*, 16(10), p.104024. https://doi.org/10.1088/1748-9326/ac26f2.

Huang, Z., Feng, M., Beggs, H., Wijffels, S., Cahill, M. and Griffin, C. (2021). High-resolution marine heatwave mapping in Australasian waters using Himawari-8 SST and SSTAARS data. *Remote Sensing of Environment*, 267, 112742. https://doi.org/10.1016/j.rse.2021.112742.

Marin, M., Bindoff, N. L., Feng, M., & Phillips, H. E. (2021). Slower long-term coastal warming drives dampened trends in coastal marine heatwave exposure. *Journal of Geophysical Research: Oceans*, 126, e2021JC017930. https://doi.org/10.1029/2021JC017930.

Phillips, H. E., Tandon, A., Furue, R., Hood, R., Ummenhofer, C., Benthuysen, J., Menezes, V., Hu, S., Webber, B., Sanchez-Franks, A., Cherian, D., Shroyer, E., Feng, M., Wijeskera, H., Chatterjee, A., Yu, L., Hermes, J., Murtugudde, R., Tozuka, T., Su, D., Singh, A., Centurioni, L., Prakash, S., and Wiggert, J. (2021). Progress in understanding of Indian Ocean circulation, variability, air-sea exchange and impacts on biogeochemistry, *Ocean Science Discussions* [preprint], https://doi.org/10.5194/os-2021-1,17(6), pp.1677-1751.

Saurabh Rathore, Rishav Goyal, Babita Jangir, Caroline C. Ummenhofer, Ming Feng, Mayank Mishra (2022). Interactions between a Marine Heatwave and Tropical Cyclone Amphan in the Bay of Bengal in 2020. *Frontiers in Climate*, 4. https://www.frontiersin.org/articles/10.3389/fclim.2022.861477.

Taylor, J., and Feng, M. (2022). A deep learning model for forecasting global monthly mean sea surface temperature anomalies, submitted to *Frontiers in Climate,* https://doi.org/10.48550/arXiv.2202.09967.

Wang, S., Feng, M.,Dong, C., &Zhu, W. (2021). Observations of SST-induced wind perturbations in the Leeuwin Current. *Journal of Geophysical Research: Oceans*, 126, e2020JC016993.https://doi.org/10.1029/2020JC016993.

X.H. Wang and G. Yang (2022). Comment on ‘‘The Cross-Shore Component in the Vertical Structure of Wave-Induced Currents and Resulting Offshore Transport’’ by Lu et al., submitted to *Journal of Geophysical Research: Oceans*.

Yang, G., X.H. Wang, Y. Zhong and T. Oliver, (2022). Modelling study on the sediment dynamics, the formation of the flooding tidal delta near Cullendulla Beach and the impact of human activities in the Batemans Bay, Australia, submitted to *Journal of Geophysical Research: Oceans*.

Zhang, Y., Du, Y., Feng, M., & Hu, S. (2021). Long-lasting marine heatwaves instigated by ocean planetary waves in the tropical Indian Ocean during 2015–2016 and 2019–2020. *Geophysical Research Letters*, 48, e2021GL095350. https://doi.org/10.1029/2021GL095350.

Dataset publication

Cowley, Rebecca; Dever, Mathieu (2022). Investigator in2019_v06 WireWalker data from RBR Concerto CTD. v2. CSIRO. Data Collection. https://doi.org/10.25919/7hnt-bj11.

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

Project leader – Prof Matthew England (UNSW)

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

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

2.4.1 Year 5 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 during year five include: (1) New Lagrangian estimates of the pathways and time-scales of flow and connectivity around the Antarctic continental shelf using a high-resolution global ocean model; (2) The rate, variability, and mechanisms of Antarctic Intermediate Water (AAIW) formation was analysed using Argo data in combination with observationally based estimates of ocean hydrography, air-sea heat and freshwater fluxes, and eddy diffusivity. A volume budget was used to identify the controlling mechanisms; (3) Recent and future projected abyssal ocean temperature trends were analysed in the framework of an interplay between wind-driven forcing, meltwater anomalies, and warming of the ocean surface (under review in *Nature*); and (4) increased glacial melt is driving slowing of the deep overturning circulation and deoxygenation of the abyss (recently submitted to *Nature Climate Change*).

During Year 5 Dr Kathy Gunn continued her work on abyssal ocean circulation and variability as a CSHOR postdoctoral fellow. Dr Gunn commenced in March 2021, replacing Dr Annie Foppert who moved to AAPP after successful completion of her 3-year CSHOR appointment.

All completed work has successfully progressed to paper submissions in high-quality international peer-review journals.

2.4.2 Project performance against milestones

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

Milestone 1: Examine the origin and fate of Antarctic Intermediate Water [AAIW] in the Southern Ocean using observed hydrography and estimates of surface buoyancy fluxes and eddy diffusivity

The origin and fate of Antarctic Intermediate Water (AAIW) was calculated using Argo data. Calculations used observationally based hydrographic and eddy diffusivity datasets. A volume budget analysis was used to identify main mechanisms, with a focus on spatial and seasonal variability of AAIW in the Southern Ocean. Subduction rates and water-mass transformation (WMT) rates by mesoscale and small-scale turbulent mixing were also estimated. The subduction of AAIW reveals a downwelling by eddy-induced flow between the Subantarctic and Polar Fronts for light AAIW and upwelling by Ekman pumping poleward of the Polar Front for dense AAIW. A new revised version has been submitted to *JPO.*

Milestone 2: Quantify drivers of Weddell gyre circulation, seasonal – interannual variability, and possible future trends

Analysis of the Weddell Gyre's variability on seasonal and interannual timescales was completed. This work incorporated an ocean-sea ice model at 0.1 degree horizontal resolution as well as coarser resolution simulations. The model was evaluated against available observations and found that the highest resolution configuration was required to reproduce observed features of the region. The simulations showed that the gyre undergoes large variability in its circulation that is not captured by summer-biased or short-term observations. The Weddell Gyre's seasonal cycle consists of a summer minimum and a winter maximum and accounts for changes that are between one third and a half of its mean transport. On interannual time scales we found that the gyre's strength is correlated with the local Antarctic easterlies and that extreme events of gyre circulation are associated with changes in sea ice concentration and the characteristics of the warm inflow at the eastern boundary. This work has appeared in *JGR-Oceans*.

Milestone 3: Analyse pan-Antarctic exchanges around the continental margin, to quantify transit times of flow around the continental shelf, including that of meltwater

Lagrangian particle tracking calculations were completed to estimate the timescales of interbasin exchange around the Antarctic continental shelf, and to improve understanding of zonal connectivity at the Antarctic margin. Virtual particles were released over the continental shelf every five days for a year and were tracked for 20 years. The peak arrival of particles from the Amundsen and Bellingshausen Seas into the Ross Sea occurs after four to five years, while peak arrival in the Weddell Sea is reached after 12-15 years. Particles sourced from the Ross Sea peak in the Adélie Land and Cape Darnley bottom water formations sites in East Antarctica after ~one year and ~three years respectively. We also find two major regions that act as barriers to along-shore transport around the shelf; one at 171°E at Cape Adare in the Ross Sea, and the other at the tip of the West Antarctic Peninsula. Analyses are complete and the publication was submitted to *JGR: Oceans*.

Milestone 4: Determine the physical mechanisms causing observed variability in Antarctic Bottom Water, and their effect on global oceans

A transient forced high-resolution global coupled ocean sea-ice model was analysed to show that abyssal warming is projected to accelerate over the next 30 years, with an increase of ~0.2°C around the Antarctic abyss. By running experiments with separate single-forcing for winds, warming and meltwater effects, we show that meltwater input around Antarctica dominates the forcing, driving a contraction of Antarctic Bottom Water (AABW) associated with isopycnal slumping, opening a pathway that allows warm Circumpolar Deep Water greater access to the continental shelf. Meltwater-induced reductions in the formation and volume of AABW result in warming and aging of the abyssal ocean. In contrast, we find that projected wind and thermal forcing has little impact on the properties, age, and volume of AABW. These results highlight the critical importance of glacial melt in setting the abyssal ocean overturning in the future, with ramifications for global ocean biogeochemistry and climate that could last for centuries. This work is under review with *Nature* (Li, England, Rintoul et al. 2022).

A novel method that combines moored current records, repeat hydrography and model output was derived to calculate volume transport of AABW. This method yielded the first multi-decadal record of the strength of the deep overturning circulation in the Australian Antarctic Basin, and shows how slowdown of abyssal circulation also reduces the amount of oxygen reaching the deepest part of the basin. We found that salinity of Antarctic shelf waters is the leading driver of multi-decadal change, and is impacted by freshening from nearby melting glaciers. The data, methods, and results of this work have recently been submitted to *Nature Climate Change*.

The impact of reducing AABW area on ocean heat content is currently being investigated using a water mass decomposition framework. We expect this analysis to be completed over the next quarter with results written for submission to *GRL* by end of the financial year.

Milestone 5: Presentations at national and international conferences

- Matt England presented a keynote talk at the Virtual Atmosphere-Cryosphere-Ocean seminar series, run by IAPSO and IAMAS, 19-23 July 2021 (VACO-21), which replaced this year's General Assembly of the IUGG. Talks were also presented at the international workshop on high-resolution ocean modelling held at Kiel Geomar in 2021.
- Other presentations:

- Kathy Gunn - Antarctic margin group meeting, online presentation, November 9, 2021.
- Matthew England presented a talk on "Building a Supportive Research Team", at a UTas Postgraduate Supervision Training session, September 21, 2021.
- Kathy Gunn – Posters at ICSHMO 2022 and AGU Ocean Sciences, 2022
- Matthew England – Oral presentations at ICSHMO 2022 and AGU Ocean Sciences, 2022
- Matthew England convened a session at AGU Ocean Sciences, 2022 on "Ice-ocean interactions and Circulation around the Antarctic Margins"
- Matthew England – Seminar at UNSW School of Maths Ocean Dynamics meeting, February 2022
- Matthew England was a keynote speaker at an event held at the ANU

entitled: The Future of Earth Science - May 5, 2022.

- Julia Neme, Maurice Huguenin and Ellie Ong presented work at the European Geophysical Union (EGU) 2022 meeting.

