climate extremes

ARC centre of excellence

Report 2019

Centre of Excellence for Climate Extremes Annual Report 2019

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Other photos: CLEX Staff including Alvin Stone.

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Vision Statement

Our goal is to transform our understanding of the processes that cause climate extremes, including their dependence on climate change and variability, and to use this process-based understanding to revolutionise our capability to predict future climate extremes.

Aims and Objectives

The Australian Research Council Centre of Excellence for Climate Extremes is the world's first fully integrated centre focused explicitly on the understanding and prediction of climate extremes. We aim to understand the processes causing climate extremes, build this understanding into the Australian prediction systems, and improve our capability to predict extremes into the future.

Climate extremes are high-impact events that can range in time scales from minutes to centuries. They are estimated to have cost the global economy US$2.4 trillion between 1979 and 2012 alone. By improving our capability to predict these extremes we will inform strategies and policies to minimise these huge sums, and reduce national and global vulnerability to climate extremes and their potential costs. Our unique focus is a response to the World Climate Research Programme's (WCRP) identification of climate extremes as a "Grand Challenge". This reflects the importance of extremes to society, the scientific challenges associated with the understanding and prediction thereof, and the lack of major, coordinated activities worldwide to address them. The Australian Research Council (ARC) Centre of Excellence for Climate Extremes (CLEX) therefore accepts the challenge set by the WCRP and will lead the charge on this globally significant problem.

Our efforts are focused on five key areas, as set out in our Strategic Plan:

Combining Australia's outstanding researchers with world-class overseas ones in CLEX will realise a unique opportunity to transform the science of climate extremes prediction. Our legacy will be a generation of outstanding graduates and early career researchers, along with scientific discovery and technical innovation that will establish Australia's leadership in climate extremes and be the envy of the international community.

World Class Research

We will undertake world-class research into processes that cause, amplify or prolong climate extremes (past, present and future) and integrate this new understanding into our national simulation systems to transform our national prediction capability.

An Outstanding Environment

Our Researcher Development Program will provide unparalleled training and mentorship to early and mid-career researchers. We will provide a superb environment for all researchers, students, and administrative and professional staff, with a focus on diversity and inclusion.

Exceptional Infrastructure

Our critical infrastructure is more than high-performance computing and data – it includes the software fabric around models and the tools to use them efficiently and effectively. We have a dedicated team of computational modelling specialists to help us optimise our research performance.

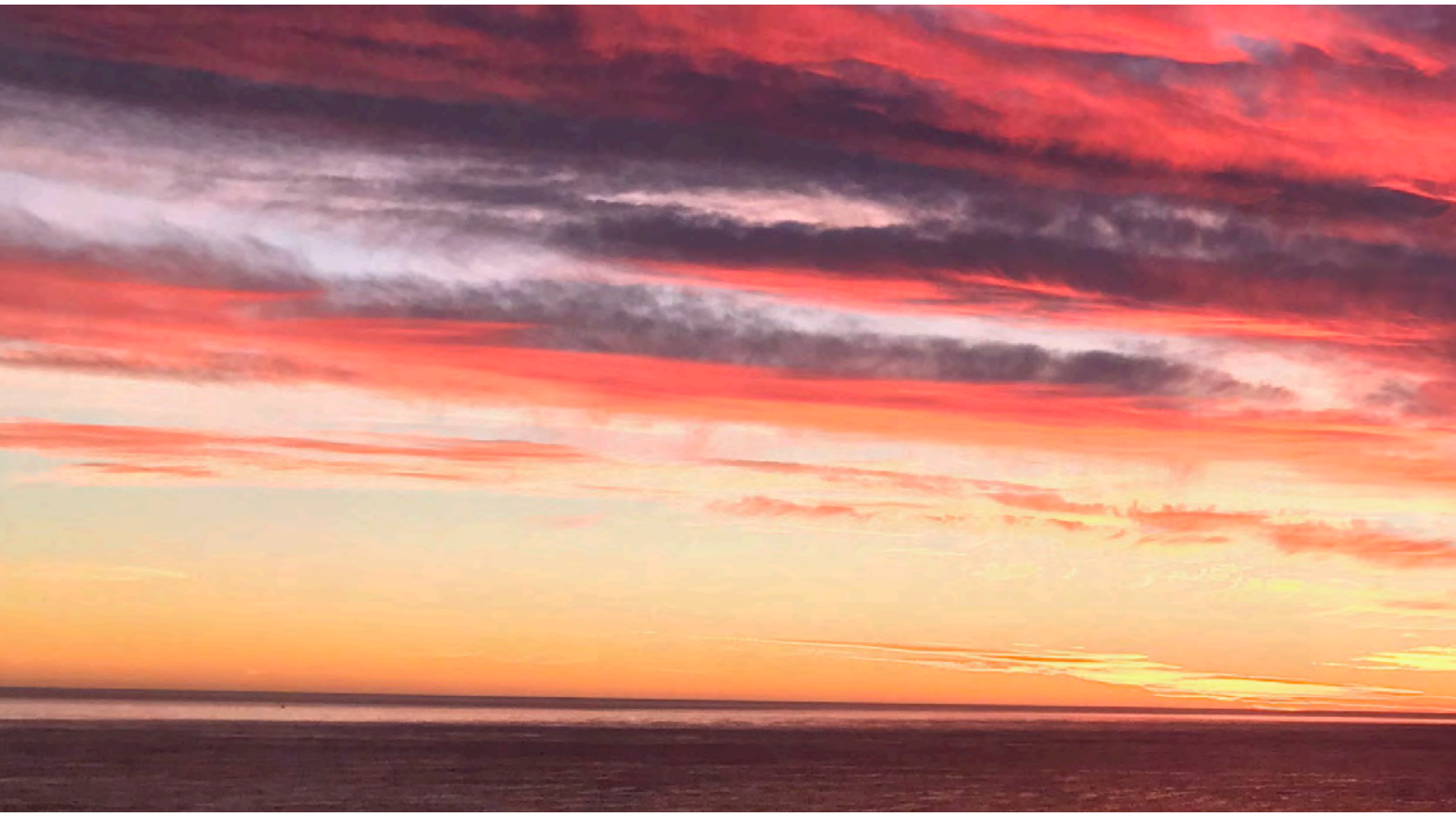
Transformative collaboration

We strive to achieve a rich national collaborative environment as a foundation for our research, and use that foundation to strongly contribute to national research priorities.

Engagement and Impact

We engage with leading partners and stakeholders. To manage our engagement and pathways-to-impact strategies we have established an outreach committee to advise the Centre Executive on the development and execution of its outreach and communications strategies.

Overview



"Climate extremes affect many facets of Australian society, including health, soil and water, agriculture, infrastructure, energy security and financial security"

The ARC Centre of Excellence for Climate Extremes (CLEX) is primarily funded by the Australian Research Council (ARC). We combine five Australian universities and a suite of outstanding national and international Partner Organisations. The establishment of the Centre – the first of its kind globally – marks a shift from investigating climate averages to a specific focus on the process-level understanding that explains the behaviour of climate extremes that directly affect Australian natural and economic systems. With this increased evidence-based understanding as our foundation, the Centre will improve our capability to predict climate extremes with the goal of reducing our national vulnerability.

CLEX was established in August 2017 with extensive investment from the ARC, the University of New South Wales, Monash University, the Australian National University, the University of Melbourne, the University of Tasmania, the Bureau of Meteorology (BoM), the New South Wales Government's Research Attraction and Acceleration Program and the New South Wales Office of Environment and Heritage. We have strong links with CSIRO and BoM, and through them with the Australian Community Climate and Earth System Simulator (ACCESS) initiative. The Centre works in partnership with the National Computational Infrastructure facility (NCI) and informs scientifically robust policy decisions via our partnerships with state and federal departments and the Earth Systems and Climate Change Hub of the National Environmental Science Programme. We have two industry partnerships already

established: Risk Frontiers, an industry-funded research centre focused on risk, and the Managing Climate Variability (MCV) program, which helps link weather and climate information with the agricultural sector.

There is an increasing need to capture the behaviour of climate extremes in national prediction systems. To date, the assumption has been that models with skill in capturing the averages will have skill in capturing extremes. Evidence has emerged that disputes this assumption, leading to the need to build new mathematical models with explicit attention to the behaviour of systems under extreme conditions. CLEX focuses on the processes underlying extreme rainfall, droughts, heatwaves and cold air outbreaks. Because these are all affected by the background climate, including variability on many time scales, we will maintain research efforts on climate variability, teleconnections and climate sensitivity. Our research is necessarily quantitative, devoted to understanding the physics, dynamics and biology of climate extremes and describing them in ACCESS. Central to our research, therefore, are the high-performance computers and data environment provided by NCI.

We aim to help reduce Australia's economic, social and environmental vulnerability to climate extremes. Climate extremes affect many facets of Australian society, including health, soil and water, agriculture, infrastructure, energy security and financial security. Our research therefore touches on many of the Federal Government's Science and Research Priorities, including its Food, Soil and Water, Transport, Energy, Environmental Change and Health priorities. By linking with Risk Frontiers, our research informs how climate extremes affect insurance risks, and via the MCV program we inform how climate extremes affect food production.

With national and international partners, we are applying new understanding to our national prediction systems and improving predictions of climate extremes. By linking with key economic sectors, we enable better decision making that builds increased national resilience to climate extremes and helps minimise risk to the Australian environment, society, and economy.

From the Chair of the Advisory Board

> "The buzz generated at the CLEX workshop, especially by the graduate students and early career researchers, was palpable."

I'm extremely pleased once again to be able to provide an introduction to the CLEX Annual Report.

2019 was a year of consolidation and progress for the Centre. As outlined in various chapters of this report, CLEX research is a truly collaborative effort that spans institutions, disciplines, age groups and cultures. It is a true credit to the centre and its leaders that such a collaborative spirit is woven into the fabric of the Centre, leading to greater scientific outcomes and impact than would otherwise be possible within the Australian climate research community.

For the second year in a row, I was able to attend the Centre's annual workshop held in November, on the Hobart waterfront. The buzz generated at the CLEX workshop, especially by the graduate students and early career researchers, was palpable. The confidence and energy of these young researchers is in no small part due to the remarkable work of the Centre's Graduate Director, A/Prof Melissa Hart. The cross-institutional researcher development program that she has created is unique and sets a high benchmark that deserves to be emulated by other research groups.

I also acknowledge the Centre's work in research translation and communication. The Knowledge Brokerage Team has co-authored and distributed several briefing notes on issues such as heatwaves and drought, the effect of marine heatwaves on ocean ecosystems and how global crop yields are affected by extreme weather. These accessible and topical reports are distributed to policymakers, industry bodies and other stakeholders. They are also publically available on the CLEX website.

As the Centre moves into 2020 and its mid-term review in the coming months, I have every confidence that it will continue to go from strength to strength.

Dr Tony Press
Chair, CLEx Advisory Board

Director's Report

I write this Director's Report at a challenging time in southern and eastern Australia. I recall an ABC news report in late January being introduced with a summary of bushfires, drought, extreme rainfall, hail and dust storms -- all in one day. The phenomenon that is the 2019/20 summer has been remarkable for the research community and the public alike, and has placed considerable pressure on many in the Centre of Excellence for Climate Extremes, via a media that really wants to know what is happening with certainty. Centre researchers have consequently been front and centre in the media, called upon to brief state governments, industry, inquiries and so on. I suspect I will be able to cut-and-paste this paragraph for the 2020 annual report, given that unravelling this summer in terms of cause and effect might take a few years of intensive research.

The Centre saw an acceleration in our research in 2019 as the combined outcome of the ramping-up of activity in 2018, an intensification of collaboration, a maturing of some research tools and the gaining of experience by PhD students and research fellows.

This report highlights progress in all four of our research programs. Development of data sets and models that underpin future research is a highlight under several of these programs. Process-level examination of why we struggle with specific elements of rainfall, heatwaves and drought, and the challenges of capturing the modes of variability and their teleconnection to the Australian continent are ongoing, but we are making important progress.

In terms of data, I will highlight two examples. Joshua Soderholm, with colleagues at Monash and the Bureau of Meteorology (BoM), has created a 20-year-long Australian operational weather radar data set that will be updated on a regular basis. The data set provides an invaluable insight into precipitation events and severe weather, including tropical cyclones and thunderstorms. At the opposite end of the time and space spectra, Mandy Freund and colleagues have produced the world's first 400-year detailed record of El Niño events using coral cores. Her work has shown that these events are shifting and possibly even becoming more intense, with important implications for our climate.

The Heatwaves and Cold Air Outbreaks research program team has produced the first global assessment of the drivers of marine heatwaves, revealing these events were often instigated thousands of miles away and were linked to nine

well-known climate oscillations. The team also found marine heatwaves had increased by 50% over the past century. This is fundamental research that will set a baseline for future studies into marine heatwaves. The Heatwaves team also explored how the El Niño Southern Oscillation (ENSO) affected heatwaves across Australia, revealing that the soil moisture and surface-energy balance of the land surface in north and north-eastern Australia modified the impacts of ENSO, with possible implications for improving regional forecasts.

The Drought research program examined the interactions between soil moisture and precipitation in Australia. The Drought program team also produced a much-improved data set for global river flows and another for land degradation. It also produced a paper that will give agricultural and ecosystem researchers a better understanding of future vegetation changes with global warming.

Finally, our Climate Variability and Teleconnections research program made important contributions, ranging from discoveries around the Indian Ocean Dipole, to the Southern Annual Mode, and from tropical variability to Antarctic sea ice. Fundamental model development took place, new processes were added, and the implications of model resolution for simulating marine heatwaves published. More detail is provided later in this report.

This year has seen a particularly vibrant annual workshop, which was a vegetarian-catered event for the first time. Presentations from colleagues across the five universities were combined with researchers from BoM and CSIRO. We also hosted our annual winter school, which continues its strong success in bringing PhD students together to learn more about our science.

Centre researchers continue to play key roles in important international reports on our climate. Nerilie Abram and Nathan Bindoff were both chapter leads on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Oceans and Cryosphere. Jason Evans was a Lead Author for the desertification chapter of the IPCC Special Report on Climate Change and Land. At the same time, Peter Strutton has been a Lead Author on the second Tropical Pacific Observing System (TPOS) report that has called for an expanded motivation for, and redesign of, the backbone of the TPOS. Andrea Taschetto was named a member of the Tropical Basin Interaction group, one of Climate Variability and Predictability's new foci. Closer to home, Christian Jakob led a national initiative examining the landscape of process-focused research in Australia.

It is hard to know where to start with awards announced in 2019. Todd Lane was elected as an Australian Meteorological and Oceanographic Society (AMOS) fellow, Christian Jakob won the 2018 Morton Medal, Andrew King was the inaugural winner of the AMOS Award for Science Outreach. Julie Arblaster and Matthew England made the Highly Cited List produced by Clarivate Analytics. The Royal Meteorological Society honoured Lisa Alexander with the Gordon Manley Weather Prize. Ariaan Purich won the Uwe Radok Award for best PhD thesis , Adele Morrison received the Meyers Medal for early career research, Nerilie Abram was awarded the Priestley Medal and Joelle Gergis received the AMOS Science Outreach Award. Amelie Meyer won Tasmania's Young Tall Poppy Award. Anna Ukkola and Amelie Meyer each won a Discovery Early Career Research Award, which is a huge achievement given how competitive these were. Anna will focus on seasonal prediction of drought and how improving land processes might improve forecasts linking UK Meteorological Office and BoM land surface research. Amelie's project aims at a better understanding of why Antarctic sea ice is changing, impacts on sea ice ecosystems, and improved predictions of future changes.

Lots more detail is provided throughout this report and I hope you find some new material, some new insights and identify opportunities for collaboration. Given the summer we have just experienced, 2020 is going to be a busy year, I think, and the more we collaborate, the faster we will make progress.

Best wishes,
Professor Andy Pitman
Director, Centre of Excellence for Climate Extremes

ARC Centre of Excellence for Climate Extremes Strategy

Our Vision: We will transform our understanding of the processes that cause climate extremes, including their dependence on climate change and variability, and to use this process-based understanding to revolutionise our capability to predict future climate extremes.

Our Research Goals

- Advance our understanding of the processes involved in extreme rainfall and build this understanding into models to improve predictions
- Understand the physical mechanisms controlling the frequency, intensity and duration of heatwaves and cold air outbreaks in Australia and build this understanding into models to improve predictions
- Advance our understanding of the controls on the frequency, intensity and duration of drought in Australia in the past, present and future and improve their representation in models to improve predictions
- Discover how climate variability, climate teleconnections and climate sensitivity are related to regional climate extremes.