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

2.4.3 Project publications

Dawson, H., **M. H. England**, V. Tamsitt, A. K. Morrison (2022). Pathways and timescales of connectivity around the Antarctic continental shelf, *Journal of Geophysical Research: Oceans*, submitted.

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

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

Goyal, R., **England, M. H.**, Jucker, M., & Sen Gupta, A. (2021). Response of Southern Hemisphere western boundary current regions to future zonally symmetric and asymmetric atmospheric changes. *Journal of Geophysical Research: Oceans*, 126, e2021JC017858. https://doi.org/10.1029/2021JC017858.

Goyal, R., Jucker, M., Gupta, A. S., & **England, M. H.** (2022). A new zonal wave 3 index for the Southern Hemisphere. Journal of Climate. Early Online Release. https://journals.ametsoc.org/view/journals/clim/aop/JCLI-D-21-0927.1/JCLI-D-21-0927.1.xml

Gunn, K. L., S. R. Rintoul, M. H. England, M. M. Bowen, 2022. Reduced overturning and abyssal ventilation in the Australian Antarctic Basin. *Nature Climate Change*, submitted.

Kajtar, J. B., **A. Santoso**, M. Collins, A. S. Taschetto, **M. H. England**, L.M. Frankcombe, 2021: CMIP5 intermodel relationships in the baseline Southern Ocean climate system and with future projections, *Earth's Future*, **9**, e2020EF001873.

Li, Q., **England, M. H.**, & McC. Hogg, A. (2021). Transient Response of the Southern Ocean to Idealized Wind and Thermal Forcing across Different Model Resolutions, *Journal of Climate*, 34(13), 5477-5496. https://doi.org/10.1175/JCLI-D-20-0981.1.

Li, Q., **England, M. H.**, A. McC. Hogg, **S. R. Rintoul** & A. K. Morrison (2022): Future abyssal ocean warming driven by glacial melt, *Nature* (in review).

Li, Z., S. Groeskamp; I. Cerovečki; **M. H. England**, 2021: The origin and fate of Antarctic Intermediate Water in the Southern Ocean. *Journal of Physical Oceanography, 51*(9), 2951-2972. doi:10.1175/jpo-d-20-0174.1.

Orihuela-Pinto, B., **Santoso, A., England, M. H.**, & Taschetto, A. S. (2022). Reduced ENSO Variability due to a Collapsed Atlantic Meridional Overturning Circulation. *Journal of Climate*, 35(16), 5307-5320. https://doi.org/10.1175/JCLI-D-21-0293.1.

Orihuela-Pinto, B., **M. H. England***, and A. S. Taschetto (2022). Interbasin and interhemispheric climate impacts of a collapsed Atlantic Overturning Circulation.

Nature Climate Change. https://doi.org/10.1038/s41558-022-01380-y. *Corresponding author)

Santoso, A., **England, M. H**., Kajtar, J. B., & Cai, W. (2022). Indonesian Throughflow Variability and Linkage to ENSO and IOD in an Ensemble of CMIP5 Models. *Journal of Climate*, 1-46. doi:10.1175/jcli-d-21-0485.1

Stokes, C. R., N. Abram, M. J. Bentley, T. L. Edwards, **M. H. England**, A. Foppert, S. S. R. Jamieson, R. S. Jones, M. A. King, J. T. M. Lenaerts, B. Medley, B. W. J. Miles, G. J. G. Paxman, C. Ritz, T. van de Flierdt, P. L. Whitehouse (2021). What is happening to the East Antarctic Ice Sheet? Nature, submitted.

Tamsitt, V., **England, M. H**., Rintoul, S. R., & Morrison, A. K. (2021). Residence Time and Transformation of Warm Circumpolar Deep Water on the Antarctic Continental Shelf. *Geophysical Research Letters*, 48(20), e2021GL096092. https://doi.org/10.1029/2021GL096092

Webb, D. J., P. Spence, R. M. Holmes, and **M. H. England** (2021). Planetary-wave induced strengthening of the AMOC forced by poleward intensified Southern Hemisphere westerly winds, *Journal of Climate*, 34(17), 7073–7090. https://doi.org/10.1175/JCLI-D-20-0858.1.

Webb, D. J., R. M. Holmes, P. Spence, and **M. H. England** (2022). Propagation of barotropic Kelvin waves around Antarctica. Ocean Dynamics 72, 405–419. https://doi.org/10.1007/s10236-022-01506-y.

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

Project leader – Dr Steve Rintoul (CSIRO)

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

This project is collecting new physical and biogeochemical observations in the Southern Ocean and using them with the historical record to develop a better physical understanding of the sensitivity of circulation and water mass formation to changes in forcing. The overall objective of the project is to quantify variability and trends in ocean circulation and water mass formation in the Australian sector of the Southern Ocean, using a combination of shipboard data, float observations and satellite data, and to identify the physical mechanisms driving change.

2.5.1 Year 5 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.

The first in depth analysis of Deep Argo float data in an Antarctic Basin was published in the Journal of Geophysical Research – Oceans

(Foppert et al. 2021). The float data reveal the pathways and variability of Antarctic Bottom Water supplied by the Ross Sea and Adélie Land coast with unprecedented detail. The work was selected as a Research Highlight by the editors of EOS, published by the American Geophysical Union.

We discovered a warming signal along the Australian East Antarctic sector. This warming is explained by a southward migration of the southernmost fronts of the Southern Ocean as well as a southward migration of the westerlies/easterlies. The change in the location of the winds is likely behind the recent acceleration in the ice mass loss from the East Antarctic Ice Sheet: more upwelling-favouring winds are located near the continental shelf, allowing warmer Circumpolar Deep Water to reach the ice shelves (Figure 4). The work is under revision at *Nature Climate Change*.

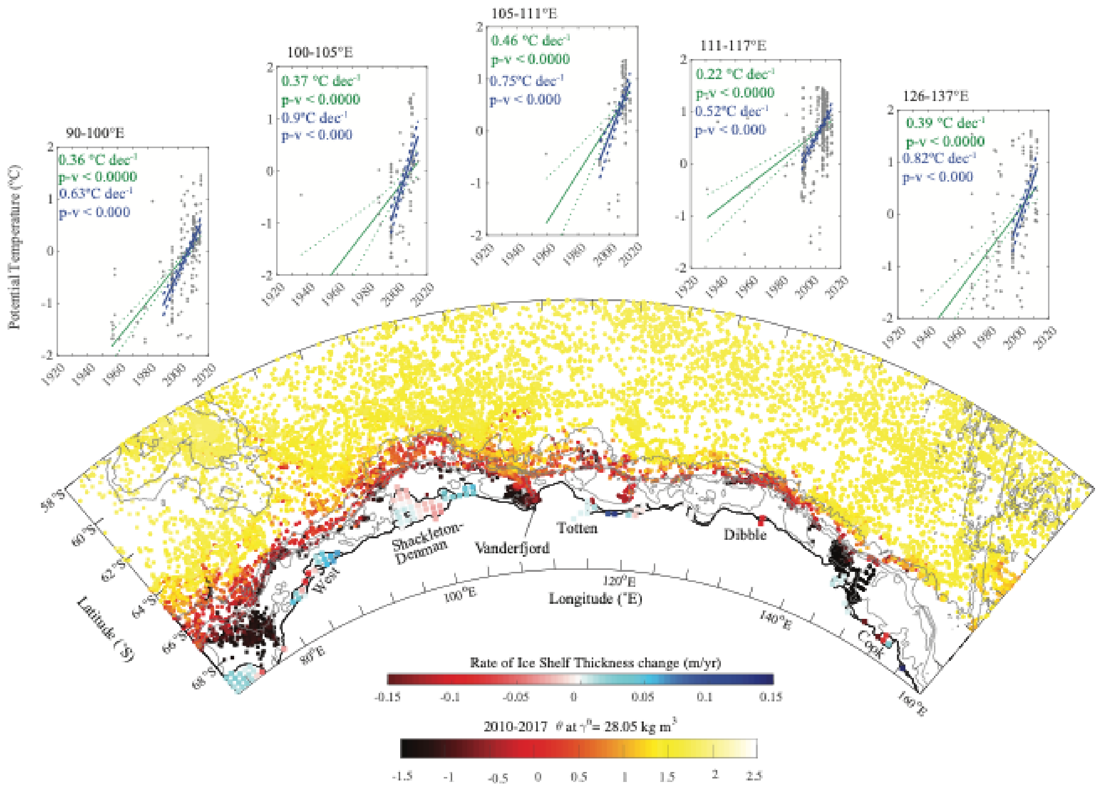


Figure 4 Past and present Warm Circumpolar Deep Water temperature. Map: potential temperature at the neutral surface 28.05 kg m-3, between 2010 and 2018. CDW upwells from the deep ocean to <500 dbar on this density surface. The rate of ice shelf thickness change (1994-2012) is also shown (Paolo et al. 2014). The 400, 700, 1000, 3000 dbars are shown as grey contours. Pannels: potential temperature change on the neutral density surface since 1930 (green) and since 1990 (blue). All the trends (degrees per decade) are significant to the 95% confidence (estimated using a bootstrap analysis with 10,000 repetitions). From Herraiz-Borreguero and Naveira-Garabato (2022).

CSHOR postdoctoral fellow Kathy Gunn has led a study that is under review at *Nature Climate Change* (Gunn et al. 2022). The work uses a novel combination of moored current records, repeat hydrography and model output to derive the first multi-decadal record of the strength of the deep overturning circulation. The results show that increased input of glacial melt has driven freshening of shelf waters and reduced formation of Antarctic Bottom Water, driving a slowdown of the deep overturning circulation and deoxygenation of the abyss.

A profiling float has provided the first detailed oceanographic observations near the Denman Glacier. The Denman drains an ice volume equivalent to 1.5m of sea level rise; its grounding line has retreated in recent decades; and it sits on a retrograde bed making it susceptible to rapid retreat through the Marine Ice Shelf Instability. The float data showed that warm water reaches the ice front of the glacier and that the ocean heat transport to the ice shelf cavity was sufficient to drive strong basal melt. The paper (van Wijk et al.) is under review at Geophysical Research Letters.