Our Research Strategy

- We undertake transformative blue-sky research with a critical mass of world-class climate system scientists based on a seven-year strategy
- We develop and respond to ground-breaking ideas with vigour and commitment
- We help build a national climate modelling infrastructure using our dedicated Computational Modelling Support team
- We educate the next generation of Australia's climate scientists by transforming the graduate student experience at the national scale
- We will openly collaborate nationally and internationally
- We will define overarching research questions that integrate Centre activities and strengths
- We will communicate our science to the public and to policy makers with honesty, accuracy and integrity.

Our Values

- Internationally outstanding science, published in elite journals
- An exemplar and vibrant centre, with a culture of inclusivity and equity
- A world-class education for our students and postdoctoral researchers
- Unrestricted access to our tools, data and knowledge
- Honest and clear communication of our science
- A desire to deliver more than we promise.

We are successful when:

- Our graduate students are outstanding and in demand
- We collaborate without impact from institutional barriers
- Our publications have impact on international science
- Our science is included in Australian and overseas models
- Researchers want to join our team
- Technology and data are no barrier to our science
- We communicate our science accurately, but without fear or favour.

climate extremes
ARC centre of excellence

Strategic Objectives:	World class research focused on climate extremes	An outstanding environment for all Centre activities	Exceptional research infrastructure	Transform collaboration at all scales	Research that engages and has impact
Success strategy	**Our research program**	**An outstanding culture for all**	**Our research infrastructure program**	**National climate science fabric**	**Our outreach program**
Strategic Actions we will:	1.1 Focus research on delivering four research programs: Extreme rainfall, heatwaves and cold air outbreaks, droughts and climate variability & teleconnections	2.1 Develop a researcher development program led by a Graduate Director	3.1 Establish an infrastructure team to advise on modelling and data systems	4.1 Establish structures that avoid silos and encourage cross-institutional research	5.1 Establish a knowledge brokerage team to deliver outreach programs
	1.2 An uncompromising focus on research excellence at all levels	2.2 Strive to reflect diversity inclusivity at all levels and actively manage well-being	3.2 Work closely with NCI to ensure our partnership is mutually beneficial	4.2 Conduct national workshops and training programs	5.2 Work with selected partner organizations to deliver bespoke research data
	1.3 Engage nationally and internationally to ensure impact	2.3 Ensure early career representation at all levels of Centre activities	3.3 Maintain a computational modeling systems team to provide expert help	4.3 Conduct regular cross-institutional research team meetings	5.3 Develop tailored STEM educational resources for schools
	1.4 Identify gaps in our research and attract additional funding to resolve them	2.4 Communicate a culture of community and belonging across the Centre	3.4 Develop components of the ACCESS model needed for our research goals	4.4 Interact with our Advisory Board on key strategic issues	5.4 Implement a media strategy, using a range of appropriate technologies
		2.5 Be an exemplar providing a superb environment for all students and staff	3.5 Develop a strategy for observations, models, and reanalysis data	4.5 Contribute strongly to Australia's Science and Research Priorities	5.5 Communicate our research to government, schools, businesses, etc.

Partnerships and Engagement

Our Partners

Administering Institution

The University of New South Wales

Collaborating Institutions

The Australian National University
Monash University
The University of Melbourne
The University of Tasmania

Australian Partner Organisations

Bureau of Meteorology
CSIRO
Managing Climate Variability Program
National Computational Infrastructure
NSW Department of Planning, Industry and Environment (formerly OEH)
Risk Frontiers
Sydney Water

International Partner Organisations and Collaborators

ETH Zurich (Switzerland)
Geophysical Fluid Dynamics Laboratory (USA)
LMD – Centre National de la Recherche Scientifique (France)
Max-Planck Institute for Meteorology (Germany)
NASA-Goddard Space Flight Center (USA)
National Center for Atmospheric Research (USA)
UK Meteorological Office (UK)
The University of Arizona (USA)

We have a large network of Partner Organisations, both in Australia and overseas. Each of our partners was carefully chosen for the expertise and resources they contribute to the overall research and outreach objectives of the Centre and the climate research community at large.

Domestically, there has been ongoing cooperation with our key research Partner Organisations, CSIRO and the Bureau of Meteorology (BoM). Frequent discussions at both the researcher-to-researcher level and at the organisational level via representation on our Advisory Board have informed our strategic and implementation plans at all levels. Joint efforts around the Australian Community Climate and Earth System Simulator (ACCESS) are ongoing, with collaboration focused on ocean and land science.

We continue to work closely with the National Computational Infrastructure (NCI) for the provision of our day-to-day high-performance computing and data needs, as well as engaging with NCI on strategic considerations linked to ongoing investment in national high-performance computing infrastructure. CLEX has worked intensively with CSIRO to port the ACCESS ESM1.5 model to NCI's new supercomputer "Gadi" and NCI's leadership around supporting data access associated with reanalyses and CMIP6 has been supported by the Centre. CLEX looks forward to leveraging the enhanced capability of Gadi in the future, and active discussions around some simulations that would have been impossible on the previous supercomputer are continuing.

Elsewhere in this report, you will read of the accomplishments of our Knowledge Brokerage Team. This team, led by Dr Ian Macadam at UNSW, has built and consolidated effective partnerships with organisations such as Risk Frontiers, state government representatives and the federally funded National Environmental Science Program's Earth Systems and Climate Change Hub. During 2019 we also maintained an active dialogue with staff within what was then the Federal Department of Environment and Energy. While not a Partner Organisation, we expect that maintaining strong and open discussions with the newly merged Department of Agriculture, Water and the Environment will prove invaluable in the longer term and we are grateful for the Department's membership of our Advisory Board.

Among our 40-odd visitors in 2019, we hosted researchers from several of our international Partner Organisations, namely: the National Center for Atmospheric Research (NCAR); ETH Zurich; the UK Meteorological Office; the Geophysical Fluid Dynamics Laboratory, (GFDL) and the Max-Planck Institute for Meteorology (MPI-M). We also welcomed collaborators from other leading laboratories in Europe, Asia, and North and South America. CLEX researchers made visits to our partners at ETH Zurich, LMD – Centre National de la Recherche Scientifique (LMD-CNRS), MPI-M, NCAR, the UK Met Office and numerous other research laboratories, thus demonstrating the interconnectedness of the Centre with global efforts to better understand climate extremes.

Our collaboration with our Partner Organisations has led to two major outcomes that we note here. In terms of research, CLEX has led some research that would have been impossible to do within Australia. The nature of climate extremes and climate variability research means many of our publications are collaborative across international borders. There are some highlights in 2019. A paper focused on extreme rainfall by Chief Investigator, Professor Lisa Alexander, (https://doi.org/10.1088/1748-9326/ab51b6) included Partner Investigators from Arizona and ETH Zurich. Chief Investigator, Professor Neil Holbrook, led a marine heatwaves paper (https://doi.org/10.1038/s41467-019-10206-z) including contributions from the US, Canada, Spain and the UK. A third example, which demonstrates both science and the need for

international collaboration on model development (https://doi.org/10.5194/gmd-2019-106), was led by Dr Andrew Kiss and involved several Chief Investigators, several current or former CLEX researchers, industry, CSIRO, BoM, NCI and Partner Organisation GFDL. Many of the Centre's publications, data sets, and model developments reflect the benefits of international and national collaboration.

Significant Research Exchanges and Visits

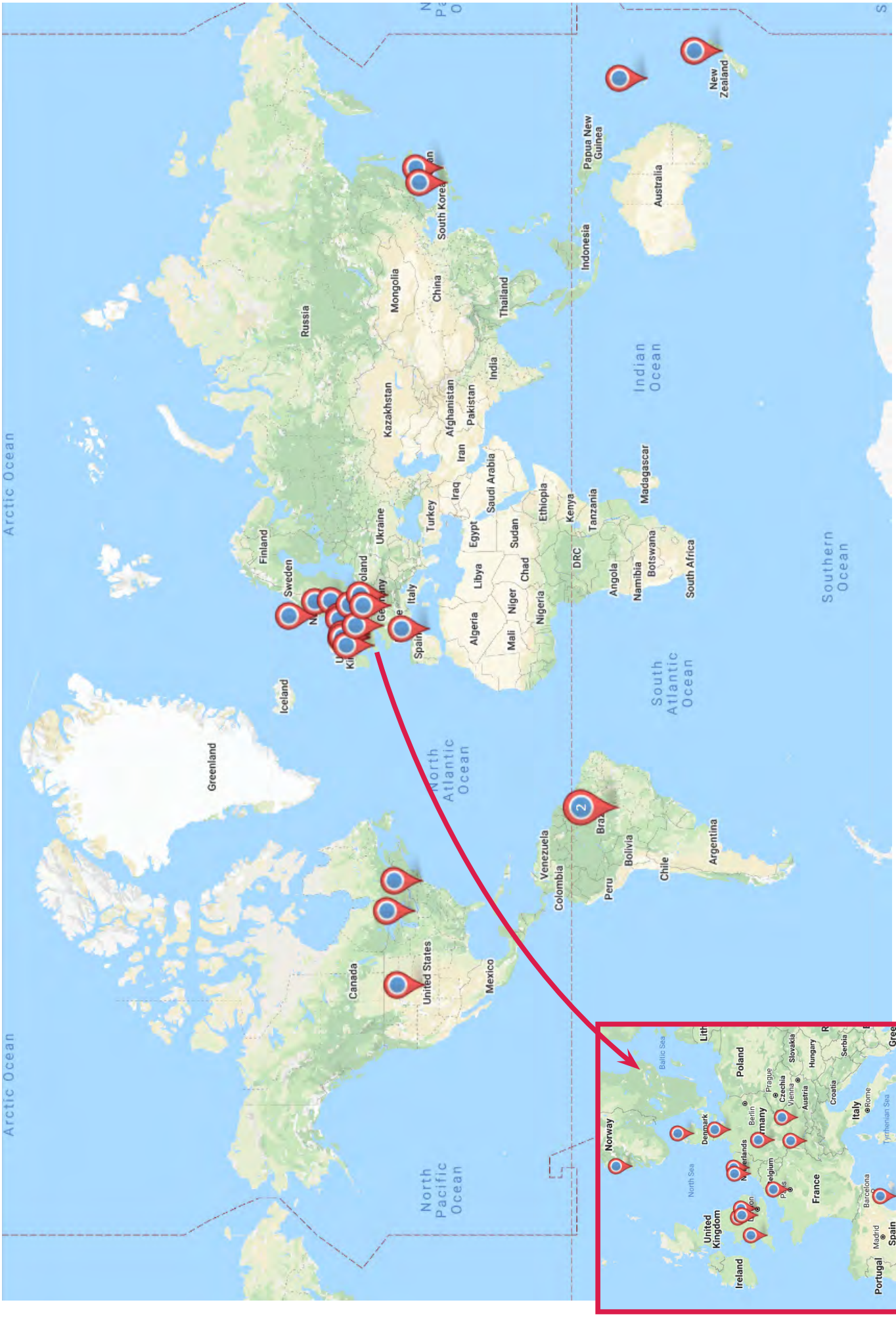
Inbound Visitors

John Allen, Central Michigan University
Caroline Bain, UK Met Office
Eleanor Blyth, Centre for Ecology and Hydrology, UK
Marleen Braun, Karlsruhe Institute of Technology, Germany
Bruce Buckley, IAG, Sydney
Robin Chadwick, UK Met Office
Joan Cuxart, Universitat de les Illes Balears, Spain
Henk Dijkstra, Utrecht University, Netherlands
Wojciech Grabowski, NCAR, USA
Stephen Griffies, GFDL, USA
Seraphine Hauser, Karlsruhe Institute of Technology, Germany
Ed Hawkins, University of Reading, UK
James Haywood, Met Office / University of Exeter, UK
Markus Jochum, Niels Bohr Institute, Denmark
Nicole Jones, University of Western Australia
Christian Keil, Ludwig-Maximilians-Universität (LMU) of Munich, Germany
Shunji Kotsuki, RIKEN Center for Computational Science, Japan
Mark Leplastrier, IAG, Sydney
Di Li Liu, NSW Department of Primary Industries
Penny Maher, University of Exeter, UK
Paige Martin, University of Michigan, USA
Hugh Morrison, NCAR, USA
David Munday, British Antarctic Survey, UK
Sujata Murty, Woods Hole Oceanographic Institution, USA
Ellie Ong, Jesus College, University of Oxford, UK
Dani Or, ETH Zurich, Switzerland
Luke Parsons, University of Washington, USA
Angeline Pendergrass, NCAR, USA
Gabriel Pontes, University of Sao Paulo, Brazil
Regina Rodrigues, Federal University of Santa Catarina, Brazil
Alessandro Savazzi, TU Delft, Netherlands
Gavin Schmidt, NASA GISS, USA
Joe Scutt Phillips, Communauté du Pacifique, New Caledonia
Shion Sekizawa, The University of Tokyo, Japan
Thomas Spengler, University of Bergen, Norway
Claudia Stephan, Max Planck Institute for Meteorology, Germany
Daithi Stone, National Institute of Water and Atmospheric Research, New Zealand
Jean-Baptiste Turmel, École Polytechnique, France
Caroline Ummenhofer, Woods Hole Oceanographic Institution, USA
Caitlin Whalen, University of Washington, USA
William Young, Scripps Institution of Oceanography, USA

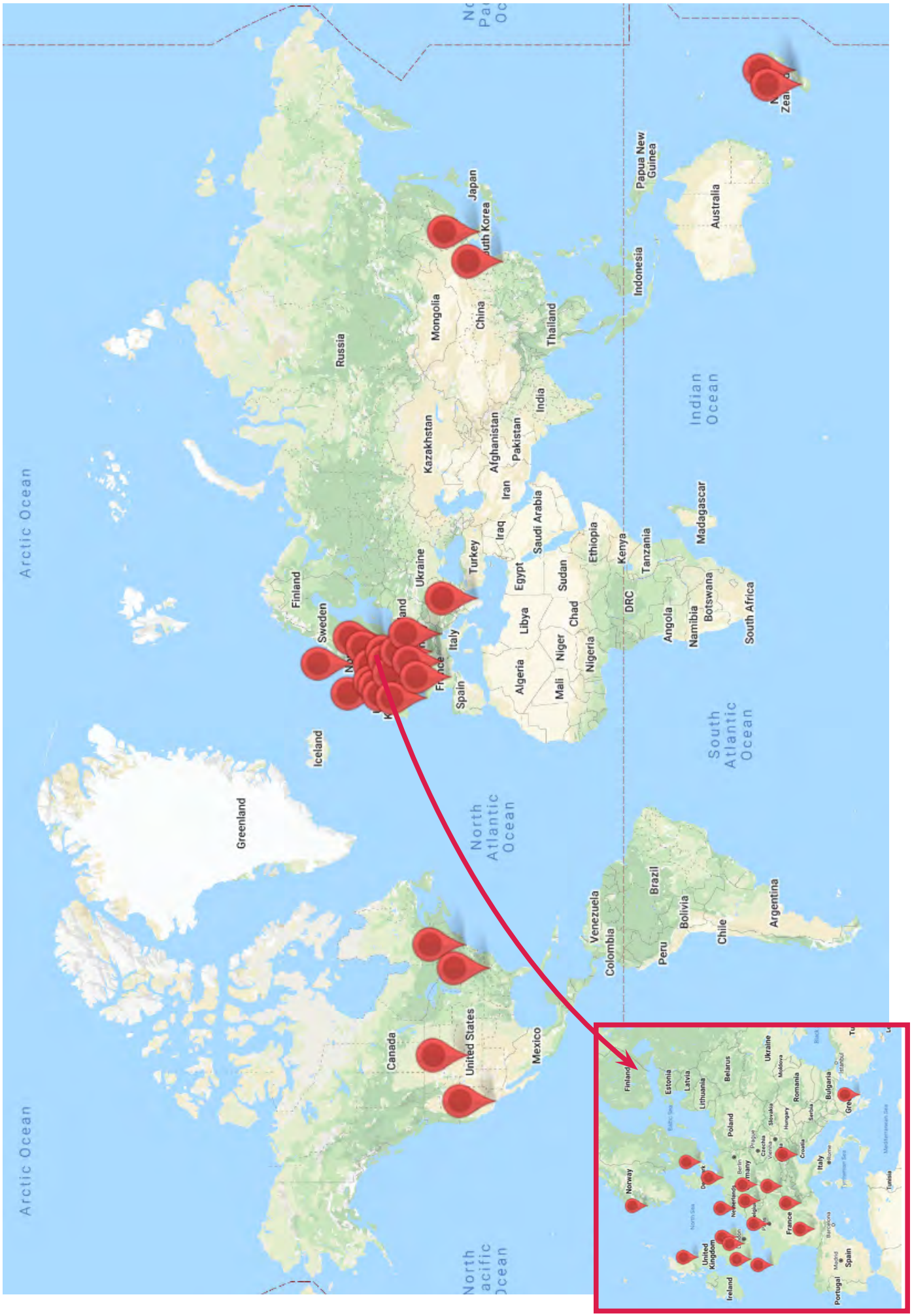
Visits to Overseas Laboratories and Partners

Gab Abramowitz, Institut des Géosciences - CNRS, Grenoble, France
Margot Bador, UCLA, Los Angeles, USA
Nathan Bindoff, Woods Hole Oceanographic Institution, USA
Craig Bishop, NIWA, Lauder, New Zealand
Navid Constantinou, Woods Hole Oceanographic Institution, USA
Navid Constantinou, IFREMER, Brest, France
Navid Constantinou, LOCEAN - IPSL, Paris, France
Ajitha Cyriac, ECMWF, Reading, UK
Ajitha Cyriac, UK Met Office, Exeter, UK
Ajitha Cyriac, Nansen Environmental and Remote Sensing Centre, University of Bergen, Norway
Dietmar Dommenget, Cerfacs, Toulouse, France
Dietmar Dommenget, LEGOS, CNRM, Paris, France
Dietmar Dommenget, DWD, Offenbach, Germany
Dietmar Dommenget, ETH Zurich, Switzerland
Dietmar Dommenget, University of North Carolina, USA
Matthew England, Woods Hole Oceanographic Institution, USA
Matthew England, ETH Zurich, Switzerland
Matthew England, LIST, Belval, Luxembourg
Melissa Hart, Nanjing University of Information Science and Technology, China
Will Hobbs, University of Southampton and University of Edinburgh, UK
Andy Hogg, University of Canterbury, New Zealand
Andy Hogg, CNRS, Paris, France
Andy Hogg, UK Met Office, Exeter, UK
Andy Hogg, NCAR, Boulder, Colorado, USA
Neil Holbrook, University of Reading, UK
Ryan Holmes, Woods Hole Oceanographic Institution, USA
Ryan Holmes, NCAR, Boulder, Colorado, USA
Sarah Jackson, UK Met Office, Exeter, UK
Sarah Jackson, ICTP, Trieste, Italy
Sarah Jackson, Vrije Universiteit Amsterdam, Netherlands
Christian Jakob, NCAR, Boulder, Colorado, USA
Christian Jakob, UCLA, USA
Jules Kajtar, MPI, Hamburg
Andrew King, NCAR, Boulder, Colorado, USA
Andreas Klocker, University of Bern, Switzerland
Todd Lane, NCAR, Boulder, Colorado, USA
Chen Li, Colorado State University, USA
Giovanni Liguori, MPI for Biogeochemistry, Jena, Germany
Giovanni Liguori, École Normale Supérieure, Paris, France
Jan Jaap Meijer, Max Planck Institute for Meteorology, Hamburg, Germany
Helen Phillips, LOCEAN/CNRS/IFREMER/LEGOS/IRD, France
Andy Pitman, Nanjing University, Nanjing
Saurabh Rathore, Niels Bohr Institute, University of Copenhagen, Denmark
Nina Ridder, National and Kapodistrian University of Athens, Greece
Nina Ridder, POSTECH, Pohang, Korea
Michael Roderick, Max Planck Institute for Meteorology, Hamburg, Germany
Michael Roderick, British Antarctic Survey, Cambridge, UK
Robert Ryan, Max Planck Institute Retreat, Fintel, Germany
Manon Sabot, University of Exeter, UK.
Steven Sherwood, UK Met Office, Exeter, UK
Anna Ukkola, UCLA, USA
Claire Vincent, University of Bergen, Norway

INBOUND TRAVEL



OUTBOUND TRAVEL



Governance, Committees and Operations

Governance and Management

Centre Advisory Board

The Australian Research Council Centre of Excellence for Climate Extremes (CLEX) is overseen by an Advisory Board, which is chaired by distinguished scientific leader Dr Tony Press. The Centre Advisory Board provides strategic oversight and advice to the Centre of Excellence as well as monitoring the Centre's performance against its stated Key Performance Indicators. The Advisory Board met in person in March 2019 and maintained regular communication throughout the year.

2020 will see a renewal of the Board as a number of existing members move on from their substantive roles. CLEX is grateful to Dr Helen Cleugh, Chris Johnston and Dr Peter May for the invaluable support and learned advice they provided during their time as members of the Centre Advisory Board.

Advisory Board Members in 2019

Dr Tony Press, Adjunct Professor, UTAS, Antarctic Climate and Ecosystems Cooperative Research Centre (Chair)

Dr Tony Press is an adjunct professor at the Antarctic Climate and Ecosystems Cooperative Research Centre, where he served as its chief executive officer from 2009 – 2014. Dr Press has had a long career in science, natural resource management, public administration and international policy.

Dr Press chaired the Antarctic Treaty's Committee for Environmental Protection (CEP) from 2002 to 2006. He was Australia's representative to the CEP and Alternative Representative to the Antarctic Treaty Consultative Meetings from 1999 to 2008, and Australia's Commissioner for the Convention on the Conservation of Antarctic Marine Living Resources from 1998 to 2008.

Dr Helen Cleugh, Director, CSIRO Climate Science Centre

Dr Helen Cleugh is an atmospheric scientist with almost 30 years' experience combining research discovery, delivery and leadership. Her research expertise lies in quantifying the interactions between the land surface and the atmosphere, and their effects on weather, climate and hydrology and water use; and carbon uptake.

Dr Cleugh is currently the Director of the CSIRO Climate Science Centre (CSC). The CSC collaborates closely with national and international research partners to deliver knowledge and information products and services to a broad community of research and end-users.

Professor Ana Deletic, Pro-Vice Chancellor Research UNSW

Professor Ana Deletic is Pro Vice-Chancellor (Research) at the University of New South Wales. Dr Deletic leads a large research group that is working on multi-disciplinary urban water issues, focusing on stormwater management and socio-technical modelling. Earlier she led the development of a number of green nature-based water treatment systems which are now widely adopted in Australia and abroad. Dr Deletic is a fellow of Engineers Australia and the Australian Academy of Technological Sciences and Engineering, and Editor of Water Research. In 2012, the Victorian State Government awarded Dr Deletic the Victoria Prize for Science and Innovation (Physical Sciences) for her lifelong achievements in stormwater research.

Ian T. Dunlop, Independent Advisor & Commentator, Climate Change & Energy

Ian Dunlop is a Cambridge educated engineer, formerly a senior executive in the international oil, gas and coal industries. He chaired the Australian Coal Association in 1987-88. From 1998-2000 he chaired the Australian Greenhouse Office Experts Group on Emissions Trading, which developed the first emissions trading system design for Australia. From 1997-2001 he was chief executive officer of the Australian Institute of Company Directors. Ian has a particular interest in the interaction of corporate governance, corporate responsibility and sustainability.

He is a director of Australia 21, a fellow of the Centre for Policy Development and a member of The Club of Rome. He advises and writes extensively on governance, climate change, energy and sustainability.

Dr Greg Holland, Willis Senior Scientist Emeritus, National Center for Atmospheric Research, Boulder, USA

Dr Greg Holland is Willis Senior Scientist Emeritus at the US National Center for Atmospheric Research (NCAR). He is also a member of the Zurich Insurance Advisory Council for Catastrophes and a key stakeholder for the European ISIpedia. Dr Holland was previously director of NCAR's Earth System Laboratory and the Capacity Center for Climate and Weather Extremes. He has served on a number of committees and review boards for the National Oceanic and Atmospheric Administration, the US National Academies, and NASA — and he chaired the Tropical Meteorological Program of the World Meteorological Organization (WMO) for 12 years.

Dr Holland's current research focuses on climate variability and change and its effect on weather and climate extremes. He holds a PhD in Atmospheric Science from Colorado State University. He is a fellow of both the American Meteorological Society and the Australian Meteorological and Oceanographic Society.

Chris Johnston, Assistant Secretary Climate Change Policy branch, Department of the Environment and Energy

Chris Johnston is the Assistant Secretary of the Climate Change Policy branch in the former Commonwealth Department of the Environment and Energy (DEE). His duties in this role include responsibility for climate change science and adaptation policy. Chris Johnston has held a number of senior positions across the DEE and the Department of Climate Change and Energy Efficiency, including in the areas of renewable energy, heritage, budget strategy and communications. He has also worked on climate change and environment policy in the Department of the Prime Minister and Cabinet.

Dr Peter May, Head of Research, Bureau of Meteorology

Now its Head of Research, Dr Peter May joined the Bureau of Meteorology (BoM) in 1990 as a research scientist, and has since overseen the development of the operational systems that underpin BoM services as well as major projects delivering climate information to the nation. He serves on a number of advisory committees and represents BoM on major national and international committees. He is presently a member of the World Meteorological Organization (WMO) Commission of Atmospheric Science Management Committee that oversees WMO weather and environmental research coordination.

Dr Jon Petch, Head of UK Meteorological Office Science Partnerships

As Head of UK Meteorological Office Science Partnerships, Dr Jon Petch is responsible for the UK Met Office's national and international relationships with other science organisations. Dr Petch has worked on physical modelling and parameterizations since joining the UK Met Office in 1997. From 2009, in parallel with the science research, he has also managed various science collaborations on behalf of the UK Met Office.

Dr Petch continues to carry out research in areas related to atmospheric processes and parameterizations, and leads the Global Atmospheric System Studies project.

Matt Riley, Director, Climate and Atmospheric Science, NSW Office of Environment and Heritage – Department of Primary Industries and the Environment

Matthew Riley is Director of Climate and Atmospheric Science at the NSW Office of Environment and Heritage (OeH). He is also the Director for the NSW and ACT Regional Climate Modelling Project (NARCliM), and leads OeH's Climate Change Impacts Research Program. In addition, he is responsible for the operation of the 43 monitoring stations of the NSW Air Quality Monitoring Network and leads the NSW Government's air quality research program. He has over two decades of experience in urban meteorology, climatology and air-quality measurement.

Centre Executive

The Centre Executive is composed of the Centre Director, who carries overall responsibility for day-to-day leadership of the Centre and its research; the Deputy Director; the Director of Engagement Impact and Partnerships; the Chief Operations Officer; the Research Development Director; and the Manager of the Computational Modelling Support team.

Each of the Centre's research programs has a pair of co-leaders who set and monitor yearly and longer-term research priorities. All Chief Investigators meet monthly by zoom to discuss Centre business and cross-nodal research activity and initiatives.

Centre Committees

To maximise the Centre's effectiveness as a cohesive entity, we have established three key committees that report to the Centre Executive, each with an important and specific remit to enhance the collaboration across the Centre and drive focus in key areas of our Centre strategy; namely, equity and diversity, outreach and pathways-to-impact, and infrastructure and technology.

Diversity and Culture Committee

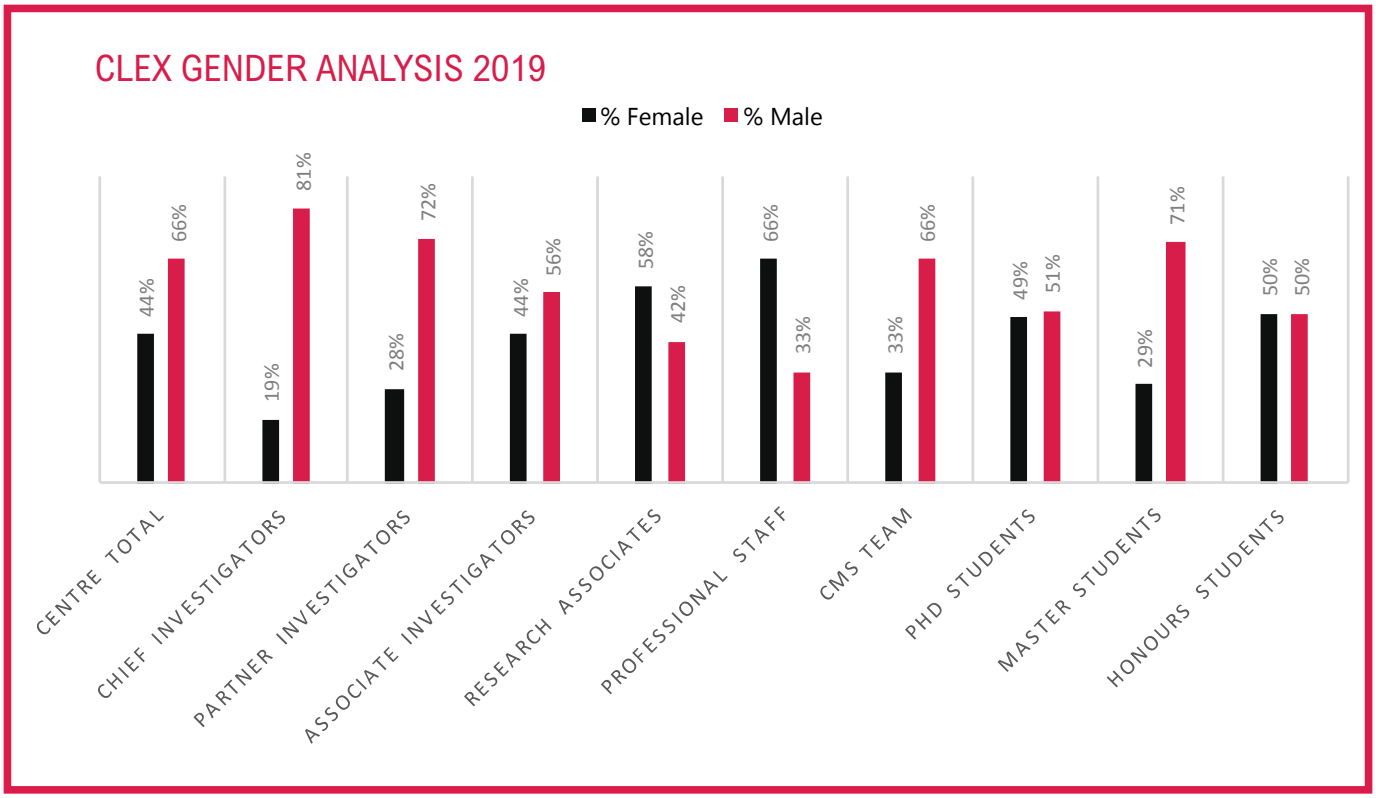
Chairs: Melissa Hart (UNSW) and Stephen Gray (UNSW)

Members: Mike Roderick (ANU), Steven Sherwood (UNSW), Claire Vincent (U. Melb), Julie Arblaster (Monash), Chen Li (Monash)

The ARC Centre of Excellence for Climate Extremes (CLEX) is committed to providing an unrivalled working environment for its students and staff. Consequently, we're committed to implementing measures that enhance the diversity of our staff and student populations and proactively ensuring we build and maintain an equitable culture. To this end, the Centre has established a Diversity and Culture Committee (DCC).

The committee provides advice and recommendations to the Centre Director and Centre Executive on matters pertaining to equity, diversity and Centre culture. The committee leads Centre-wide initiatives and drafts policies and procedures within its sphere of influence. The DCC's activities are based on research and on benchmarking of best practice in the equity, diversity and culture landscape in Science, Technology, Engineering and Mathematics (STEM) and in higher education generally.

In 2019 the committee was active in pursuing these goals via visible initiatives and continually advocating within the Centre for the importance of making equity, diversity and inclusion (EDI) core to the Centre's fabric. Highlights of the year include:



- Finalisation and distribution of the Centre's equity plan
- Launching and awarding the inaugural CLEX Career Development Award for women and people from other under-represented groups, valued at $10,000
- Distributing enormously popular weekly emails on wellbeing and EDI topics (aka "Hump Day Tips")
- Updating the Centre's event code of conduct and response plan
- Running a kindness-in-science exercise at the CLEX annual workshop dinner

Soliciting agreement from all Chief Investigators to adhere to the principles of the Panel Pledge to ensure greater visibility of women at scientific conferences, workshops and meetings https://malechampionsofchange.com/commit-to-the-panel-pledge/.