2.5.2 Project performance against milestones

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

Milestone 1: Investigate cross-slope exchange of warm CDW in East Antarctica using the COSIMA model outputs and observed hydrography

Document impact of CDW on ice shelf melt in East Antarctica

We discovered the replacement of cold Dense Shelf Water by warm Circumpolar Deep Water in front of the Vanderford ice shelf calving front, whose grounding line has retreated by 17 km since later 1990s. This discovery reveals the potential for the cold regime of the East Antarctic continental shelf to shift to a warm regime, characteristic of the West Antarctic continental shelf. Such a shift would endanger the stability of the East Antarctic Ice Sheet in the Australian Antarctic Territory, much of which is grounded below sea level.

Document changes in water masses properties near the Shackleton ice shelf

We discovered a sixty-year long freshening trend in the water masses that surround the Shackleton ice shelf. The system has shifted from an intense Dense Shelf Water (DSW) production region to a weak DSW one, followed by increased upwelling of warm Circumpolar Deep Water since the 1990s. A paper has been submitted to Journal of Geophysical Research-Oceans.

Document drivers of CDW upwelling and variability

Model experiments are being used to elucidate how CDW upwells onto two regions of the continental shelf of East Antarctica using the COSIMA model. In the first study, drivers of warm CDW upwelling into Vincennes Bay are assessed. We show that intrusions of warm CDW are likely regulated by the strength of the Antarctic Slope Current (ASC), that is, weaker ASC, stronger CDW intrusions. Submission of this paper is expected by the end of June 2022.

In a second study, the drivers of warm CDW upwelling into the Shackleton-Denman region are assessed. The aim of this experiment is to understand the modelled Antarctic Slope Front and to design an observing platform to determine the spatial and temporal variability of the Front, and its influence on transport of warm CDW to the Antarctic continental shelf. The study is being used to design a field campaign to be carried out in 2025.

Milestone 2: Quantify the impact of ice shelf melt in the carbon cycle of the Southern Ocean

We show that the concentration of Fe in meltwater-enriched surface seawater near Pine Island Glacier is relatively low. Estimated meltwater endmember concentration suggests that the supply of micronutrients far exceeds the available ligand pool, resulting in the inefficient export of supplied micronutrients. With Antarctic glacial melting predicted to increase markedly over the coming decades, our study implies that this fertilisation pathway is unlikely to increase proportionally with melt rate, without an increased supply of chelating ligands into the mCDW to solubilise Fe and other important micronutrients. The paper is expected to be submitted by the end of June 2022.

Milestone 3: Produce a new bathymetry product for East Antarctica and assess potential for warm Circumpolar Deep Water (CDW) upwelling and circulation to the East Antarctic ice shelves (80E to 160E)

We have produced a new bathymetry map using bottom-of-the-dive depths with which to compare the current bathymetry data base normally used for Antarctic studies. This new bathymetry led to the discovery of a large over 1000m deep trough leading to the Vanderford Glacier- ice shelf cavity.

A map of CDW properties has been produced and it has now been merged to the new bathymetry map to document the likely entry pathways of CDW to the Antarctic continental shelf of East Antarctica. A final draft of the paper is expected to be ready by the end of June 2022.

Milestone 4: Evaluate the changing characteristics of Subantarctic Mode Water (SAMW) using observations from the Southern Ocean Time Series (SOTS) and the SR3 Repeat hydrographic section

Using more than a decade of mooring observations at the SOTS site, we have constructed robust seasonality of hydrography, biogeochemistry, and air-sea exchange, including the oceanic uptake of CO_2, in the Subantarctic Zone south of Tasmania. There are signs of an upward trend in net primary production since 2016, particularly in the last three years. The combination of increased stratification and primary productivity in the summer are offsetting the atmospheric uptake, and the change in surface ocean CO2 is smaller than the global mean anthropogenic trend. A downward trend in the previous five years reinforces the idea that natural variability remains larger than anthropogenic change at the site. A paper is expected to be submitted by the end of June (Shadwick et al., Observed amplification of carbon cycle seasonality at the Southern Ocean Time Series, in prep.), and a new PhD student project is focused on linking changes in productivity and carbon export to the Southern Annular mode at SOTS.

Milestone 5: Develop plans for collaborative fieldwork

The "Multidisciplinary Investigations of the Southern Ocean (MISO) voyage" is now approved. The proposal will support a 60-day voyage on RV Investigator in January 2024 to complete a repeat hydrographic section between Antarctica and Perth. The research program includes physical oceanography, biogeochemistry, biology, atmospheric physics and chemistry, and air-sea interaction. The goal is to identify the sources of bias at high latitudes in present climate models and to provide the observations needed to develop, test and refine parameterisations needed to address the biases.

New proposals were submitted to the Australian Antarctic Science Program for future fieldwork, including:

- Cross-Shelf exchange in East Antarctica Connecting Observations and Models (CSEACOM). The objective is to carry out a comprehensive observational campaign targeting the Antarctic Slope Current, one of the least known currents in the Southern Ocean.

- Linking carbon cycling and water mass transformation in Prydz Bay. This project is developing a proof of concept for an autonomous observing system to enable the estimate of carbon uptake and export as well as a better understanding of the contribution of freshwater and nutrients from ice shelf melt.

- Denman Marine. The objective of the project is to assess the vulnerability of the Denman glacier to irreversible retreat.

- Eastern Australian Sector Expedition (EASE). The objective of this project is to assess the vulnerability of the Wilkes Subglacial Basin to a warming ocean, and test the hypothesis that the volcanic activity around the Balleny islands drives a massive phytoplankton bloom in the area.

- Marginal Ice Zone. The objective of this project is to better understand the physical mechanisms that drive sea ice retreat and how susceptible these processes are to a changing climate.

Milestone 6: Publish a synthesis of studies of the nature and drivers of change in the East Antarctic sector of the Southern Ocean

A community-wide review of Antarctic Bottom Water (Silvano et al. 2022) will be submitted in May in a special issue of Frontiers in Marine Science. A summary of CSHOR contributions to analysis of change in the East Antarctic sector of the Southern Ocean is in preparation and will be ready for submission in June.

Milestone 7: Investigate dynamics of coastal polynyas, with a focus on water mass transformation and ocean-ice shelf interaction

Data collected by instrumented elephant seals have determined the most important factors that determine the formation of Dense Shelf Water: sea ice formation, meltwater input and topography (Portela et al. 2021). This work also highlighted the importance of spatial variability in water mass transformation within a single polynya and raised further questions, most notably: why does Mackenzie Polynya form DSW while other East Antarctic polynyas do not?

A paper will be submitted in May 2022 describing the complex interplay of factors that determine whether DSW forms on the shelf, some of which may be strongly altered under a changing climate, with potentially important consequences for the ventilation of the deep ocean, the global meridional overturning circulation, and the transport of ocean heat to Antarctic ice shelves.

An ARC Discovery project (DP220102525), "Is there a climatic tipping point for Antarctic Bottom Water formation" was funded. The project will assess tipping points in Antarctic Bottom Water (AABW) formation processes in the Cape Darnley polynya, in East Antarctica, under past, present and future climate scenarios. This project is expected to start in the second half of 2022.

Several Argo floats have been deployed in the East Antarctic shelf near a coastal polynya. One of the Argo floats deployed in Prydz Bay in February 2020 resurfaced and sent data back covering 25 months of full water column temperature and salinity profiles every 5 days. This data will be used to study the freshwater budget in Prydz Bay and sea ice formation processes. The analysis of the full time series will commence in the second half of 2022. A master student is currently looking at the first 13 months of the time series. The second Argo float was deployed in Vincennes Bay, a region where DSW is hindered by the presence of warm Circumpolar Deep Water (CDW), and by meltwater produced by CDW reaching the base of the ice shelf. The float is expected to resurface in the next Austral summer (around January 2023).

2.5.3 Project publications

Dias, F. B., C. M. Domingues, S. J. Marsland, **S. R. Rintoul**, P. Uotila, M.D.; R. Fiedler, M. M. Mata, N. L. Bindoff, A. Savita, 2021. Subpolar Southern Ocean response to changes in the surface momentum, heat and freshwater fluxes under 2xCO2. J. Climate, 34, 8755-8775, https://doi.org/10.1175/JCLI-D-21-0161.1

Foppert, A., **Rintoul, S. R**., Purkey, S. G., Zilberman, N., Kobayashi, T., Sallèe, J.-B., E. M. van Wijk, and L. O. Wallace (2021). Deep Argo reveals bottom water properties and pathways in the Australian-Antarctic Basin. Journal of Geophysical Research: Oceans, 126, e2021JC017935. https://doi.org/10.1029/2021JC017935.

Gunn, K. L., S. R. Rintoul, M. H. England, M. M. Bowen, 2022. Reduced overturning and abyssal ventilation in the Australian Antarctic Basin. Nature Climate Change, in review.

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

Latour, P. van der Merwe, K. Wuttig, A. T. Townsend, M. Corkill, T. M. Holmes, **S. R. Rintoul**, R. Schlitzer, C. Weldrick, T. L. Noble, R. F. Strzepek, M. Gault-Ringold and A. R. Bowie, 2022. Biological uptake and scavenging prevent transport of Mn-rich waters from the Antarctic shelf. Global Biogeochemical Cycles, submitted.

McMahon CR, Roquet F,Baudel S, Belbeoch M, Bestley S,Blight C, Boehme L, Carse F, Costa DP, Fedak MA, Guinet C, Harcourt R, Heslop E, Hindell MA, Hoenner X, Holland K, Holland M, Jaine FRA, Jeanniard du Dot T, Jonsen I, Keates TR, Kovacs KM, Labrousse S, Lovell P, Lydersen C,March D, Mazloff M, McKinzie MK, Muelbert MMC, O'Brien K, Phillips L, Portela E, Pye J, **Rintoul S**, Sato K, Sequeira AMM, Simmons S, Tsontos VM, Turpin V, van Wijk E, Vo D, Wege M, Whoriskey FG, Wilson K and Woodward B (2021). Animal Borne Ocean Sensors –AniBOS – An Essential Component of the Global Ocean Observing System. Front. Mar. Sci. 8:751840. doi: 10.3389/fmars.2021.751840

Meijer, J. J., H. E. Phillips, N. L. Bindoff, **S. R. Rintoul**, A. Foppert, 2021. Cyclogenesis in a standing meander of the Subantarctic Front inferred from along-stream changes in temperature and salinity. Journal of Physical Oceanography, https://doi.org/10.1175/JPO-D-21-0049.1

Mortenson, E., A. Lenton, **E.H Shadwick**, T.W Trull, M. Chamberlain and X. Zhang, Divergent trajectories of ocean warming and acidification (2021), Environmental Res. Lett. doi:10.1088/1748-9326/ac3d57

Portela, E., **Rintoul, S. R**., Bestley, S., **Herraiz-Borreguero, L**., van Wijk, E., McMahon, C. R., F. Roquet and M. Hindell (2021). Seasonal transformation and spatial variability of water masses within MacKenzie polynya, Prydz Bay. Journal of Geophysical Research: Oceans, 126, e2021JC017748. https://doi.org/10.1029/2021JC017748

Portela, E., **S. R. Rintoul, L. Herraiz-Borreguero**, F. Roquet, S. Bestley, T. Tamura, E. van Wijk, C. R. McMahon, C. Guinet, R. Harcourt, and M. A. Hindell, 2022. Controls on Dense Shelf Water formation in four East Antarctic polynyas. Journal of Geophysical Research – Oceans, submitted.

Ribeiro, N., **L. Herraiz-Borreguero, S. R. Rintoul**, G. D. Williams, C. McMahon, M. A. Hindell and C. Guinet, 2022. Sixty years of warming on the continental shelf adjacent to the Shackleton Ice Shelf in East Antarctica. Submitted.

Ribeiro, N., **L. Herraiz-Borreguero, S. Rintoul**, C. R. McMahon, M. Hindell, R. Harcourt, G. Williams, 2021. Warm modified Circumpolar Deep Water intrusions drive ice shelf melt and inhibit Dense Shelf Water formation in Vincennes Bay, East Antarctica. Journal of Geophysical Research – Oceans, 126, e2020JC016998, https://doi.org/10.1029/2020JC016998

Rohr, T., A. Richardson, A. Lenton, **E.H. Shadwick**, and M. Chamberlain, Marine carbon cycling: are climate models biased by zooplankton? Science Advances, submitted.

Rohr, T., A. Richardson, **E.H. Shadwick**, and A. Lenton, Recommendations for the Formulation of Grazing in Marine Biogeochemical and Ecosystem Models, Progress in Oceanogr., in revision

Silvano, A., S. Purkey, A. L. Gordon, P. Castagno, A. Stewart, **S. Rintoul**, A. Foppert, S. Aoki, A. C. Naveira Garabato, C. Hayatte Akhoudas, J.-B. Sallée, , E. P. Abrahamsen, A. J. S. Meijers, M. P. Meredith, S. Zhou, T. Tamura, K. I. Ohshima, P. Falco, G. Budillon, T. Hattermann, M. A. Janout, H. H. Hellmer, **L. Herraiz-Borreguero**, M. M. Bowen, E. Darelius, S, Østerhus, K. Nicholls, C. Stevens, L. Cimoli, G. D. Williams, A. Morrison, A. Hogg and F. A. Haumann, 2022. Observing Antarctic Bottom Water. Frontiers in Marine Science, for submission in July2022.

Stammerjohn, S., Scambos, T. A., Adusumilli, S., Barreira, S., Bernhard, G. H., Bozkurt, D., Bushinsky, S. M., Clem, K. R., Colwell, S., Coy, L., De Laat, J., du Plessis, M. D., Fogt, R. L., Foppert, A., Fricker, H. A., Gardner, A. S., Gille, S. T., Gorte, T., Johnson, B., Keenan, E., Kennett, D., Keller, L. M., Kramarova, N. A., Lakkala, K., Lazzara, M. A., Lenaerts, J. T. M., Lieser, J. L., Li, Z., Liu, H., Long, C. S., MacFerrin, M., Maclennan, M. L., Massom, R. A., Mikolajczyk, D., Montgomery, L., Mote, T. L., Nash, E. R., Newman, P. A., Petropavlovskikh, I., Pitts, M., Reid, P., **Rintoul, S. R**., Santee, M. L., **Shadwick, E. H.**, Silvano, A., Stierle, S., Strahan, S., Sutton, A. J., Swart, S., Tamsitt, V., Tilbrook, B., Wang, L., Williams, N. L., & Yuan, X. (2021). Antarctica and the Southern Ocean, Bulletin of the American Meteorological Society, 102(8), S317-S356.

Tamsitt, V., M. H. England, **S. R. Rintoul**, and A. K. Morrison, 2021. Residence time and transformation of warm Circumpolar Deep Water on the Antarctic continental shelf. Geophysical Research Letters, 48, e2021GL096092. https://doi.org/10.1029/2021GL096092

van der Merwe P., D. Lannuzel, P. King, K. Zurcher, I. Boyden-Floyd, M. Filleul, J. Jung, Y. Lee, S-T Yoon, G. Williams, D. Guihen, **L. Herraiz-Borreguero**, R. Coleman, W. S. Lee, 2022, Does increasing glacial meltwater result in enhanced surface trace-metal fertilization in Pine Island Bay, Antarctica, Global Biogeochemical Cycles, submitted

van Wijk E. M., **S. R. Rintoul**, L. O. Wallace, N. Ribeiro, **L. Herraiz-Borreguero**, 2022. Profiling float observations highlight vulnerability of Denman Glacier to ocean heat flux, Geophysical Research Letters, submitted.

Zhang, X., M. Nikurashin, B. Pena-Molino, **S. R. Rintoul** and E. Doddridge, 2022. A theory of standing meanders of the Antarctic Circumpolar Current and their response to wind. Journal of Physical Oceanography, accepted.

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

Project leader – Dr Xuebin Zhang (CSIRO)

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

Over the past 5 years, the project team has made significant progress in understanding both global and regional sea levels, and underlying mechanisms by mainly working on: (1) identifying key processes for the Southern Ocean heat uptake and redistribution in observations and CMIP5/6 model simulations; (2) carrying out specifically-designed ocean model perturbation experiments to reveal distinct responses of the Southern Ocean to different surface forcing; (3) quantifying uncertainty in Antarctica surface mass balance and modelling the evolution of Antarctic Ice Sheet from the Last Glacial Maximum to 2500; (4) producing high-resolution sea-level fingerprints due to land ice mass change projections on global unstructured mesh grid; (5) identifying novel aspects of dynamic sea level distribution in the CMIP5/6 models, and dynamical downscaling of global climate models; (6) better closing regional sea-level budget, matching observations and projections over their overlapping period, and improved regional sea-level projections for the future.

2.6.1 Year 5 highlights and progress against project objectives

It has been another successful year for the sea level project. 7 Journal manuscripts were published (including 4 by Nature, Science, and Nature Climate Change) and 7 manuscripts were submitted (including one under revision for Nature), two is to be submitted soon.

For the first time the Argo array observations since 2005 were used to constrain climate model projections of ocean warming and thermosteric sea level rise by the end of this century based on the Emergent Constraints methodology, which was published by Nature Climate Change (Lyu et al. 2021). Our analysis shows that without dramatic reductions in greenhouse gas emissions, by the end of this century the upper 2,000 metres of the ocean is likely to warm by 11-15 times the amount of warming observed during 2005-19. Water expands as it gets warmer, so this warming will cause sea levels to rise by 17-26 centimetres.

A suite of ocean model perturbation experiments following the Flux-anomaly-forced model intercomparison project (FAFMIP) protocol were carried out to separate buoyancy and momentum forcing on ocean heat and sea level distributions. Findings have been wrapped into three manuscripts: first focusing on comparison between model perturbation experiments and a theoretical framework in terms of ocean interior response to different atmospheric forcing (Lyu et al., submitted, a); second focusing on ocean heat transport processes (Lyu et al., submitted, b; Figure 5); third focusing on impacts of Antarctic iceberg melting on Southern Ocean circulation and sea level (Zhang J. et al., submitted). These modelling-based studies provided some novel insights into Southern Ocean heat uptake and redistribution, and response of Southern Ocean to freshwater forcing.

The project team also contributed to an international collaboration publication by Nature Climate Change about ozone forcing on Southern Ocean warming over the historical period (1955-2000), which found that tropospheric ozone increases, not considered much before, played a comparable role as stratospheric ozone depletion (Liu et al. 2022).

Over the past year, our project members attended several international conferences (AGU Fall Meeting, ICSHMO, Ocean Science Meeting, WCRP workshop on Attribution of multi-annual to decadal changes in the climate system, FAFMIP annual workshop) to deliver talks and chair sessions.