Infrastructure Committee

Chair: Gab Abramowitz (UNSW)

Members: Nathan Bindoff (UTAS), Claire Carouge (UNSW), Dietmar Dommenget (Monash), Jason Evans (UNSW), Andy Hogg (ANU), Neil Holbrook (UTAS) and Craig Bishop (U. Melb)

The CLEX Infrastructure Committee's primary role is to aid the Computational and Modelling Support (CMS) team in the prioritisation and delivery of the services it provides. This includes engaging in the decision-making process around which modelling systems and data sets should be considered in or out of scope, as well as identifying emerging modelling systems or data sets that offer new opportunities for CLEX. The committee is also tasked with helping the CMS team allocate, compute and store resources to CLEX research programs, as well as helping manage the relationship with National Computational Infrastructure and other relevant National Collaborative Research Infrastructure Strategy capabilities.

These roles are intended to help maintain strong communication between CLEX researchers and the CMS team, as well as support the CMS team in prioritising competing requests for its time.

This year the committee discussed issues such as:

- negotiation and communication around the CLEX transition to the Gadi supercomputer
- prioritisation of requests for in-depth CMS team engagement with new modelling capabilities
- prioritisation of new data set hosting
- strategies for improving the efficiency of existing storage
- management of resource allocation transfers from ARCCSS to CLEX
- strategies for managing increased demand with finite resources as CLEX projects increase their requirements over time
- development and communication of best practice 'housekeeping' guidelines for researchers to maximise available resources to active research projects.

Outreach Committee

Chair: Peter Strutton, UTAS

Members: Nerilie Abram (ANU), Dietmar Dommenget (Monash), Christian Jakob (Monash), Ian Macadam (UNSW), Amelie Meyer (UTAS), Alvin Stone (UNSW)

The CLEX Outreach Committee (OC) contributes to the Centre's aim to "use our new knowledge and new capability to bridge from our science to impact, by working with stakeholders to reduce Australia's vulnerability to climate extremes." The committee works closely with the Knowledge Brokerage Team (KBT), led by Dr Ian Macadam.

In 2019, the committee and KBT invested considerable effort into evaluating options for school outreach that are consistent with the Centre's Key Performance Indicators and KBT budget. This has culminated in two efforts: a workshop to engage high school teachers with researchers at the 2020 meeting of the Australian Meteorological and Oceanographic Society, and an evaluation of how best to improve the Monash Simple Climate Model for broader high school engagement. The KBT is also exploring the possibility of CLEX visiting teacher fellowships.

A growing area of activity in 2019 was the production of Briefing Notes on timely aspects of climate science or topical, high-profile publications from CLEX. These have been produced by the KBT with input from the OC, highlighting the role of the committee as a sounding board for KBT activities. These Briefing Notes are disseminated to stakeholders such as Federal and State Governments, National Environmental Science Program hubs (Earth Systems and Climate Change Science, Clean Air and Urban Landscapes) and organisations such as Risk Frontiers and the Managing Climate Variability Program. As they evolve, the OC and KBT aim to hone the way in which they are pitched.

Moving forward, the committee and KBT look forward to developing deeper CLEX engagement with state governments and industry, in areas of emerging climate challenges.

Centre Business Team

The transformative research that the ARC Centre of Excellence for Climate Extremes (CLEX) continues to deliver is supported by a dedicated team of professional staff.

Stephen Gray is the Centre's Chief Operations Officer and brings extensive ARC Centre of Excellence management experience to the role. He is supported by Vilia Co in the role of Finance and Resources Manager. The operations team is further comprised of Executive Assistants Jenny Rislund (UNSW), Sook Chor (Monash), Christine Fury (UTAS) Alina Bryleva (ANU) and Karla Fallon (U.Melb).

In addition to the underpinning work of the CLEX business team, our Media and Communications Manager Alvin Stone (UNSW) continues his superb work of profiling the Centre's research and generously sharing his time and expertise with other communicators in the national Centres of Excellence community. Our Knowledge Brokerage Team is responsible for the translation of the Centre's research to a range of end users.

You can read more about the great outcomes emerging from the work of Dr Ian Macadam and Dr James Goldie elsewhere in this report.

Leadership Development

As is evident from the Researcher Development Program chapter that follows, we are strongly committed to providing leadership training, guidance and opportunities for all ARC Centre of Excellence for Climate Extremes (CLEX) researchers, including our students and Early Career Researchers (ECRs) and our professional and technical staff.

CLEX is unique among Australian Centres of Excellence in appointing a dedicated, full time senior Graduate Director to build a fully integrated leadership and professional development program for our staff and students.

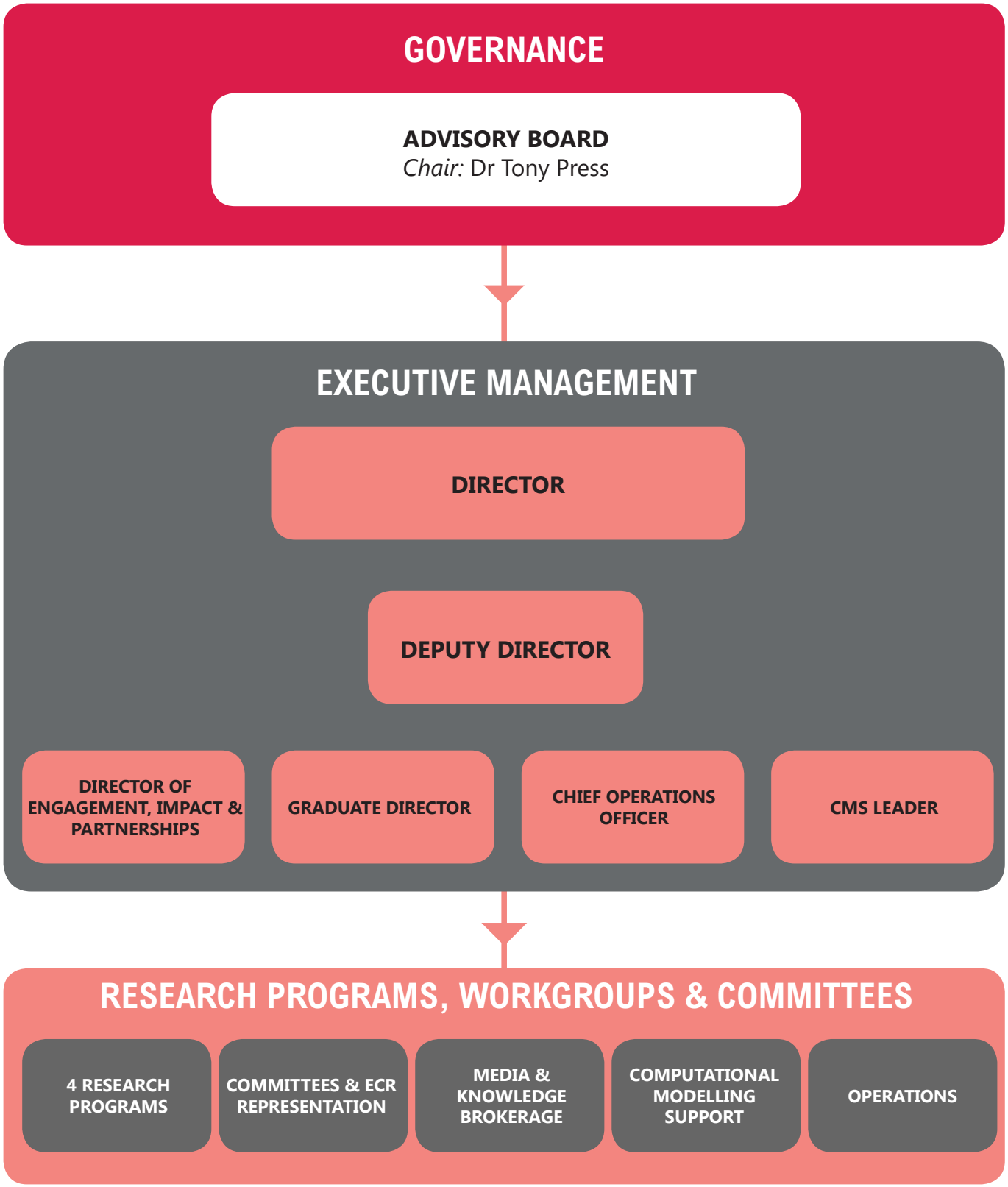
Furthermore, our students and ECRs are represented via our Early Career Researcher Committee (ECRC), with an ECR representative attending Centre Executive meetings. Our ECRC also organises ECR professional development and training events, including dedicated ECR events at national Australian Meteorological and Oceanographic Society annual meetings, and helps facilitate dedicated ECR funding applications that enable our ECRs to lead small projects that expand beyond the scope of their research programs.

Equity and Diversity

The ARC Centre of Excellence for Climate Extremes fosters a culture of diversity and inclusion. Our goal is to make the Centre a progressive organisation that enables all staff and students, regardless of background, to do their best work in a professional and compassionate environment. Our equity plan is an ambitious document to guide the Centre's efforts to fulfil our aim of being an exemplar in this space. We are serious about creating a respectful research environment for our diverse population of researchers to ensure our staff and students can reach their full potential, and about making a meaningful contribution to addressing historical prejudices and inequality in Science, Technology, Engineering and Mathematics (STEM) disciplines.

As noted earlier in this section, the Centre's Diversity and Culture committee spearheaded a range of initiatives in 2019 by way of implementing the three key objectives of the CLEX equity plan. Those objectives cover recruitment; inclusivity; and wellbeing and culture.

Organisational Chart



Director

Professor Andy Pitman
University of New South Wales

Deputy Director

Professor Todd Lane
University of Melbourne

Graduate Director

A/Professor Melissa Hart
University of New South Wales

Chief Operations Officer

Stephen Gray
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Australian national University

Dr Gab Abramowitz
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Professor Lisa Alexander
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A/Professor Julie Arblaster
Monash University

Professor Nathan Bindoff
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University of Tasmania

Professor Christian Jakob
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Professor Michael Roderick
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*Indicates submission in 2019

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Xihan Zhang*
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Ca**llum Shaw**
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Zimeng Su*
UTAS

Yuxin Wang
UTAS

Ziyan Zhang*
UTAS

Chief Investigator Biographies

Prof Andy Pitman

Director, ARC Centre of Excellence for Climate Extremes

Professor Andy Pitman was born in Bristol and was awarded a bachelor's degree with honours in physical geography and a PhD in Atmospheric Science by the University of Liverpool, UK. He also holds a Postgraduate Certificate in Educational Leadership from Macquarie University. He has been at the University of New South Wales since 2007. He was the director of the ARC Centre of Excellence for Climate System Science (2011-2017) and is now Director of the ARC Centre of Excellence for Climate Extremes.

Prof Pitman's research focus is on terrestrial processes in global and regional climate modelling, model evaluation and earth systems approaches to understanding climate change. His leadership, collaboration and research experience is extensive both nationally and internationally. Between 2004 and 2010 he convened the ARC Research Network for Earth System Science, which facilitated interaction between individuals and groups involved in climate system science. He is a member of the Australian Community Climate and Earth System Simulator initiative, the Academy of Science's National Committee for Earth System Science, and the NSW Minister for Climate Change's Science Advisory Committee. He is also heavily engaged in e-research, including most recently on the taskforce assessing the roadmap for national research infrastructure.

Internationally, Prof Pitman is closely affiliated with the World Climate Research Programme (WCRP). He was a long-term member and former chair of the WCRP's Land Committee for the Global Land Atmosphere System Study. As co-chair, he jointly led one of the first major international intercomparison exercises: the Project for the Intercomparison of Land Surface Parameterization Schemes, which is supported by WCRP and the International Geosphere Biosphere Programme. He also sat on the Science Steering Committee of the Integrated Land Ecosystem-Atmosphere Processes Study and is currently Co-coordinator of the Land Use Change: Identification of Robust Impacts project.

Prof Pitman is a regular invitee for keynote presentations and is a passionate communicator about science, contributing regularly to the media on the science of climate change. He was a Lead Author for Intergovernmental Panel on Climate Change (IPCC) Assessment Reports 3 and 4, contributing to the award of the Nobel Peace Prize to the IPCC in 2007. He was Review Editor of the 2013 IPCC report. He has also contributed to the Copenhagen Diagnosis, an Australia-led update of the science of climate change. He has held editorial positions with the *Journal of Climate* and the Annals of the Association of American Geographers' *Journal of Geophysical Research-Atmospheres*, and is currently an associate editor for the International *Journal of Climatology*.

Awards and accolades received by Prof Pitman include: NSW Scientist of the Year Award (2010), the Australian Meteorological and Oceanographic Society (AMOS) Medal (2009), the Dean's Award for Science Leadership at Macquarie University (2005), the Priestley Medal for Excellence in Atmospheric Science Research (2004) and the Geoff Conolly Memorial Award (2004). He jointly won the International Justice Prize for the Copenhagen Diagnosis (2010) and was among Sydney Magazine's list of the 100 most influential people (2010). He is a fellow of AMOS and of the American Meteorological Society.

Prof Pitman has a long track record of nurturing early career researchers and has supervised multiple PhD students through to successful completion. He has published over 200 papers in peer-reviewed journals and has authored 20 book chapters.

Prof Todd Lane

Deputy Director, ARC Centre of Excellence for Climate Extremes

Professor Todd Lane was awarded his PhD in Applied Mathematics from Monash University in 2000, having completed his bachelor's degree in 1997. He was a post-doctoral fellow with the National Center for Atmospheric Research (USA) from 2000-2002 and a staff scientist from 2003-2005. He joined the University of Melbourne in 2005, where he is now Professor in the School of Earth Sciences. Between 2010-2014 he was an ARC Future Fellow.

Prof Lane's primary research focus is on atmospheric processes. He is internationally recognised as an expert on tropical thunderstorms, atmospheric waves, and turbulence. He has made important contributions to many aspects of mesoscale meteorology, convective cloud dynamics, and high-resolution atmospheric modelling. His research within the Centre is focused on extreme rainfall and involves the use of high-resolution cloud and weather prediction models to determine the processes controlling rainfall extremes, and to better predict them. Of particular emphasis is the formation of organised convective systems and their roles in rainfall extremes.

Prof Lane has held numerous leadership positions, including president of the Australian Meteorological and Oceanographic Society (2014-2015), chair of the American Meteorological Society's Committee on Mesoscale Processes (2012-2015), and editor of *Monthly Weather Review* (2016-2018). He has received awards from the American Meteorological Society, the Australian Academy of Science, and NASA; and he is a fellow of the Australian Meteorological and Oceanographic Society.

A/ Prof Melissa Hart

Graduate Director of the ARC Centre of Excellence for Climate Extremes

Associate Professor Melissa Hart used her former role as graduate director of the ARC Centre of Excellence for Climate System Science to lead and develop a national, cross-institutional graduate program which reimagined the traditional Australian PhD. She continues this work as Graduate Director overseeing the Researcher Development Program at the ARC Centre of Excellence for Climate Extremes. With a vital combination of breadth, depth, support and collaboration, both of these graduate programs have provided more than 120 graduate students with the skills, knowledge, and experience fundamental to developing world-leading climate science researchers.

A/Prof Hart completed her Bachelor of Science (Hons) in 2001 and her PhD in Atmospheric Science in 2006, at Macquarie University. During her PhD studies she worked part-time at the well-respected air quality consultancy, Holmes Air Sciences (now Pacific Environment).

She then spent two years as a postdoctoral researcher at Portland State University, Oregon, working on the National Science Foundation-funded FUSE (Feedback between Urban Systems and the Environment) project. This was followed by five years in a faculty position in the Department of Geography, the University of Hong Kong, China.

A/Prof Hart's main research focus is in the area of urban climate, in particular the impact of land-use, surface characteristics and anthropogenic activities on the climate of cities, and quantification of the magnitude of the Urban Heat Island. She is also working in the area of air pollution meteorology, in particular, air pollution impacts from hazards reduction burns.

A/Prof Hart holds an honorary position in the Department of Geography, the University of Hong Kong, and is a member of the Science Advisory Panel for ClimateWatch Hong Kong and China, and of the Bureau of Meteorology's Course Advisory Committee.

Prof Nerilie Abram
Chief Investigator

Professor Nerilie Abram uses palaeoclimate records to study how Earth's climate has behaved in the past, to provide a long-term perspective on recent climate change.

She has a particular focus on reconstructing climate variability in the tropical Indian Ocean and Antarctica, and how this impacts Australia's rainfall patterns. Her work also involves proxy-model comparisons to assess forcing mechanisms behind natural and anthropogenic climate changes, and to help test climate model performance in historical and last millennium experiments.

Prof Abram holds an ARC Future Fellowship. In 2015 she received the Dorothy Hill Award from the Australian Academy of Science for her research achievements. She was Coordinating Lead Author of the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, released in September 2019.