Dr Zhang was invited to give a plenary talk about regional sea level projection at the WCRP sea-level conference in Singapore (similar top-level sea-level conference happened 5 years ago in New York)

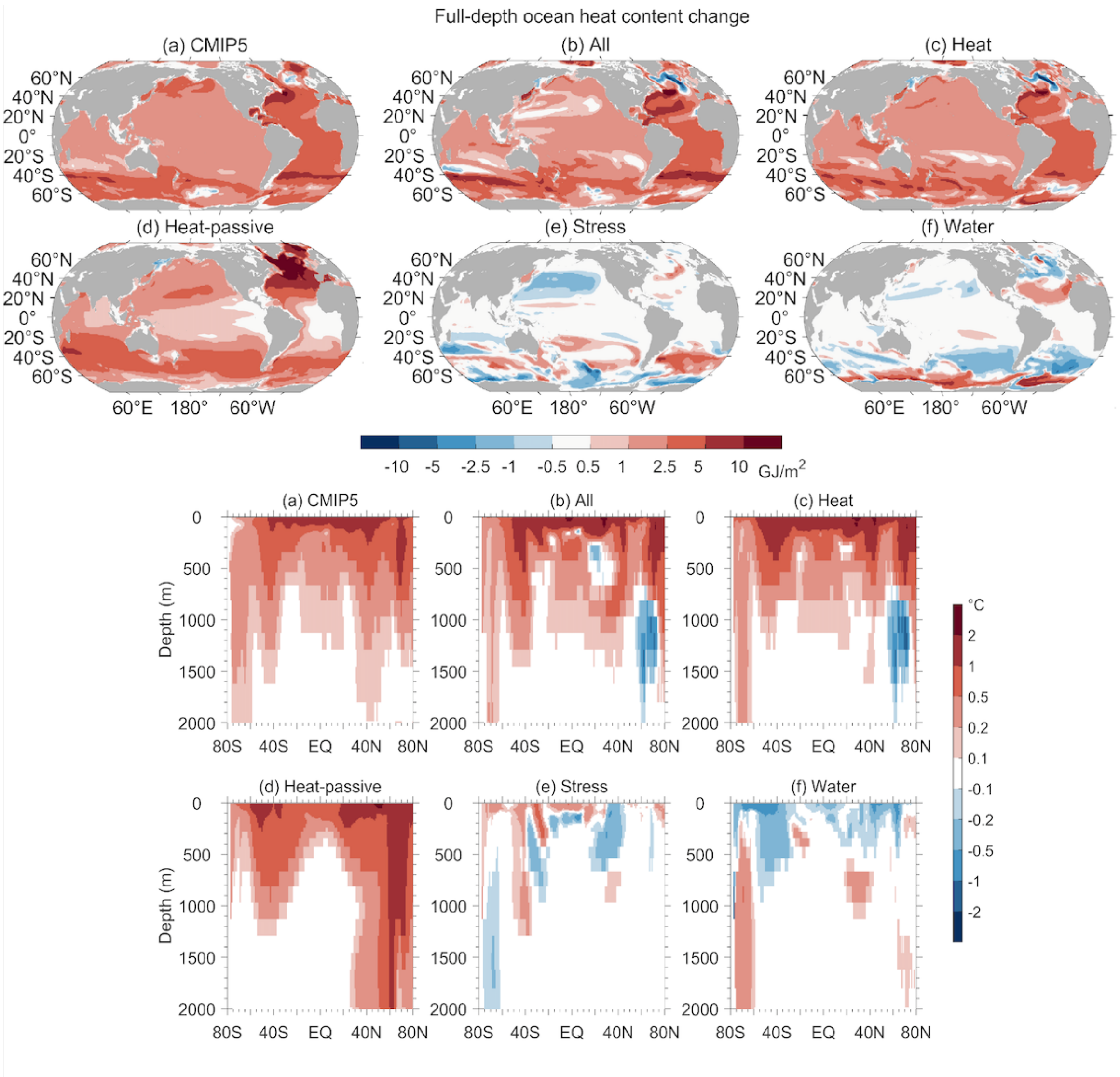


Figure 5 Changes in (upper panels) full-depth integrated ocean heat content and (lower panels) global zonal mean ocean temperature by the time of CO_2 doubling from CMIP5 models and various perturbation experiments using a global ocean sea-ice model (ACCESS-OM2): (a) Multi-model average from CMIP5 1pctCO2 experiment; (b) FAFMIP all-forcing experiment; (c) heat flux forcing experiment; (d) passive transport of surface heat uptake from a passive tracer; (e) wind stress forcing experiment; (f) freshwater flux forcing experiment.

2.6.2 Project performance against milestones

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

Milestone 1: Investigation of mechanisms about the Southern Ocean non-linear responses to the surface forcing, by examining the eddy-compensation effect in low/high-resolution model simulations and comparing model experiments in which the flux perturbations are applied individually versus simultaneously

Various ocean model perturbation experiments have been designed to separate impacts from different atmospheric forcing (e.g., wind stress, heat flux and freshwater flux), following our previous modelling contribution to the FAFMIP. Based on these model experiment results, we revisited three idealised processes (pure warming, pure freshening, and pure heave) from a theoretical framework to see to what extent they could represent realistic Southern Ocean responses to the individual surface forcing (Lyu et al., submitted, a). The ocean heat transport processes, including resolved versus parameterised, overturning versus horizontal gyre, were also examined in these perturbation experiments (Lyu et al., submitted, b; Figure 5). Moreover, different climatological iceberg melting schemes have been applied in a global ocean-sea ice model to test the impact on representation of ocean dynamics and sea levels, which may guide to reduce mean state biases in the Southern Ocean simulation (Zhang J. et al., submitted).

Milestone 2: Producing next generation of total sea level projections, by summing up all contributing global and regional sea level components, such as updated dynamic sea level and refined regional sea level fingerprints related to land ice melting

Regional sea level projection methodology has been modified and tuned up further, which has been used to generate updated sea level projections based on our own processing of dynamic sea level from the CMIP6 models and high-resolution sea-level fingerprints due to land ice melting using the Ice Sheet System Model (ISSM) sea level module, as well as latest findings from the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) and IPCC Sixth Assessment Report (AR6). A dataset of regional sea level projections globally from present to 2100 has been produced.

Milestone 3: Developing refined regional sea level fingerprints associated with melting of land ice driven by available ISMIP6 ice sheet model output

Regional sea level fingerprints driven by the ensemble simulations of Antarctic ice sheet have been produced on global unstructured mesh grids using the ISSM sea level module and findings have been wrapped into a manuscript (Zhang S. et al., submitted)

Milestone 4: Updating historical sea level reconstruction and producing new estimates of observed changes in ocean heat content and thermosteric sea level changes from 1970 to the ARGO period (UNSW)

This milestone has been achieved very well. We tested sensitivity of ocean heat content and thermosteric sea level to vertical interpolation schemes and produced new observational estimates of ocean heat content and thermosteric sea level time series from 1958, which has been wrapped up into a manuscript (Li, Y. et al, submitted). We also updated the well-known Church & White sea level reconstruction by including time-varying sea-level fingerprints and better representation of vertical land motion, which shows better agreement with the sum of all sea level contribution terms than the original reconstruction (i.e., achieving better regional sea level budget closure).

Milestone 5: Submission of paper on GRACE and GRACE Follow-on analysis for Antarctica. Analysing the impact of climate variability on GRACE-based estimates of Greenland mass change (UTAS)

We continued analysing the GRACE and GRACE Follow-on data for both Antarctica and Greenland. We have undertaken analysis of mass change over the whole ice sheet and drainage basins within Antarctica, with a particular focus on the role of climate variability in the observed trends in ice sheet mass change. We have found, through Empirical Orthogonal Function (EOF) and multiple variable regression analyses of the GRACE data, that the two dominant variability modes are closely related to the cumulative Southern Annular Mode (SAM) and ENSO indices and that about 40% of the 2002-2021 GRACE mass trend can be associated with SAM. A manuscript was submitted to Nature in early 2022 and is currently under revision (King et al., submitted).

2.6.3 Project publications

Lyu, K., X. Zhang and J. A. Church (2021). Projected ocean warming constrained by the ocean observational record. *Nature Climate Change*, 11, 834–839, https://doi.org/10.1038/s41558-021-01151-1.

Liu, W., M. I. Hegglin, R. Checa-Garcia, S. Li, N. P. Gillett, **K. Lyu, X. Zhang** and N. C. Swart (2022). Disentangling the impacts of stratospheric ozone depletion and tropospheric ozone increases on Southern Ocean warming, *Nature Climate Change*, 12, 365–372, https://doi.org/10.1038/s41558-022-01320-w

Mortenson, E., A. Lenton, E. H. Shadwick, T. W. Trull, M. C. Chamberlain, **X. Zhang (2021)**. Divergent trajectories of ocean warming and acidification, *Environmental Research Letters*, doi:10.1088/1748-9326/ac3d57.

Power, S. and co-authors (including **X. Zhang**) (2021). Decadal climate variability in the tropical Pacific: characteristics, causes, predictability and prospects, *Science,* 374 (6563), eaay9165, DOI: 10.1126/science.aay9165

Savita, A., C. M. Domingues, T. Boyer, V. Gouretski, M. Ishii, G. C. Johnson, J. M. Lyman, J. K. Willis, S. J. Marsland, W. Hobbs, **J. A. Church**, D. P. Monselesan, P. Dobrohotoff, R. Cowley and S. E. Wijffels (2021). Quantifying spread in spatio-temporal changes of upper-ocean heat content estimates: an internationally coordinated comparison. *Journal of Climate*, doi: 10.1175/JCLI-D-20-0603.

Sohail, T., J. D. Zika, D. B. Irving, and **J. A. Church** (2022). Observed poleward freshwater transport since 1970. *Nature*, 602, 617-622, https://doi.org/10.1038/s41586-021-04370-w

Wang, J., J. A. Church, X. Zhang, G., Jonathan, L. Zanna and **X. Chen** (2021). Evaluation of the local sea-level budget at tide gauges since 1958. Geophysical Research Letters, *Geophysical Research Letters,* 48, e2021GL094502. Doi:10.1029/2021GL094502

Jin, Y., X. Zhang, J. A. Church, X. Bao, Projected extreme sea level changes in the marginal seas near China based on dynamical downscaling, *Journal of Climate*, submitted

King, M., K. Lyu, X. Zhang, Climate variability as a major forcing of recent Antarctic ice-mass change, *Nature*, submitted.

Li, Y., J. A. Church, T. J. McDougall and P. M. Barker. Sensitivity of Observationally Based Estimates of Ocean Heat Content and Thermal Expansion to Vertical Interpolation Schemes, *Geophysical Research Letters*, submitted.

Lyu, K., X. Zhang, J. A. Church, Q. Wu, R. Fiedler and F. Dias, Roles of surface forcing in the Southern Ocean temperature and salinity changes: perspectives from model perturbation experiments and a theoretical framework. *Journal of Physical Oceanography*, submitted

Lyu, K., X. Zhang, and J. A. Church, Drivers of ocean warming patterns and meridional ocean heat transport under transient climate change*, Journal of Climate*, submitted

Zhang, J., X. Zhang, M. King and K. Lyu, The Response of the Southern Ocean to Iceberg Freshwater Forcing, *Journal of Geophysical Research*, submitted.

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

Li, Z., **X. Zhang** and N. Holbrook, ENSO modulations of sea surface temperatures around Australia: west coast versus southeast coast, in preparation.

Wang, J., J. A. Church and X. Zhang, Updating sea-level reconstruction since 1900, in preparation.