Dr Gab Abramowitz
Chief Investigator

Dr Abramowitz's primary research interest is model evaluation in climate science, ecology and hydrology. Currently his research focuses on two main areas: model dependence in multi-model ensemble climate prediction and the standardisation of model evaluation in land surface research.

Climate research teams share literature, data sets and even sections of model code. Among the questions Dr Abramowitz considers are T*o what extent do different climate models constitute independent estimates of a prediction problem? What is the most appropriate statistical framework with which to define independence? What are the implications of ignoring model dependence?*

Dr Abramowitz is also leading the development of modelevaluation.org, a web application that provides automated land surface, hydrological and ecological model evaluation tools as well as observational data sets.

He co-chairs the Global Energy and Water Cycle Experiment's Global Land-Atmosphere System Study panel.

Prof Lisa Alexander
Chief Investigator

Professor Lisa Alexander holds a Bachelor of Science, a Master of Science in Applied Mathematics and a PhD from Monash University. Between 1998 and 2006 she worked as a research scientist at the UK Meteorological Office – Hadley Centre, with a year on secondment at Australia's Bureau of Meteorology.

Prof Alexander's primary research focuses on understanding the variability and driving mechanisms of climate extremes. Of particular significance is her ongoing work assessing global changes in temperature and rainfall extremes, which has contributed significantly to the Intergovernmental Panel on Climate Change (IPCC) assessments.

She was awarded the 2011 Priestley Medal by the Australian Meteorological and Oceanographic Society and the 2013 Australian Academy of Science Dorothy Hill Award for her contribution to this field of research. She contributed to the IPCC assessments in 2001 and 2007 and to the 2012 Special Report on Extremes and was a Lead Author of the IPCC's 5th Assessment Report.

Prof Alexander also chairs a World Meteorological Organization Commission for Climatology Expert Team and is Co-chair of the World Climate Research Programme Grand Challenge on Extremes.

A/ Prof Julie Arblaster
Chief Investigator

Julie Arblaster is an associate professor in the School of Earth, Atmosphere and Environment at Monash University, having moved there in 2016 after many years at Australia's Bureau of Meteorology and the National Center for Atmospheric Research (NCAR), USA, before that.

Associate Professor Arblaster's research interests lie in using climate models as tools to investigate mechanisms of recent and future climate change, with a focus on shifts in the Southern Hemisphere atmospheric circulation, tropical variability and climate extremes. She is particularly interested in the interplay between the predicted recovery of the Antarctic ozone hole over coming decades and greenhouse gas increases in future climate projections, with its potential impacts on the surface, ocean circulation and sea ice. Recent work has also focused on explaining extreme events in Australia, such as record-breaking temperatures and rainfall, from a climate perspective, both in terms of the role of human influences and the diagnosis of the climate drivers.

A/Prof Arblaster's research incorporates the use of observations, multi-model data sets and sensitivity experiments with a single model. Her strong collaboration with NCAR and participation in various international committees and reports enhances her engagement with the latest advances in climate research internationally.

A/Prof Arblaster was awarded the 2014 Australian Academy of Science Anton Hales Medal for research in earth sciences and the 2018 Priestley Medal from the Australian Meteorological and Oceanographic Society. She was an active member of the World Climate Research Programme's Stratosphere-troposphere Processes and their Role in Climate scientific steering group from 2011-2016 and served as a Lead Author of the IPCC's 5th Assessment Report. She was also a lead author on the latest World Meteorological Organization/United Nations Environment Programme Scientific Assessment of Ozone Depletion report. A/Prof Arblaster is a member of the National Climate Science Advisory Committee and the National Committee on Earth System Science.

Prof Nathanial Bindoff
Chief Investigator

Professor Bindoff is a physical oceanographer, specialising in ocean climate and the earth's climate system, with a focus on understanding the causes of change in the oceans.

Prof Bindoff was the Coordinating Lead Author for the Oceans chapter in the Intergovernmental Panel on Climate Change (IPCC) 4th and 5th Assessment Reports (AR4 & AR5). He contributed to the IPCC's winning of the Nobel Peace Prize in 2007, shared with Al Gore, and is now a Coordinating Lead Author of the Detection and Attribution chapter in the IPCC's AR5.

He and colleagues documented some of the first evidence for changes in the Indian, North Pacific, South Pacific and Southern oceans and the first evidence of changes in the Earth's hydrological cycle from ocean salinity. His current interests are primarily in understanding how the changing ocean can be used to infer changes in atmosphere and whether these changes can be attributed to rising greenhouse gases and for projecting future changes and its impacts on regional climates. He led the Climate Futures for Tasmania project for the study of impacts of climate change on Tasmania.

Prof Bindoff's most recent work is on documenting the decline in oxygen content of the oceans. He has also worked in the Antarctic, to determine the total production of Adelie Land Bottom Water formation and its contribution to Antarctic Bottom Water Formation and its circulation. His group has contributed to the development of some of the largest and highest-resolution model simulations of the oceans for the scientific study of mixing in the oceans.

Prof Bindoff has served on 14 international committees, been the invited speaker at 22 conferences and workshops and co-chaired two workshops. He was guest editor on two special volumes of *Deep Sea Research*, and convened the Oceans session of the Climate Change Congress, Copenhagen, March 2009. He has published more than 100 scientific papers, seven book chapters and eight conference papers and 43 reports. He has a H index of 39 and greater than 10000 citations (Google Scholar).

Prof Craig Bishop
Chief Investigator

Professor Craig Bishop was born in Melbourne and was awarded a bachelor's degree with honours and a PhD in Applied Mathematics from Monash University.

Prof Bishop's innovative ensemble-based data assimilation and ensemble-forecasting techniques are now used by leading environmental forecasting agencies such as the European Centre for Medium Range Weather Forecasting, the UK Meteorological Office, the German weather service, the Swiss weather service, the US National Weather Service, the US Navy and the Japanese, Korean and Brazilian meteorological agencies.

After completing his PhD Prof Bishop was a postdoctoral researcher at the University of Reading, where he was awarded the Royal Meteorological Society's L.F. Richardson Prize for his PhD work on the dynamics of baroclinic waves in deformation fields. He then worked as a visiting scientist at the NASA Goddard Space Flight Center, where he received the Universities Space Research Association 1994 Excellence in Scientific Research Award. This was followed by an appointment to the faculty of the Pennsylvania State University's prestigious Department of Meteorology – then the largest atmospheric science department in the US. There he was granted early tenure and promotion. However, to obtain a better understanding of the operational weather prediction problem, he left Penn State for the Marine Meteorology Division of the Naval Research Laboratory (NRL) in Monterey, California. There he was awarded six outstanding contribution awards, three NRL Alan Berman publication awards, and one NRL Edison Patent Award. He returned to Australia as Professor of Weather Prediction at the University of Melbourne in June 2018.

Prof Bishop's current research mainly focuses on the data assimilation science of using models, observations and advanced estimation theory to initialise ensemble forecasts and to identify and account for systematic and stochastic aspects of model error in ensemble forecasting.

Prof Bishop is a founding co-chair of the World Meteorological Organization's Working Group on Predictability, Dynamics and Ensemble Forecasting. He is an associate editor of the *Quarterly Journal of the Royal Meteorological Society*. He served as chair of the Science Steering Committee of the Joint (NASA, National Oceanographic and Atmospheric Administration, US Navy, US Air Force, National Science Foundation) Center for Satellite Data Assimilation from 2007 to 2010. He was elected to the International Commission on Dynamical Meteorology in 2010 and as a fellow of the American Meteorological Society in 2012. In 2015, he served as the PhD student-elected distinguished visiting scientist of the University of Reading's internationally renowned Department of Meteorology.

A/Prof Dietmar Dommenget
Chief Investigator

Associate Professor Dietmar Dommenget completed his Diploma (MSc.) in Physics at the University of Hamburg. He started studying climate dynamics and climate model development at the Max Planck Institute for Meteorology in 1996 and finished his PhD in 2000.

A/Prof Dommenget joined the ECCO (Estimating the Circulation and Climate of the Ocean) project in a postdoctoral position at the Scripps Institution of Oceanography in La Jolla, California, to study the predictability of El Niño in a joint observational data assimilation scheme. After three years in California he returned to Germany in 2003 for a fixed-term faculty position as a lecturer in the Meteorology Department at the Helmholtz Centre for Ocean Research in Kiel.

Since 2010 A/Prof Dommenget has been Senior Lecturer at Monash University in the atmospheric and climate science group of the School of Earth, Atmosphere and Environment. His research focuses on large-scale climate dynamics. He works with climate models at all levels of complexity. Most of his work centres on the development, conducting and analysis of coupled general-circulation models, but he has also developed simple conceptual models of natural climate variability.

Most of A/Prof Dommenget's work focuses on sea surface temperature variability in the tropical and extratropical oceans. He is most widely known for his work on the interpretation of patterns and modes of climate variability. His most recent projects focus on El Niño, climate model developments and climate change. A/Prof Dommenget developed a new type of climate model for the conceptual understanding of the climate response to external forcing, which is a fast and simple tool for researchers, students and the public to understand the interactions in the climate system. An outreach program based on this is called the Monash Simple Climate Model.

Prof Matthew England
Chief Investigator

Professor Matthew England obtained his PhD in 1992 from the University of Sydney. He is a former Fulbright Scholar and was a postdoctoral research fellow at the Centre National de la Recherche Scientifique, France, from 1992-1994. He was a research scientist in CSIRO's Climate Change Research Program from 1994-1995 and was a CSIRO Flagship Fellow in 2005. Since 1995, Prof England has been with the University of New South Wales, where he held an ARC Federation Fellowship from 2006-2010. He commenced an ARC Laureate Fellowship in 2011 and is presently Deputy Director of the UNSW Climate Change Research Centre. In 2014 he was elected a fellow of the Australian Academy of Science and in 2016 a fellow of the American Geophysical Union.

Prof England's research explores global-scale ocean circulation and the influence it has on regional climate, large-scale physical oceanography, ocean modelling, and climate processes, with a particular focus on the Southern Hemisphere. Using ocean and coupled climate models in combination with observations, he studies how ocean currents affect climate and climate variability on time scales of seasons to centuries. His work has made significant impact on the treatment of water-mass physics in models, on the methodologies of assessment of ocean and climate models, on our understanding of large-scale Southern Hemisphere climate modes, and on the mechanisms for regional climate variability over Australia.

Prof England has served on two Prime Minister's Science, Engineering and Innovation Council Expert Working Groups (Antarctic and Southern Ocean Science; and Energy-Carbon-Water); the Climate Variability and Predictability (CLIVAR) International Working Group for Ocean Model Development; and the ARC Earth System Science Network board. He was co-chair of the CLIVAR Southern Ocean Region Implementation Panel 2008-2014 and is currently a member of the World Climate Research Programme/CLIVAR/Global Energy and Water Cycle Experiment Drought Interest Group.

He was awarded the Land & Water Australia Eureka Prize for Water Research and the Banksia Foundation Mercedes-Benz Australian Research Award in 2008. In 2007 he received the Royal Society of Victoria Research Medal. Other awards include the Sherman Eureka Prize for Environmental Research (2006); the Australian Meteorological and Oceanographic Society Priestley Medal (2005); the Australian Academy of Science Frederick White Prize (2004); a Fulbright Scholarship (1991-1992); and the University Medal, University of Sydney (1987).

Prof England has authored more than 180 peer-reviewed journal papers. He has been a Contributing Author for two Intergovernmental Panel on Climate Change (IPCC) Assessment Reports. He was the convening lead author of the 2009 Copenhagen Diagnosis. He has supervised more than 20 PhD students through to graduation, and taught more than 3000 undergraduate students. He was an associate editor for *Reviews of Geophysics* 2005-2009 and an associate editor for the *Journal of Climate* 2008-2015.

Prof Jason Evans
Chief Investigator

Professor Jason Evans completed his undergraduate degrees in physics and mathematics at Newcastle University in 1996 and was awarded his PhD in Environmental Management from the Australian National University in 2001. He then spent six years as a postdoctoral and then research fellow at Yale University in the USA. In 2007 he returned to Australia to take up a position in the Climate Change Research Centre at UNSW, where he remains today.

Prof Evans' expertise is in the area of regional climate, land-atmosphere interactions, the water cycle and climate change. His focus is on regional climate change and its impacts.

His research program brings together advanced modelling tools with extensive observational data sets, with an emphasis on satellite-based, remotely sensed earth observations. The research finds new and improved techniques to combine data with regional climate and land-surface models, to help solve problems of national and international significance.

Prof Evans is Co-chair of the Global Energy and Water Exchange's (GEWEX) Hydroclimate Panel and Australasia region coordinator of the Coordinated Regional Climate Downscaling Experiment, both elements of the World Climate Research Programme. He is a Lead Author on the Intergovernmental Panel on Climate Change Special Report on Climate Change and Land, also known as the Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. He has been an editor of the Journal of Climate since 2016.

Prof Evans has been awarded an Australian Research Fellowship and a Future Fellowship from the Australian Research Council. In 2008 he won the Australian Agricultural Industries Young Innovators and Scientists Award, given by the Department of Agriculture, Fisheries and Forestry and Land & Water Australia, for his work on land-atmosphere coupling over irrigation districts. In 2015 he was granted the President's Mid-Career Plenary Lecture by the Modelling and Simulation Society of Australia and New Zealand, in recognition of his contributions to modelling of the regional climate. In 2017 he was a Green Globe Sustainability Champion finalist for his work on regional-scale climate projections and adaptation, as well as the Australian Meteorology and Oceanography Society's Priestley Medal for mid-career excellence in climate and related sciences.

Prof Andy Hogg
Chief Investigator

Professor Andy Hogg completed his undergraduate degree in physics at the Australian National University in 1996 and was awarded his PhD in Geophysical Fluid Dynamics from the University of Western Australia in 2002. He then spent three years as a postdoctoral fellow at the Southampton Oceanography Centre, where he developed a new, high-resolution coupled ocean-atmosphere model. In 2004 he returned to ANU to take up a position as an ARC postdoctoral fellow. He is currently based at ANU's Research School of Earth Sciences.

Prof Hogg's research interests centre on physical processes governing the ocean and climate. His work within the ARC Centre of Excellence for Climate Extremes will be focused on understanding ocean-atmosphere interactions in the Southern Ocean, and particularly the exchange of heat, momentum and carbon between different components of the climate system. He will play a key role in developing tools to understand the climate system at progressively finer scales.

Due to Prof Hogg's unique contributions to understanding of the Southern Ocean, he was awarded the Frederick White Prize from the Australian Academy of Science in 2012, the Nicholas P. Fofonoff Award from the American Meteorological Society and the Australian Meteorological and Oceanographic Society's Priestley Award in 2015.

Prof Neil Holbrook
Chief Investigator

Professor Holbrook uses his background in applied mathematics and physical oceanography, and his expertise in ocean and climate dynamics at seasonal to multi-centennial time scales, to better diagnose the important mechanisms underpinning climate variability and climate change. By developing a strong understanding of natural climate variability on all time scales, his research helps to reduce the uncertainties associated with human-induced (anthropogenic) climate change, as well as the potential risks associated with abrupt climate change and likely changes in climatic extreme events.

Prof Holbrook's 's particular foci are in regional- to large-scale ocean and climate dynamics, climate change detection, attribution and risks. His research activities include the investigation of planetary scale ocean wave dynamics; interannual (in particular, El Niño - Southern Oscillation) to multi-centennial-scale climate variability; climate change; and dynamic/climatic influences on ocean (plankton) productivity. He also has interests in understanding the complex feedbacks in both climate science and climate change adaptation; thermodynamic and statistical modelling of tropical cyclone genesis and intensity; and climate and vector-borne disease. His interdisciplinary interests include both observational and modelling studies. On the modelling side, Prof Holbrook primarily works with simple- to intermediate-complexity ocean and climate dynamic, thermodynamic and ecosystem models. He is one of Australia's original National Greenhouse Advisory Committee PhD scholars, and has been working in climate change science for 20 years.

Prof Holbrook has published extensively in the international literature on the ocean's role in climate, climate variability, climate extremes and climate change. He was awarded leadership of Australia's National Climate Change Adaptation Research Network for Marine Biodiversity and Resources. He is President of the International Association of Meteorological and Atmospheric Sciences/International Union of Geodesy and Geophysics International Commission on Climate, an associate editor of the Australian Meteorological and Oceanographic Journal, and a fellow of the Australian Meteorological and Oceanographic Society. He is also a University of Sunshine Coast/University of Tasmania/Griffith University Collaborative Research Network research leadership fellow (Sustainability, UTAS); a visiting professor at Macquarie University; and an international participant in the South-west Pacific Ocean Circulation and Climate Experiment.

Prof Christian Jakob
Chief Investigator

Professor Christian Jakob was awarded his PhD in Meteorology from the Ludwig Maximilians University, Munich, in 2001. As a research and senior research scientist for the European Centre for Medium-Range Weather Forecasts from 1993 to 2001, he worked on the development and evaluation of the model representation of clouds, convection and precipitation. From 2002 to 2007 he was Senior and Principal Research Scientist at Australia's Bureau of Meteorology, and since 2007 he has been a professor at Monash University. He currently is the Chair of Climate Modelling at Monash's School of Earth, Atmosphere and Environment.

Prof Jakob's experience and current interests are in the development and evaluation of the processes crucial to the energy and water cycles in global atmospheric models. Internationally, he is engaged in many collaborative scientific activities. He is a past co-chair of the World Climate Research Programme's (WCRP) Modelling Advisory Council. He led the prestigious Working Group on Numerical Experimentation from 2008 to 2012 and was the first university-based researcher to be appointed in that position. He was chair of the WCRP's Global Energy and Water Cycle Experiment (GEWEX) Modelling and Prediction Panel from 2007 to 2010. Before that, Prof Jakob successfully led the GEWEX Cloud System Study, in which a group of about 150 scientists collaborated on the development and evaluation of cloud and convection representation in models. He co-led the Tropical Warm Pool International Cloud Experiment in 2006.

As recognition of his prominent position in the climate science field, Prof Jakob was a Lead Author for the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report, Working Group 1. In 2016, his research was recognised by the Ascent Award of the American Geophysical Union's Atmospheric Sciences Section, and he was elected a fellow of the Australian Meteorological and Oceanographic Society (AMOS) in 2018. He was awarded the AMOS Morton Medal in 2019.

Prof Michael Reeder
Chief Investigator

Professor Michael Reeder completed a PhD in Applied Mathematics at Monash University, before holding postdoctoral positions at the University of Munich (Germany) and the NASA Goddard Space Flight Center (USA). He subsequently returned to Monash University as a member of staff, rising through the ranks to professor. Prof Reeder has also held long-term visiting positions at the National Center for Atmospheric Research (USA), the State University of New York at Albany (USA), the University of Reading (UK), and the University of Leeds (UK).

Prof Reeder's research is focused principally on the dynamics of weather producing systems. He has published on a wide variety of topics, including fronts, tropopause folding, extratropical cyclones, Rossby waves, heat waves, tropical cyclones, gravity waves, solitary waves, convection, boundary layers, the Hadley and Walker circulations, the Madden-Julian Oscillation, and bushfires. He has been the principal supervisor for more than 40 graduate students.

Prof Reeder is a past president and a current fellow of the Australian Meteorological and Oceanographic Society (AMOS). He is a winner of the AMOS Distinguished Research Award and the Loewe Prize (Royal Meteorological Society, Australian Branch), and has given the AMOS Clarke Lecture.

Prof Michael Roderick
Chief Investigator

Professor Michael Roderick graduated with a Bachelor of Applied Science in Surveying from the Queensland University of Technology in 1984 and subsequently worked as a surveyor across northern Australia until 1990. He completed a Postgraduate Diploma in Geographic Information Systems at the University of Queensland in 1990. After working with the Department of Agriculture in Perth (1991-1993), he joined Curtin University (CU). He was a lecturer at the School of Spatial Sciences, CU, from 1993-1996 and completed a PhD in satellite remote sensing and environmental modelling at CU in 1994. He joined the Australian National University as a research fellow in 1996 and currently holds a joint appointment as Professor between ANU's Research School of Earth Sciences and Research School of Biology.

Prof Roderick's principle research interests are in environmental physics, climate science, ecohydrology (including plant-water relations), remote sensing and ecological dynamics. He has made major international contributions to understanding the water-energy-carbon linkage.

An advocate of national and international scientific collaboration, Prof Roderick co-instigated and co-organised the first international scientific meeting to address the observed decline in evaporative demand and its implications for the terrestrial water balance, hosted in 2004 by the Australian Academy of Science. He has also acted as an advisor to the US National Science Foundation's program on ecohydrology. From 2001-2006, he led the Theoretical Developments in Carbon Cycle Science program of the Cooperative Research Centre for Greenhouse Accounting.

In 1999, Prof Roderick received the J.B.S. Haldane Prize of the British Ecological Society for research linking water-energy-carbon-nutrients at a leaf scale, and in 2004 he received a Top100 award for his research on evaporation. He was awarded the Australasian Science Prize in 2009 for his research on evaporation and changing water availability. In 2013 he was awarded the John Dalton Medal by the European Geosciences Union for his groundbreaking research on trends in the water cycle. In 2015 Prof Roderick was elected a fellow of the American Geophysical Union for his contributions to the science of evaporation and transpiration, including interpretation of changes in evapotranspiration under global environmental change.

Prof Roderick is also an active supervisor and mentor to emerging scientists. He is currently supervising three PhD scholars, and has seen eight of his PhD scholars graduate since 2001.

Prof Steven Sherwood
Chief Investigator

Professor Steven Sherwood received his bachelor's degree in physics from the Massachusetts Institute of Technology in 1987. He was awarded a Master of Science in Engineering Physics from the University of California in 1991 and a PhD in Oceanography from the Scripps Institution of Oceanography, University of California, in 1995. He carried out postdoctoral research at Victoria University of Wellington (NZ) from 1996-1997 and was a research scientist at the NASA Goddard Earth Sciences and Technology Center from 1998-2000. In 2001 he joined the faculty of Yale University, reaching the rank of professor in 2007. At the beginning of 2009 he moved to Australia, where he is Professor and former director of the Climate Change Research Centre at University of New South Wales.

Prof Sherwood is an established leader in atmospheric science. In particular, he has made significant contributions to the understanding of moisture-related processes in the atmosphere. His areas of study include atmospheric humidity; convective systems; interactions between clouds, air circulation and climate; remote sensing of storms; and observed warming trends. Within the ARC Centre of Excellence for Climate Extremes Prof Sherwood and his team contribute to the research programs in Extreme Rainfall and Climate Variability.

Prof Sherwood was a Lead Author of the chapter on Clouds and Aerosols in the 2013 Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report, Working Group I, and a Contributing Author to the IPCC's previous report in 2007. He also co-authored the first US Climate Change Science Program report, Temperature Trends in the Lower Atmosphere; contributed to The Copenhagen Diagnosis update on the science in 2009 and 2011; and contributed to the National Academy of Science's Climate Science Questions and Answers, published in 2010. He currently serves on the editorial board of Environmental Research Letters, and on the steering committee of the World Climate Research Programme's Grand Challenge on Clouds, Circulation and Climate Sensitivity.

In addition to those international activities, Prof Sherwood has co-authored more than 100 papers published in peer-reviewed journals. Some of these papers have been covered extensively by the international media; for example, his 2005 paper in Science on atmospheric warming, which was named as one of the top 100 scientific discoveries of the year by Discover magazine, and his 2014 study on climate sensitivity, published in Nature.

Awards received by Prof Sherwood include the 2002 National Science Foundation CAREER Award and the 2005 American Meteorological Association's Clarence Leroy Meisinger Award. In 2014 he was a Eureka Prize finalist, and in 2015 he won an ARC Laureate Fellowship. Since 2001, Prof Sherwood has given at least 60 invited presentations at scientific meetings or colloquia worldwide. He has also given many public presentations, including a briefing in the US House of Representatives, television and radio appearances, and public lectures at many venues.

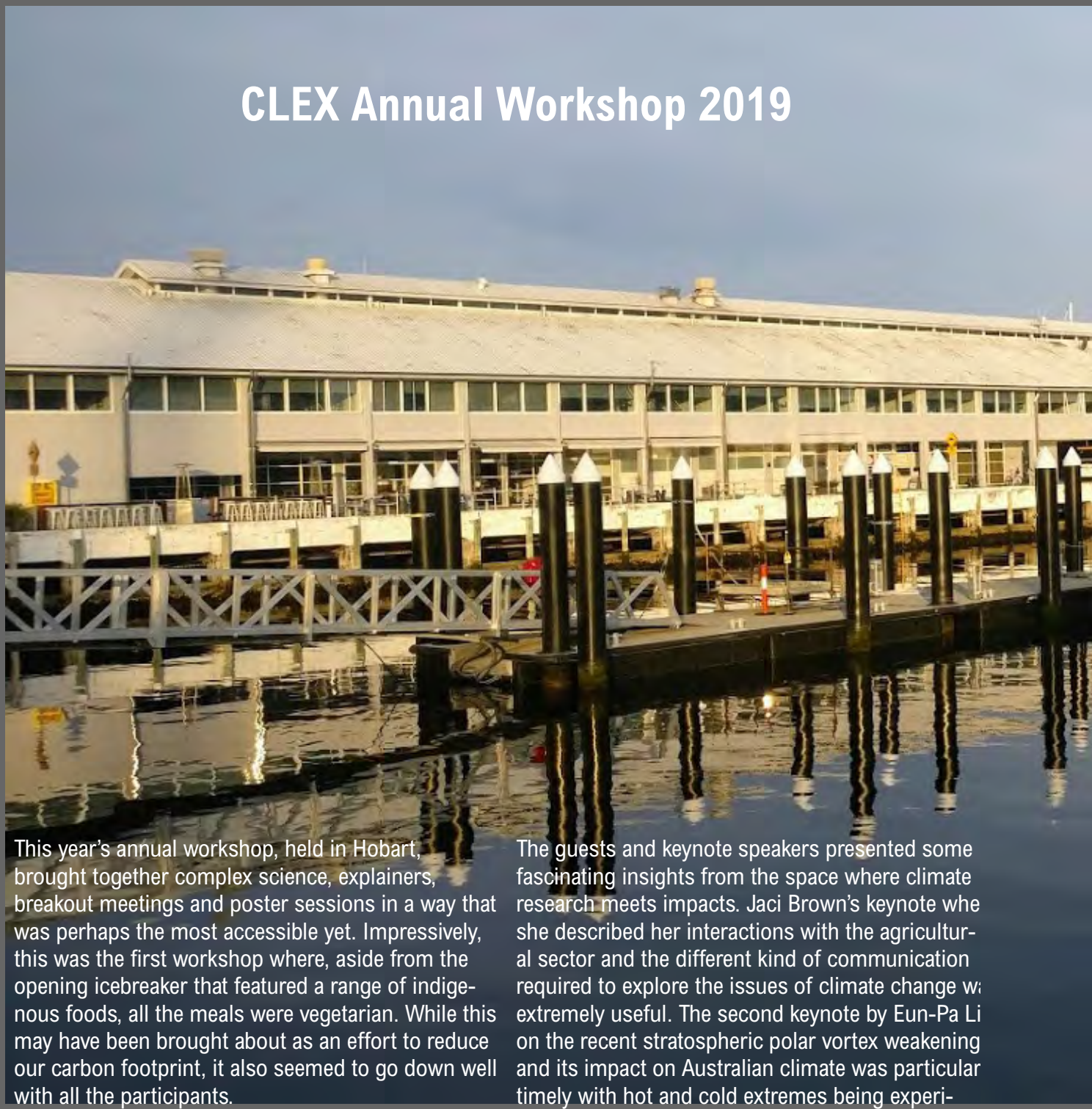
A/Prof Peter Strutton
Chief Investigator

Associate Professor Peter Strutton received his bachelor's degree with honours in marine science from Flinders University of South Australia in 1993. He went on to complete his PhD in Marine Science in 1998. He then left Australia to take up a postdoctoral position with the Monterey Bay Aquarium Research Institute in California, a position he held until 2002. From 2002-2004 he was an assistant professor with the State University of New York's Marine Sciences Research Centre and from 2004-2010 he was an assistant, then associate professor at Oregon State University's College of Oceanic and Atmospheric Sciences. In 2010 he returned to Australia on an ARC Future Fellowship and since then has been Associate Professor at the Institute for Marine and Antarctic Studies, University of Tasmania.

A/Prof Strutton's research focuses on biological oceanography, and his standing as an Antarctic and Southern Ocean scientist is recognised internationally. He has considerable expertise on how modes of variability, such as El Niño and internal ocean waves, affect nutrients in the ocean, biological productivity and carbon cycling. In the ARC Centre of Excellence he contributes to the Climate Variability research program and he is developing projects in the area of marine heatwaves. He concentrates on the drivers of observed changes in biogeochemical cycles, including oxygen, carbon and nutrients.

A/Prof Strutton is an experienced supervisor and mentor of early career researchers. He currently oversees two postdoctoral researchers and several PhD and honours students. He has an extensive publication record that spans Antarctica to the tropical Pacific and the Labrador Sea. He is a past editor for the journal Geophysical Research Letters and former leader of the Bluewater and Climate Node for Australia's Integrated Marine Observing System. A/Prof Strutton also serves on the Scientific Steering Committee and Biogeochemistry Task Team for the redesign of the Tropical Pacific Observing System (tpos2020.org).

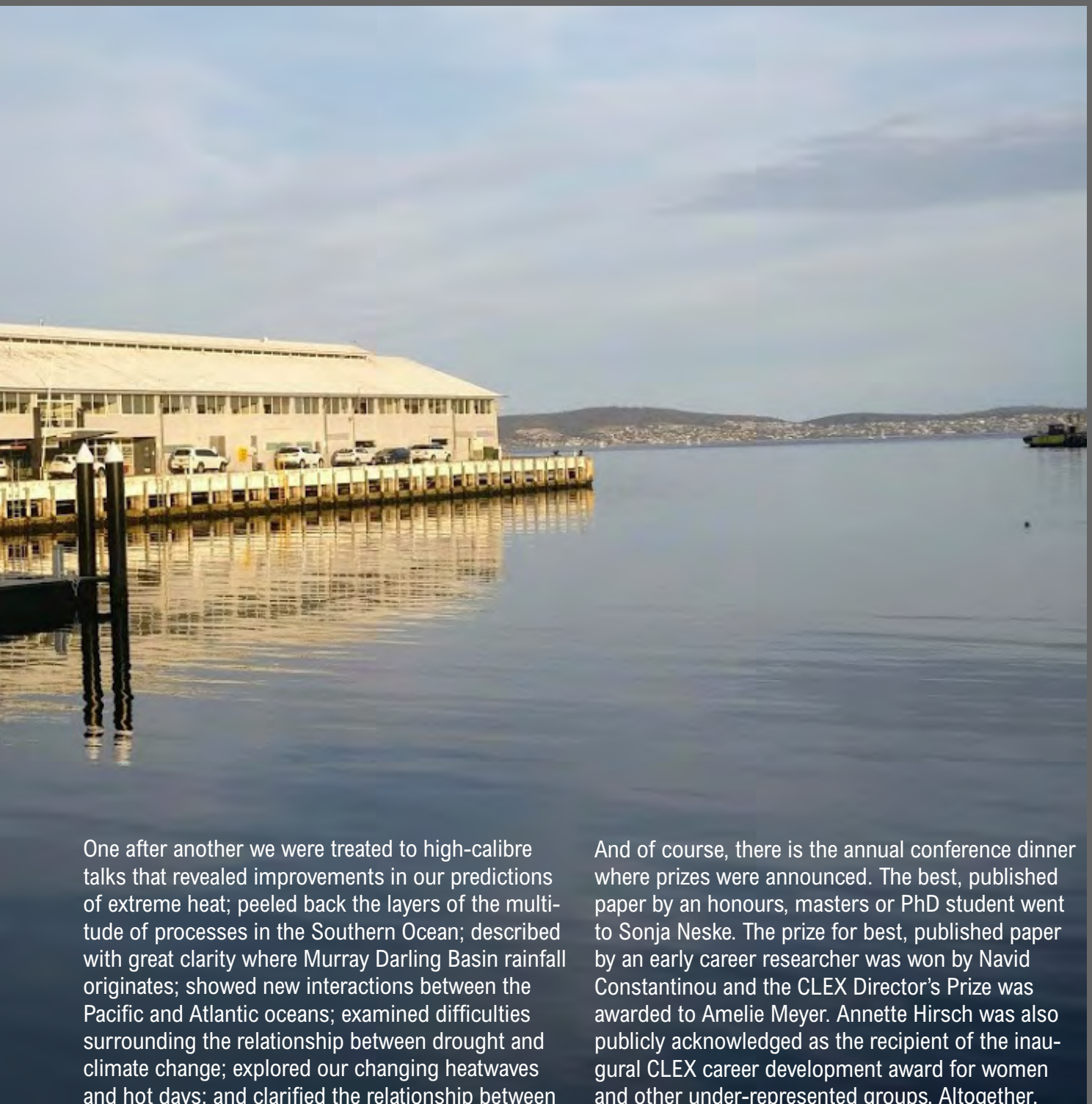
CLEX Annual Workshop 2019



This year's annual workshop, held in Hobart, brought together complex science, explainers, breakout meetings and poster sessions in a way that was perhaps the most accessible yet. Impressively, this was the first workshop where, aside from the opening icebreaker that featured a range of indigenous foods, all the meals were vegetarian. While this may have been brought about as an effort to reduce our carbon footprint, it also seemed to go down well with all the participants.