3 Financial management

The Centre's revenue of the five-year period to 2021-22 is AU$20m. This section provides an overview of the Centre's finances in the 2021-22 financial year.

3.1 Revenue

There was no revenue from QNLM this year, as funds were fully paid last financial year. CSIRO's contributions were $1,890,877 (Figure 6).

For the life of the project, CSIRO contributed $7,500m (91% of Agreement funds of $8,250m) and QNLM $10m (100% of Agreement funds) (Figure 7). In the last few years, significant global disruption due to COVID-19 impacted CSIRO's ability to travel both domestically and internationally as well as our ability to recruit internationally.

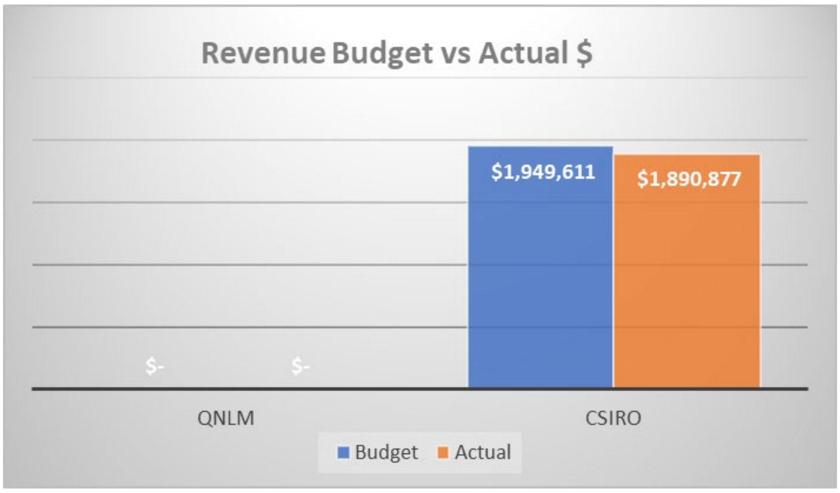


Figure 6 Revenue 2021-22 Budget vs Actual $

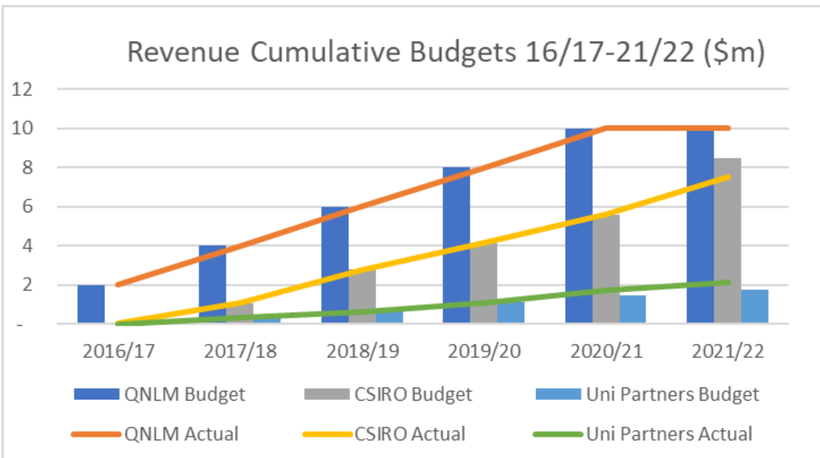


Figure 7 Revenue: Cumulative budgets to 2021-22 ($m)

3.2 Expenditure

The Total 2021-22 expenditure incurred was $4,582m acquitted to each partner as shown in Table 1.

Table 1 Total expenditure in 2021-22

Fund Source	2021-22 Budget	2021-22 Actual
QNLM	$2,361,929	$2,306,964
CSIRO	$1,949,767	$1,890,877
UNSW (In kind)	$200,000	$219,278
UTAS (In kind)	$100,000	$164,955

As explained in the revenue section above, CSIRO was not able to incur expenditure as originally planned primarily in the areas of travel and recruitment of a postdoctoral fellows (Labour costs).

3.3 Partner in-kind contribution

The Financial year 2021-22 University partners consolidated in-kind contribution was $384k, with contributions from each partner being UNSW $219k and UTAS $165k.

The University partners Total In-kind contribution at 30 June 2022 was $2,138m, which reflect total contributions from UNSW $1,516m and UTAS $622k.

3.4 Summary Outcome

CSIRO's total expenditure at 30 June 2022 was $16,801m, which reflects a $1,449m underspend as per the Agreement, proportionally allocated as $699.4k to QNLM and $749.4k to CSIRO (Table 2 and Figure 8). Plus an amount from UNSW to be confirmed.

Table 2 Total Expenditure breakdown by category budget vs actual

Expenditure by Category	WOL Budget	CSIRO WOL Actual	Uni WOL Actual	WOL Actual
Labour	10,183,387	7,279,453	1,728,035	19,190,875
Overheads	5,747,128	5,592,917	164,303	11,504,348
Travel	663,573	652,800	28,234	1,344,607
Operating	1,105,912	975,933	217,564	2,299,409
Payments to Partners	1,750,000	1,750,000		3,500,000
Capital	550,000	550,000		1,100,000
Total Expenditure	**20,000,000**	16,801,102	2,138,136	**18,939,238**

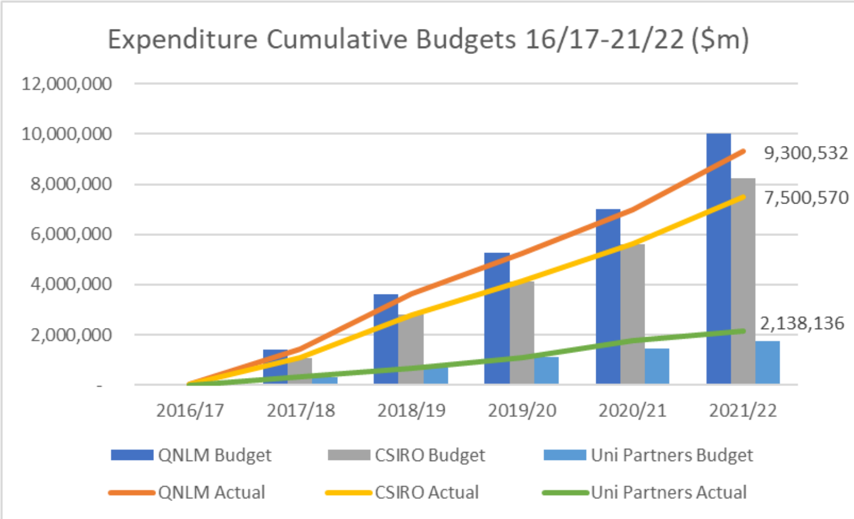


Figure 8 Expenditure: Cumulative budgets to 2021-22 ($m)

4 Management and co-ordination

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

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

Steering and Advisory Committee Members are listed in the Acknowledgement Section (page 8).

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

The **CSHOR Steering Committee** convened via video conference on 10 December 2021 and for the CSHOR science review meeting on 24 and 27 May 2022. Due to international travel restrictions associated with the COVID-19 pandemic it was not possible for the Steering and Advisory Committees to meet face-to-face, as planned for 2021-22. The Advisory Committee was invited to attend the CSHOR science review in May 2022. Unfortunately, due to time zone variations, only one member was able to attend. Advisory Committee members were able to view a recording of the science review meetings and several provided a written response to the science review.

The **CSHOR Research Leadership Team** met on 10 December 2021, 17 February 2022, and 24 and 27 May 2022 (With the Steering Committee).

The Director also attended various virtual meetings at QNLM in Qingdao including CSHOR budget review and planning meetings in November and December 2021, and the QNLM Annual Meeting in January 2022.

Appendix A Abbreviations and acronyms

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

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

Appendix B Project and support staff

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

[1] UNSW Scientia Professor of Climate Dynamics

[2] UNSW Research Associate

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

SUPPORT STAFF[4]	
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
Brenda Tuckwood	Finance and Projects Advisor, CSIRO Oceans and Atmosphere

[4] Provided by CSIRO

Appendix C PhD Students

Hannah Dawson	University of New South Wales, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Yanzhen Du	Institute of Oceanology, Chinese Academy of Sciences, China Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
Rishav Goyal	University of New South Wales, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Meng Han[5]	University of Tasmania, Australia Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
Zhanjiu Hao	Institute of Oceanology, Chinese Academy of Sciences, China Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
Maurice Huguenin	University of New South Wales, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Zhi Li[6]	University of New South Wales, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Maxime Marin	University of Tasmania, Australia Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
Julia Neme	University of New South Wales, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Ellie Ong	University of New South Wales, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Bryam Pinto	University of New South Wales, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Christina Schmidt	University of New South Wales, Australia Project 4 Southern Ocean dynamics and water mass formation team member

[5] Scholarship holder - China Scholarship Council.

[6] Scholarship holder - China Scholarship Council.

Annette Stellema	University of New South Wales, Australia Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
Sen Wang[7]	Nanjing University of Information Science and Technology Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
David Webb	University of New South Wales, Australia Project 4 Southern Ocean dynamics and water mass formation team member
Gang Yang	University of New South Wales, Australia Project 3 Coupled warm pool dynamics in the Indo-Pacific team member
Jingwei Zhang	University of Tasmania, Australia Project 6 Southern Ocean sea level change project team
Shujing Zhang	University of Tasmania, Australia Project 6 Southern Ocean sea level change project team
Wenjun Zhu	University of New South Wales, Australia Project 3 Coupled warm pool dynamics in the Indo-Pacific team member

[7] Scholarship holder - China Scholarship Council.

Appendix D Conference and workshop participation

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

D.1 First Quarter (July to September)

CLIVAR Pacific Panel research focus meetings on tropical Pacific decadal variability, July and August 2021: Drs Santoso and Zhang attended.

Virtual Atmosphere-Cryosphere-Ocean (VACO-21) seminar series, run by the International Association for the Physical Sciences of the Oceans (IAPSO) and the International Association of Meteorology and Atmospheric Sciences (IAMAS), July 2021: Prof England attended.

3rd International Conference on Maritime Sciences and Advanced Technology (MSAT), August 2021: Dr Santoso attended.

Asia Oceania Geosciences Society (AOGS) 2021 virtual conference, August 2021: Dr Zhang attended.

Australian Research Council (ARC) Centre of Excellence for Climate Extremes drought meeting, September 2021: Dr Santoso attended.

World Climate Research Programme (WCRP) workshop on attribution of multi-annual to decadal changes in the climate system, September 2021: Dr Lyu attended.

UTas Postgraduate Supervision Training session, September 2021: Prof England attended.

D.2 Second Quarter (October to December)

Monetary Authority of Singapore Meeting, October 2021: Dr Santoso attended.

Australian Antarctic Program Partnership (AAPP) Symposium, Hobart, October 2021: Drs Rintoul, Shadwick, and Herraiz-Borreguero attended.

Australian Centre for Excellence in Antarctic Science Workshop, Hobart, October 2021: Dr Herraiz-Borreguero attended.

ARC Centre of Excellence for Climate Extremes tropical variability seminar, November 2021: Drs Santoso and Wang attended.

ENSO workshop hosted by Pohang University of Korea, November 2021: Dr Cai attended.

The 11th International conference on tropical Marine Environmental Changes, November 2021: Drs Cai and Feng attended.

Atmosphere-ocean science forum, November 2021: Dr Cai attended.

Bureau of Meteorology Annual Research and Development Workshop, November 2021: Dr Feng attended.

Climate Variability and Predictability Program (CLIVAR) Pacific Panel research focus meetings on tropical Pacific decadal variability, November 2021: Dr Zhang attended.

The Virtual Forum for Operational Oceanography, November/December 2021: Dr Feng attended.

Antarctic margin group meeting, November 2021: Dr Gunn attended.

Southern Ocean Acidification in the Cryosphere Pavilion at COP26, November 2021: Dr Shadwick attended.

AGU Fall Meeting, December 2021: Dr Lyu attended.

D.3 Third Quarter (January to March)

13th International Conference on Southern Hemisphere Meteorology and Oceanography (ICSHMO), February 2022. CSHOR convened a conference session. Drs Cai, Santoso, Wang, Zhang, Lyu, Feng, Chapman, Peña-Molino, Herraiz-Borreguero, Gunn, and Prof England attended.

WCRP sea-level conference, February 2022: Dr Zhang attended.

AGU Ocean Sciences Meeting, March 2022. Drs Santoso, Phillips, Herraiz-Borreguero, Lyu, and Prof England attended.

International Indian Ocean Science Conference, March 2022. Dr Phillips attended.

D.4 Fourth Quarter (April to June)

NOAA/AOML seminar series, April 2022. Dr Santoso gave an invited presentation titled, 'ENSO, IOD, and the Indonesian Throughflow: interactions and future projections.'

The Future of Earth Science, May 2022. Prof England was a keynote speaker at this Australian National University event.

European Geophysical Union (EGU), May 2022, students Julia Neme, Maurice Huguenin and Ellie Ong presented work at the meeting.

Climatic impact of tropical variability on Africa, June 2022. Hosted by Drs. Cai, Santoso, and Wang. Dr Zhang and McPhaden and Prof England also attended.

NESP Webinar: There and back again: the impacts of back-to-back El Niño and La Niña over the last 15 years, June 2022. Drs Wang and Santoso presented.

NESP Science Days, June 2022. Dr Santoso attended and presented summary on ENSO projections.

Appendix E Publications

1. Bi, D., Wang, G., Cai, W., Santoso, A., Sullivan, A., Ng, B., & Jia, F. (2022). Improved Simulation of ENSO Variability Through Feedback From the Equatorial Atlantic in a Pacemaker Experiment. *Geophysical Research Letters, 49*(2), e2021GL096887. https://doi.org/10.1029/2021GL096887
2. Cai, W., Ng, B., Wang, G., Santoso, A., Wu, L., & Yang, K. (2022). Increased ENSO sea surface temperature variability under four IPCC emission scenarios. *Nature Climate Change*. doi:10.1038/s41558-022-01282-z
3. Cai, W., Santoso, A., Collins, M., Dewitte, B., Karamperidou, C., Kug, J.-S., . . . Zhong, W. (2021). Changing El Niño–Southern Oscillation in a warming climate. *Nature Reviews Earth & Environment*. doi:10.1038/s43017-021-00199-z
4. Cyriac, A., Phillips, H. E., Bindoff, N. L., & Feng, M. (2022). Characteristics of Wind-Generated Near-Inertial Waves in the Southeast Indian Ocean. *Journal of Physical Oceanography, 52*(4), 557-578. doi:10.1175/jpo-d-21-0046.1
5. Dias, F. B., Domingues, C. M., Marsland, S. J., Rintoul, S. R., Uotila, P., Fiedler, R., . . . Savita, A. (2021). Subpolar Southern Ocean Response to Changes in the Surface Momentum, Heat, and Freshwater Fluxes under 2xCO2. *Journal of Climate, 34*(21), 8755-8775. doi:10.1175/jcli-d-21-0161.1
6. Du, Y., Feng, M., Xu, Z., Yin, B., & Hobday, A. J. (2022). Summer Marine Heatwaves in the Kuroshio-Oyashio Extension Region. *Remote Sensing, 14*(13), 2980. doi:10.3390/rs14132980.
7. Feng, M., Lengainne, M., Sunanda, M., Sen Gupta, A., & Vialard, J. (2022). Extreme events and impacts in the Indian Ocean. In C. Ummenhofer & R. Hood (Eds.), *The Indian Ocean and its role in the global climate system*: Elsevier. https://www.elsevier.com/books/the-indian-ocean-and-its-role-in-the-global-climate-system/ummenhofer/978-0-12-822698-8.
8. Feng, M., Zhang, Y., Hendon, H. H., McPhaden, M. J., & Marshall, A. G. (2021). Niño 4 West (Niño-4W) Sea Surface Temperature Variability. *Journal of Geophysical Research: Oceans, 126*(9), e2021JC017591. https://doi.org/10.1029/2021JC017591
9. Foppert, A., Rintoul, S. R., Purkey, S. G., Zilberman, N., Kobayashi, T., Sallèe, J.-B., . . . Wallace, L. O. (2021). Deep Argo Reveals Bottom Water Properties and Pathways in the Australian-Antarctic Basin. *Journal of Geophysical Research: Oceans, 126*(12), e2021JC017935. https://doi.org/10.1029/2021JC017935
10. Goyal, R., England, M. H., Jucker, M., & Sen Gupta, A. (2021). Response of Southern Hemisphere Western Boundary Current Regions to Future Zonally Symmetric and Asymmetric Atmospheric Changes. *Journal of Geophysical Research: Oceans, 126*(11), e2021JC017858. https://doi.org/10.1029/2021JC017858
11. Goyal, R., Jucker, M., Gupta, A. S., & England, M. H. (2022). A new zonal wave 3 index for the Southern Hemisphere. *Journal of Climate*, 1-25. doi:10.1175/jcli-d-21-0927.1
12. Goyal, R., Jucker, M., Sen Gupta, A., & England, M. H. (2021). Generation of the Amundsen Sea Low by Antarctic Orography. *Geophysical Research Letters, 48*(4), e2020GL091487. https://doi.org/10.1029/2020GL091487
13. Goyal, R., Sen Gupta, A., Jucker, M., & England, M. H. (2021). Historical and Projected

Changes in the Southern Hemisphere Surface Westerlies. *Geophysical Research Letters, 48*(4), e2020GL090849. https://doi.org/10.1029/2020GL090849
14. Holgate, C., Evans, J. P., Taschetto, A. S., Sen Gupta, A., & Santoso, A. (2022). The impact of interacting climate modes on east Australian precipitation moisture sources. *Journal of Climate*, 1-31. doi:10.1175/jcli-d-21-0750.1
15. Hsu, J.-Y., Feng, M., & Wijffels, S. (2022). Rapid restratification of the ocean surface boundary layer during the suppressed phase of the MJO in austral spring. *Environmental Research Letters, 17*(2), 024031. doi:10.1088/1748-9326/ac4f11
16. Hu, S., Li, S., Zhang, Y., Guan, C., Du, Y., Feng, M., . . . Hu, D. (2021). Observed strong subsurface marine heatwaves in the tropical western Pacific Ocean. *Environmental Research Letters, 16*(10), 104024. https://doi.org/10.1088/1748-9326/ac26f2
17. Huang, Z., Feng, M., Beggs, H., Wijffels, S., Cahill, M., & Griffin, C. (2021). High-resolution marine heatwave mapping in Australasian waters using Himawari-8 SST and SSTAARS data. *Remote Sensing of Environment, 267*, 112742. https://doi.org/10.1016/j.rse.2021.112742
18. Jeong, YC., Yeh, SW., Lim, YK. Santoso, A, Wang, G. (July 2022). Indian Ocean warming as key driver of long-term positive trend of Arctic Oscillation. *npj Climate and Atmospheric Science* 5, 56. https://doi.org/10.1038/s41612-022-00279-x
19. Jia, F., Cai, W., Gan, B., Wu, L., & Di Lorenzo, E. (2021). Enhanced North Pacific impact on El Niño/Southern Oscillation under greenhouse warming. *Nature Climate Change*. doi:10.1038/s41558-021-01139-x
20. Li, S., Cai, W., & Wu, L. (2021). Weakened Antarctic Dipole Under Global Warming in CMIP6 Models. *Geophysical Research Letters, 48*(16), e2021GL094863. https://doi.org/10.1029/2021GL094863
21. Li, X., Cai, W., Meehl, G. A., Chen, D., Yuan, X., Raphael, M., . . . Song, C. (2021). Tropical teleconnection impacts on Antarctic climate changes. *Nature Reviews Earth & Environment*. doi:10.1038/s43017-021-00204-5
22. Li, Z., England, M. H., Groeskamp, S., Cerovečki, I., & Luo, Y. (2021). The Origin and Fate of Subantarctic Mode Water in the Southern Ocean. *Journal of Physical Oceanography, 51*(9), 2951-2972. doi:10.1175/jpo-d-20-0174.1.
23. Liu, W., Hegglin, M. I., Checa-Garcia, R., Li, S., Gillett, N. P., Lyu, K., . . . Swart, N. C. (2022). Stratospheric ozone depletion and tropospheric ozone increases drive Southern Ocean interior warming. *Nature Climate Change, 12*(4), 365-372. doi:10.1038/s41558-022-01320-w
24. Lyu, K., Zhang, X., & Church, J. A. (2021). Projected ocean warming constrained by the ocean observational record. *Nature Climate Change*. doi:10.1038/s41558-021-01151-1
25. Mao, Y., Zou, Y., Alves, L. M., Macau, E. E. N., Taschetto, A. S., Santoso, A., & Kurths, J. (2022). Phase Coherence Between Surrounding Oceans Enhances Precipitation Shortages in Northeast Brazil. *Geophysical Research Letters, 49*(9), e2021GL097647. https://doi.org/10.1029/2021GL097647
26. Marin, M., Bindoff, N. L., Feng, M., & Phillips, H. E. (2021). Slower Long-Term Coastal Warming Drives Dampened Trends in Coastal Marine Heatwave Exposure. *Journal of Geophysical Research: Oceans, 126*(11), e2021JC017930. https://doi.org/10.1029/2021JC017930
27. McMahon, C. R., Roquet, F., Baudel, S., Belbeoch, M., Bestley, S., Blight, C., . . . Woodward, B. (2021). Animal Borne Ocean Sensors – AniBOS – An Essential Component of the Global