As always, the heart of the workshop was the science itself. The annual workshops give us an opportunity to see what all the research programs are doing and find those spaces where the programs connect. The Variability and Teleconnections research program made a very good case with a simple hand-drawn diagram that their work intersected and even underpinned every single research program.

The guests and keynote speakers presented some fascinating insights from the space where climate research meets impacts. Jaci Brown's keynote whe she described her interactions with the agricultural sector and the different kind of communication required to explore the issues of climate change wa extremely useful. The second keynote by Eun-Pa Li on the recent stratospheric polar vortex weakening and its impact on Australian climate was particular timely with hot and cold extremes being experienced across the country. While technically she said this was not a stratospheric warming event, there was some good discussion about whether or not the sudden warming was connected to Australia's unusual weather. James Risbey's talk on day two that described the synoptic and large-scale processes that led to extra-tropical rainfall extremes, with a particular focus on a Hobart event, was a thorough explainer of the processes. His specially fashioned pointer also turned out to be very useful.



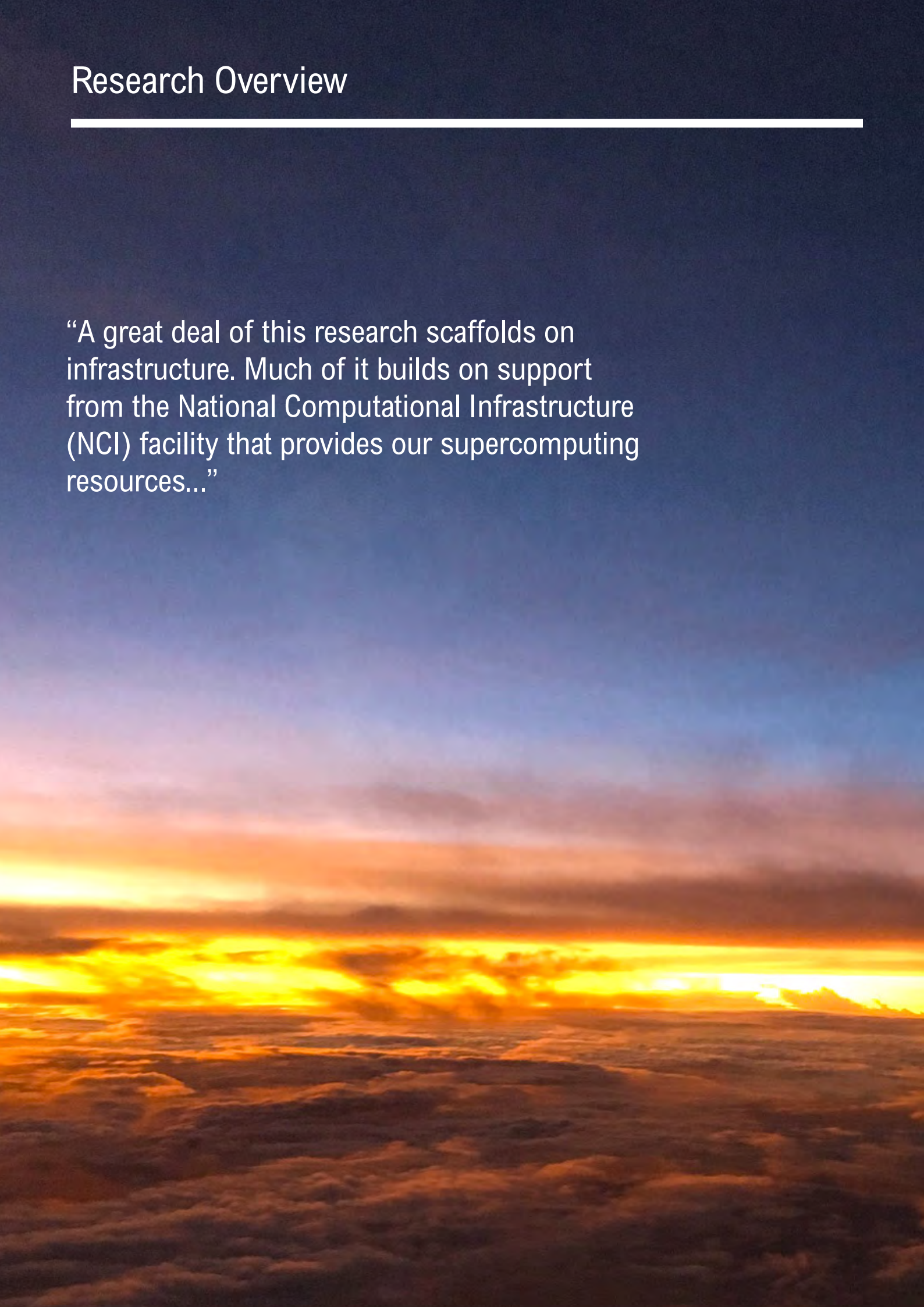
One after another we were treated to high-calibre talks that revealed improvements in our predictions of extreme heat; peeled back the layers of the multitude of processes in the Southern Ocean; described with great clarity where Murray Darling Basin rainfall originates; showed new interactions between the Pacific and Atlantic oceans; examined difficulties surrounding the relationship between drought and climate change; explored our changing heatwaves and hot days; and clarified the relationship between atmospheric rivers in Australia and rainfall extremes.

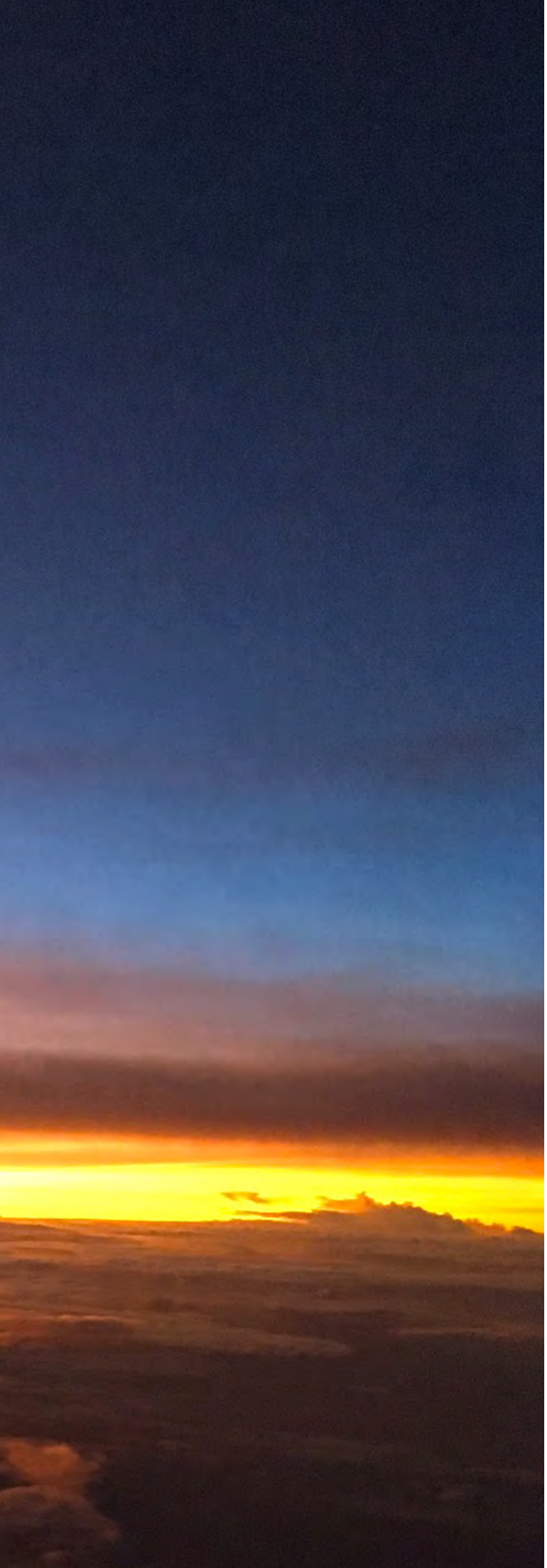
The breakout sessions also seemed to work well and the idea of having two separate sessions, so that researchers could move between them produced some very useful results that will help focus the future direction of the Centre of Excellence. The poster sessions gave an opportunity for almost 100 CLEX researchers to showcase their latest work. The buzz in the room was palpable as colleagues engaged with each other to discuss those finding and to make new connections.

And of course, there is the annual conference dinner where prizes were announced. The best, published paper by an honours, masters or PhD student went to Sonja Neske. The prize for best, published paper by an early career researcher was won by Navid Constantinou and the CLEX Director's Prize was awarded to Amelie Meyer. Annette Hirsch was also publicly acknowledged as the recipient of the inaugural CLEX career development award for women and other under-represented groups. Altogether, this was an outstanding workshop with much of its success coming from the planning and behind the scenes work of this year's workshop committee – Christine Fury, Stephen Gray, Melissa Hart, Ian Macadam, Andy Pitman, Gabriela Semolina Pilo and Peter Strutton. It's set a very high bar for next year's annual workshop. ■

Research Overview

“A great deal of this research scaffolds on infrastructure. Much of it builds on support from the National Computational Infrastructure (NCI) facility that provides our supercomputing resources...”





Through 2019, the ARC Centre of Excellence for Climate Extremes (CLEX) focused its research activities on its four key programs:

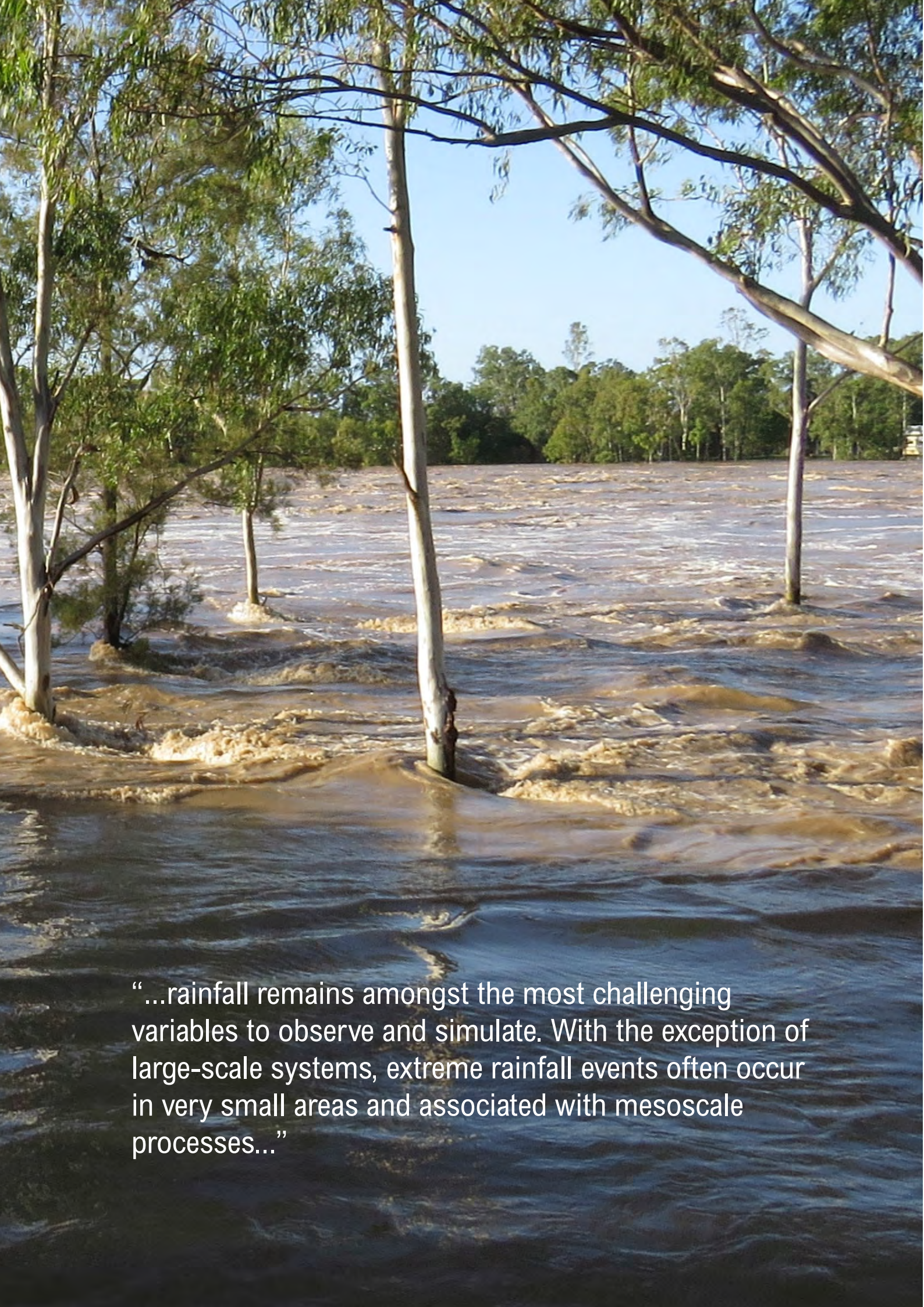
- Extreme Rainfall
- Drought
- Heatwaves and Cold Air Outbreaks
- Climate Variability and Teleconnections.

In 2019 all of the Centre's research associates were in place and contributing within and across research programs. In addition, the numbers of PhD students grew and consequently each research program and each node of the Centre contributed strongly to research goals. In the following reports from each CLEX research program, advances in our science are highlighted. Some of this research is led by PhD students, some by research fellows and some by more senior staff, but it is almost always the case that teams have formed across the Centre of Excellence to tackle research problems.

A great deal of this research scaffolds on infrastructure. Much of it builds on support from the National Computational Infrastructure (NCI) facility that provides our supercomputing resources. NCI also provides the disk storage that enables our use of data from the Coupled Model Intercomparison Project which is used commonly across the Centre. NCI also hosts the ERA-I reanalysis, and other observation and model simulations that are fundamental to our research. We could not be a world-class research centre without NCI, and we could not utilise NCI effectively without the very strong support from our experts in the Computational Modelling Systems team.

There are several key characteristics of the research we report here. First, it is almost all published in elite international journals. Second, almost all of it requires scale – intellectual capacity, technical skill and time. A lot of our research would never be attempted on a three-year ARC Discovery-type funding timeline. Secondly, we are very proud of model development progress. Whether it be in parameterizing processes in rainfall modelling, in how land processes influence droughts or heatwaves, or how ocean processes can be improved, model development is hard. The scale of our Centre, the technical support available and our strong collaboration with research groups around the word means our model development work can be integrated into the larger-scale models we use and help improve how extremes are simulated.

In the following we highlight some achievements in 2019. We also highlight the statement of intent for 2020 for each research program. As always, if anyone reading this wants to discuss collaboration on these priorities we are always willing to explore opportunities. An e-mail to the research program lead is the best first step in making contact.



“...rainfall remains amongst the most challenging variables to observe and simulate. With the exception of large-scale systems, extreme rainfall events often occur in very small areas and associated with mesoscale processes...”

RPI: Extreme RainfalII

Highlights

- Successful extreme rainfall workshop in Melbourne
- World-leading work to accurately down-scale climate models to predict rainfall at 1km
- Strong participation in RV Investigator cruise for Australian component of YMC
- Robust results from comparing 27 CMIP-5 models to determine how extreme rainfall may change in a warming climate
- Coordination of international model evaluation initiatives for extreme rainfall
- Prizes and awards won by CIs Lisa Alexander, Todd Lane, Christian Jakob and AI Joshua Soderholm.