Ocean Observing System. *Frontiers in Marine Science, 8*(1625). doi:10.3389/fmars.2021.751840
28. Mortenson, E., Lenton, A., Shadwick, E., Trull, T., Chamberlain, M., & Zhang, X. (2021). Divergent trajectories of ocean warming and acidification. *Environmental Research Letters, 16*(12), 124063. https://doi.org/10.1088/1748-9326/ac3d57
29. Orihuela-Pinto, B., England, M. H., & Taschetto, A. S. (2022). Interbasin and interhemispheric impacts of a collapsed Atlantic Overturning Circulation. *Nature Climate Change*. doi:10.1038/s41558-022-01380-y
30. Orihuela-Pinto, B., Santoso, A., England, M. H., & Taschetto, A. S. (July 2022). Reduced ENSO Variability due to a Collapsed Atlantic Meridional Overturning Circulation. *Journal of Climate, 35*(16), 5307-5320. doi:10.1175/jcli-d-21-0293.1
31. Peña-Molino, B., Sloyan, B. M., Nikurashin, M., Richet, O., & Wijffels, S. E. (2022). Revisiting the Seasonal Cycle of the Timor Throughflow: Impacts of Winds, Waves and Eddies. *Journal of Geophysical Research: Oceans, 127*(4), e2021JC018133. https://doi.org/10.1029/2021JC018133
32. Phillips, H. E., Tandon, A., Furue, R., Hood, R., Ummenhofer, C., Benthuysen, J., . . . Wiggert, J. (2021). Progress in understanding of Indian Ocean circulation, variability, air-sea exchange and impacts on biogeochemistry. *Ocean Sci. Discuss., 2021*, 1-109. doi:10.5194/os-2021-1
33. Portela, E., Rintoul, S. R., Bestley, S., Herraiz-Borreguero, L., van Wijk, E., McMahon, C. R., . . . Hindell, M. (2021). Seasonal Transformation and Spatial Variability of Water Masses Within MacKenzie Polynya, Prydz Bay. *Journal of Geophysical Research: Oceans, 126*(12), e2021JC017748. https://doi.org/10.1029/2021JC017748
34. Power, S., Lengaigne, M., Capotondi, A., Khodri, M., Vialard, J., Jebri, B., . . . Henley, B. J. (2021). Decadal climate variability in the tropical Pacific: Characteristics, causes, predictability, and prospects. *Science, 374*(6563), eaay9165. doi:10.1126/science.aay9165
35. Saurabh Rathore, Rishav Goyal, Babita Jangir, Caroline C. Ummenhofer, Ming Feng, Mayank Mishra (2022). Interactions between a Marine Heatwave and Tropical Cyclone Amphan in the Bay of Bengal in 2020. *Frontiers in Climate, 4*. https://www.frontiersin.org/articles/10.3389/fclim.2022.861477.
36. Ribeiro, N., Herraiz-Borreguero, L., Rintoul, S. R., McMahon, C. R., Hindell, M., Harcourt, R., & Williams, G. (2021). Warm Modified Circumpolar Deep Water Intrusions Drive Ice Shelf Melt and Inhibit Dense Shelf Water Formation in Vincennes Bay, East Antarctica. *Journal of Geophysical Research: Oceans, 126*(8), e2020JC016998. https://doi.org/10.1029/2020JC016998
37. Santoso, A., England, M. H., Kajtar, J. B., & Cai, W. (2022). Indonesian Throughflow Variability and Linkage to ENSO and IOD in an Ensemble of CMIP5 Models. *Journal of Climate*, 1-46. doi:10.1175/jcli-d-21-0485.1
38. Savita, A., Domingues, C. M., Boyer, T., Gouretski, V., Ishii, M., Johnson, G. C., . . . Wijffels, S. E. (2021). Quantifying spread in spatio-temporal changes of upper-ocean heat content estimates: an internationally coordinated comparison. *Journal of Climate*, 1-59. doi:10.1175/jcli-d-20-0603.1
39. Sohail, T., Zika, J. D., Irving, D. B., & Church, J. A. (2022). Observed poleward freshwater transport since 1970. *Nature, 602*(7898), 617-622. doi:10.1038/s41586-021-04370-w
40. Stammerjohn, S., Scambos, T. A., Adusumilli, S., Barreira, S., Bernhard, G. H., Bozkurt, D., . . . Yuan, X. (2021). Antarctica and the Southern Ocean. *Bulletin of the American*

Meteorological Society, 102(8), S317-S356. doi:10.1175/bams-d-21-0081.1
41. Tamsitt, V., England, M. H., Rintoul, S. R., & Morrison, A. K. (2021). Residence Time and Transformation of Warm Circumpolar Deep Water on the Antarctic Continental Shelf. *Geophysical Research Letters, 48*(20), e2021GL096092. https://doi.org/10.1029/2021GL096092
42. Wang, G., Cai, W., Santoso, A., Wu, L., Fyfe, J. C., Yeh, S.-W., . . . McPhaden, M. J. (2022). Future Southern Ocean warming linked to projected ENSO variability. *Nature Climate Change*. doi:10.1038/s41558-022-01398-2
43. Wang, J., Church, J. A., Zhang, X., Gregory, J. M., Zanna, L., & Chen, X. (2021). Evaluation of the Local Sea-Level Budget at Tide Gauges Since 1958. *Geophysical Research Letters, 48*(20), e2021GL094502. https://doi.org/10.1029/2021GL094502
44. Wang, S., Feng, M., Dong, C., & Zhu, W. (2021). Observations of SST-Induced Wind Perturbations in the Leeuwin Current. *Journal of Geophysical Research: Oceans, 126*(6), e2020JC016993. https://doi.org/10.1029/2020JC016993
45. Wang, S., Jing, Z., Wu, L., Cai, W., Chang, P., Wang, H., . . . Yang, H. (2022). El Niño/Southern Oscillation inhibited by submesoscale ocean eddies. *Nature Geoscience, 15*(2), 112-117. doi:10.1038/s41561-021-00890-2
46. Webb, D. J., Holmes, R. M., Spence, P., & England, M. H. (2022). Propagation of barotropic Kelvin waves around Antarctica. *Ocean Dynamics, 72*(6), 405-419. doi:10.1007/s10236-022-01506-y
47. Webb, D. J., Spence, P., Holmes, R. M., & England, M. H. (2021). Planetary-Wave-Induced Strengthening of the AMOC Forced by Poleward Intensified Southern Hemisphere Westerly Winds. *Journal of Climate, 34*(17), 7073-7090. doi:10.1175/jcli-d-20-0858.1
48. Yang, G., Wang, X. H., Cheng, Z., Zhong, Y., & Oliver, T. (2021). Modelling study on estuarine circulation and its effect on the turbidity maximum zone in the Yalu River Estuary, China. *Estuarine, Coastal and Shelf Science, 263*, 107634. https://doi.org/10.1016/j.ecss.2021.107634
49. Yang, K., Cai, W., Huang, G., Hu, K., Ng, B., & Wang, G. (2022). Increased variability of the western Pacific subtropical high under greenhouse warming. *Proceedings of the National Academy of Sciences, 119*(23), e2120335119. doi:10.1073/pnas.2120335119
50. Yang, Y., Wu, L., Guo, Y., Gan, B., Cai, W., Huang, G., . . . Xie, S.-P. (2021). Greenhouse warming intensifies north tropical Atlantic climate variability. *Science Advances, 7*(35), eabg9690. doi:10.1126/sciadv.abg9690
51. Yeh, S.-W., Wang, G., Cai, W., & Park, R. J. (2022). Diversity of ENSO-Related Surface Temperature Response in Future Projection in CMIP6 Climate Models: Climate Change Scenario Versus ENSO Intensity. *Geophysical Research Letters, 49*(4), e2021GL096135. https://doi.org/10.1029/2021GL096135
52. Zhang, Y., Du, Y., Feng, M., & Hu, S. (2021). Long-Lasting Marine Heatwaves Instigated by Ocean Planetary Waves in the Tropical Indian Ocean During 2015–2016 and 2019–2020. *Geophysical Research Letters, 48*(21), e2021GL095350. https://doi.org/10.1029/2021GL095350

CONTACT US

t 1300 363 400
+61 3 9545 2176
e csiroenquiries@csiro.au
w www.csiro.au

WE DO THE EXTRAORDINARY EVERY DAY

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

Our innovations contribute billions of dollars to the Australian economy every year. As the largest patent holder in the nation, our vast wealth of intellectual property has led to more than 150 spin-off companies.

With more than 5,000 experts and a burning desire to get things done, we are Australia's catalyst for innovation.

WE IMAGINE
WE COLLABORATE
WE INNOVATE

FOR FURTHER INFORMATION

Centre for Southern Hemisphere Oceans Research
Director – Dr Wenju Cai
t +61 3 9239 4419
e wenju.cai@csiro.au
Project Support Officer - Ms Leonie Wyld
t +61 3 6232 5435
e leonie.wyld@csiro.au
w https://cshor.csiro.au/