Team

Co-leads

Prof Lisa Alexander (UNSW)
Prof Todd Lane (U.Melb)

Chief Investigators

Prof Craig Bishop (U.Melb)
Prof Jason Evans (UNSW)
Prof Christian Jakob (Monash University)
Prof Michael Reeder (Monash University)
Prof Steven Sherwood (UNSW)

Partner Investigators

Dr Sandrine Bony (LMD/CNRS)
Dr Elizabeth Ebert (BoM)
Dr Wojciech Grabowski (NCAR)
Dr Cathy Hohenegger (Max Planck Institute for Meteorology)
Dr Sean Milton (UK Met Office)
Dr Alain Protat (BoM)
Prof Bjorn Stevens (Max Planck Institute for Meteorology)
Dr Matt Wheeler (BoM)

Research Associates

Dr Margot Bador (UNSW)
Dr Diego Carrio Carrio (U.Melb)
Dr Stacey Hitchcock (U.Melb)
Dr Malcolm King (Monash University)
Dr Dr Nina Ridder (UNSW)
Dr Claire Vincent (U.Melb)
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PhD Students

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In 2019 The ARC Centre of Excellence for Climate Extremes (CLEX) Extreme Rainfall research program strongly focused on the fundamentals of observing rainfall extremes and simulating them with weather and climate models. This is because rainfall remains amongst the most challenging variables to observe and simulate. With the exception of large-scale systems, extreme rainfall events often occur in very small areas and associated with mesoscale processes. This poses a real challenge for climate models because it means that small-scale processes, which are difficult to reproduce in climate models, can have large impacts on rainfall and its extremes.

Despite this, in a world-first achievement, Centre researchers made enormous strides in finding a way through this conundrum. Generally, climate models can reproduce areas on 100km grids or larger, with outputs every few hours, but have struggled to accurately produce the resolutions needed by infrastructure engineers to highlight individual rainfall events and prepare for how they may change in the future. This has meant that it is possible to make general projections about how rainfall might change but not in a way that is meaningful for urban planning. However, CLEX researchers have now created a world-first approach that accurately downscales climate models to predict rainfall events at scales of 1km and with outputs every six minutes. This new approach was tested against historical rain gauge observations across Melbourne and captured these events with some accuracy.

The Extreme Rainfall program team also looked at hybrid cyclones around Australia, focusing on two damaging examples in South Australia that led to storm-force winds and storm surges. Both examples had significant impacts on infrastructure. Hybrid cyclones are relatively cold in the upper troposphere, like a typical extratropical cyclone, and warm in the lower troposphere, like a tropical cyclone. The researchers found that hybrid cyclones primarily fall from May to September, usually over the Tasman Sea or Great Australian Bight. The researchers were then able to use models to understand the characteristics of these cyclones, revealing where the strongest precipitation occurred and the processes that led to their formation. These processes were similar to those we find in tropical cyclones.

This combination of improving observations and better understanding the processes that inform climate models came together in another practical way through a paper that looked at how tropical cyclones may change for our neighbours to the north, in the Philippines. The climate models found that as the Earth warms, the Philippines would experience fewer but more intense cyclones. This region has recently borne the brunt of some of the strongest cyclones ever recorded, so this was valuable news for a nation that will need to adapt to the future impacts of climate change.

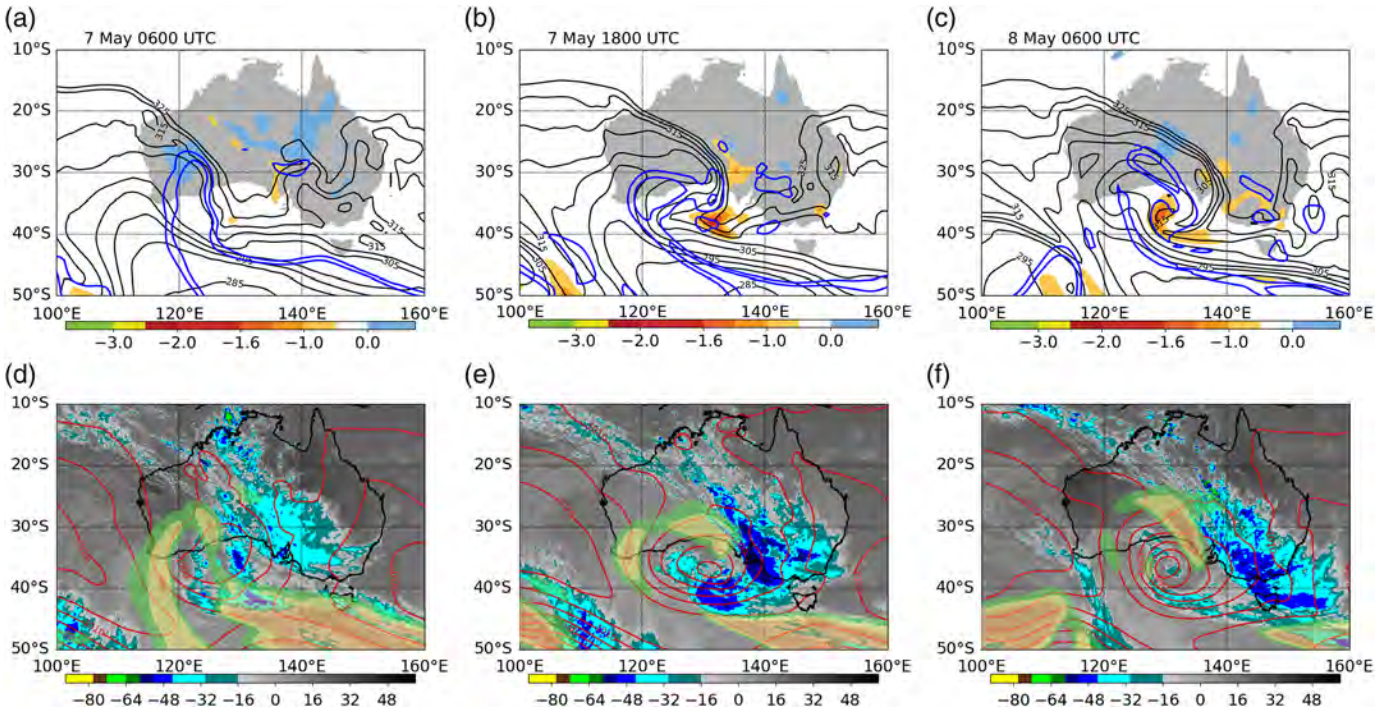


Fig1 – Hybrid Cyclones. Development of the May c2016 yclone between 0600 UTC 7 May and 0600 UTC 8 May. (a–c) 315 K PV (blue contours at −1, −2 PVU), 950–750 hPa mean PV (shading, PVU), and 950–750 hPa mean equivalent potential temperature (black contours, K). (d, e, f) brightness temperature of the false-colour infrared satellite imagery (shading, °C) derived from the GridSat-B1 data set, 315 K wind speed (semi-transparent shading at 30, 35, 40 m s−1), and sea level pressure (red contours, hPa) from Quniting et al, 2019. https://doi.org/10.1002/qj.3431]

Returning to Australia, cross-program research with the CLEX Drought research program revealed that the wetness of the ground can have a direct impact on how much rain falls. The researchers found a strong link between soil moisture and rainfall but in opposite directions for the north and south of Australia. The researchers found that wetter ground tended to lead to more rainfall (and vice-versa) in northern Australia in the wet and transition seasons. This suggests a positive coupling is present between soil moisture and rainfall. However, in the south and east of the country in winter, they found the opposite – that drier ground tended to lead to more rainfall (and vice-versa). There was a suggestion in this research that as climate models increase their resolution this coupling between the land and atmosphere may be considerably different to what has been estimated previously, with consequent implications for future rainfall estimates.

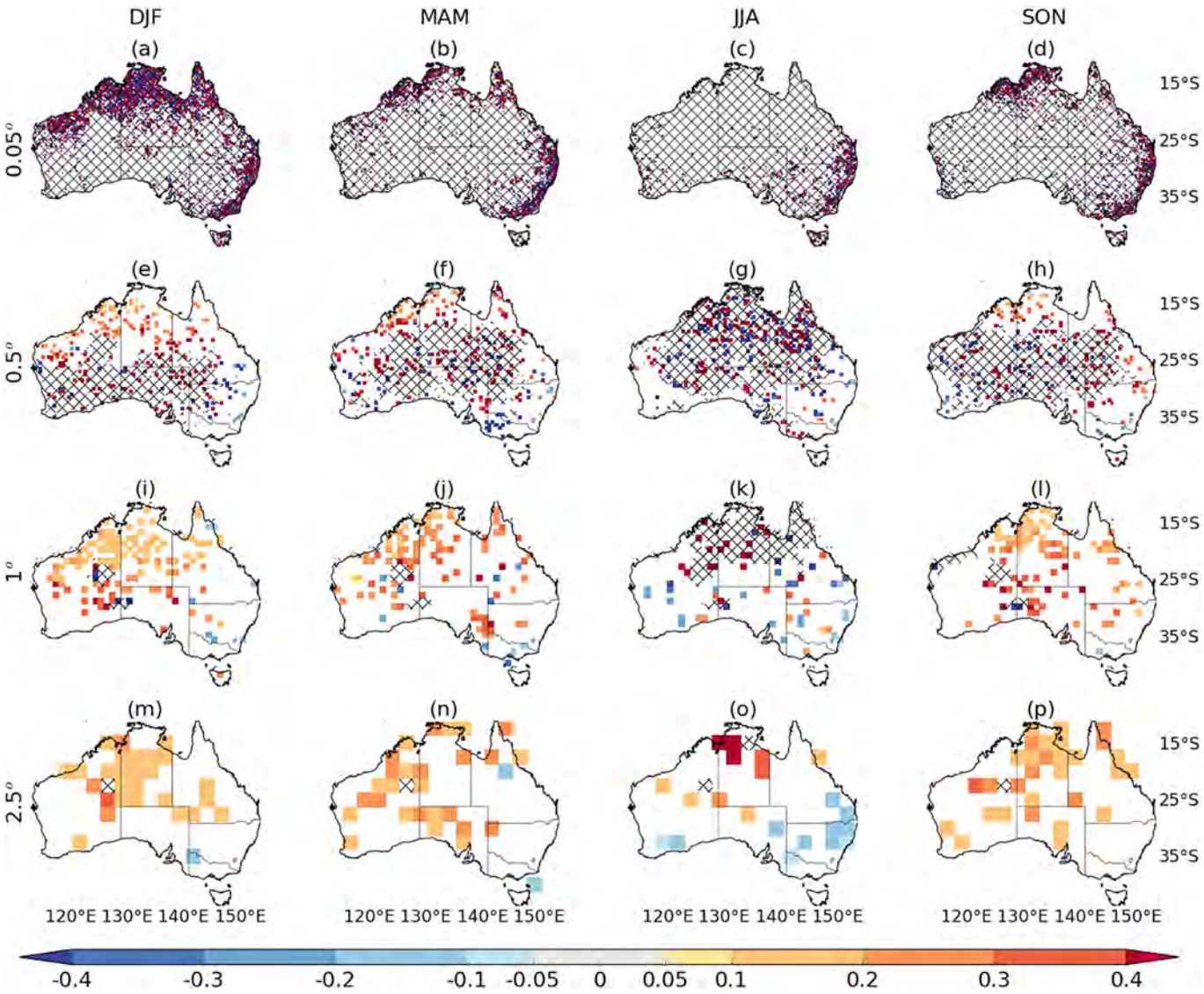


Fig 2: Correlation between soil moisture and next-day rainfall, 1979–2015. Only grid cells with $p < 0.05$ (two tailed) are colored. Maximum sample size N is 590; N < 15 are hatched. Only the first day of consecutive rainfall days was considered. Correlations are shown for local conditions (1-D assumption upheld) at (a–d) 0.05° (wind speeds ≤0.25 m/s), (e–h) 0.5° (wind speeds ≤2 m/s), (i–l) 1° (wind speeds ≤4 m/s), and (m–p) 2.5° (wind speeds ≤10 m/s). DJF = December, January, February; JJA = June, July, August; MAM = March, April, May; SON = September, October, November. From Holgate et al, 2019. https://doi.org/10.1029/2018JD029762

As shown in the examples above, improving our understanding of real-world conditions and our ability to forecast them in the future requires constant improvement and testing of our models.

Centre researchers compared a suite of 27 CMIP- 5 climate models used by the IPCC to determine if they gave a consistent signal for how extreme rainfall may change under a warming climate. The results were robust, with an increase outside the range of natural variability in the intensity of extreme precipitation events over the majority of land areas. Improvements in models or their outputs can also lead to new insights into future rainfall projections. An area known as the South Pacific Convergence Zone is the main source of rainfall for thousands of islands in the Pacific. However, understanding how this rainfall may change with global warming has been blurred, due to high uncertainties in climate models caused by sea surface temperatures. Centre researchers produced a statistical correction to reduce these uncertainties that, when applied, revealed a 25% drop in future precipitation for the south-western Pacific and revealed the mechanism that caused this substantial decline.

But for every answer the Extreme Rainfall program produces, it also seems to uncover new challenges. Research this year by the program revealed that radiative convective equilibrium (RCE) – where the cooling of the atmosphere by radiation is balanced by heating from condensation and heat transfer from the Earth's surface – breaks down in grid squares less than 1000km along each side. This has consequences for how we investigate rainfall extremes with models that can resolve the motion in convective clouds. Several studies using these so-called cloud-resolving models that have studied rainfall extremes used the RCE assumption in areas much smaller than 1000 x 1000km2 and have shown that convection is self-organising. Our results question whether the processes leading to this in the models can be found in such a small region in the real world.

Understanding the smaller-level processes that lead to changes in extreme rainfall and how they can best be represented in climate models is a constantly evolving area of research for the Extreme Rainfall program. Exploring the dynamic components of these changes, Centre researchers found that atmospheric convergence lines played an important role in changes in precipitation. The implications of this research are that weather time scales will be needed by climate models to tease out the dynamic component of future changes in extreme rainfall.

This year, our researchers were able to help us understand rainfall patterns across the maritime continent and down into tropical Australia by using a simplified model. They were able better understand the relationship between rainfall and the thermal structure of the atmosphere in the tropics, finding a clear relationship between humidity, precipitation and a high contrast between temperatures at different atmospheric heights. This revealed new atmospheric interactions that helped explain some of the issues climate models have for this region.

Idealised numerical model simulations were used by Centre researchers to understand how rainfall forms, comparing systems with organised convection to those with unorganised convection. Surprisingly, they found the instantaneous rain rate did not change between the two forms of convection but that organised convection still produced more rainfall because it stayed for longer periods over a single area.

The Extreme Rainfall program team also used models to reproduce observed phenomena to understand the processes that lead to their formation and to get a deeper insight into the climate system. An example of this is a well-known, regular and structured storm in Darwin — colloquially known as Hector the Convector. It was the focus of a study that looked at how strong up-draughts from storms brought moisture into the stratosphere. The study refined our understanding of these up-draughts and found that many of them did not actually bring moisture to this part of the atmosphere.

This investigation using Hector the Convector as a starting point highlights the importance of observations in making climate models more effective. It's why fundamental research into ratifying observations and creating observational data sets is such an important part of our work.

The power of improving our observations can also be seen in a recent paper that focused on convection and the tropical monsoon and how this affects annual rainfall over Australia and Africa. Climate models do not reproduce the changes in this region very well, so observations of clouds and rainfall are vital in helping us understand the processes. CLEX researchers found large-scale monsoon circulation suppressed rainfall in some areas and even shifted important high-top clouds away from areas of convection that may otherwise have produced rain. These insights highlighted factors that lead to poor model performance for this region, opening the way to future improvements.

Observations by themselves can also reveal climate insights. Measurements taken of cloud structures from 13 years of Darwin radar data revealed the contrast in conditions that can generate powerful localised storms that may lead to flash flooding events or widespread soaking rains. While giving insight into these differing convective events it also highlighted the value of Australia's radar network to climate scientists, and how it can improve our models.

Observations again played a role in a study to the north of Australia in the Maritime Continent. Investigating flood events around Jakarta, Indonesia, observations indicated that the Indian Ocean Dipole played a greater role in extreme rainfall events in this region than El Niño. The results suggested this was a direct result of local topography, which created very localised responses to large-scale conditions.

The foundational importance of observations is why determining the accuracy of existing observational data sets is an important part of our program. In 2016, researchers were involved in a voyage on the RV Investigator as part of the Clouds, Aerosols, Precipitation, Radiation and Atmospheric Composition Over the Southern Ocean (CAPRICORN) experiment, which took in-situ measurements of a range of important climate metrics. These measurements have now been used by Extreme Rainfall researchers to identify the accuracy of key data sets for the Southern Ocean, used by the international climate community in their climate models. While some small

biases were uncovered, in general the data sets appeared to be fairly robust.

Our researchers then used these same measurements to determine the accuracy of observations retrieved by the Japanese geostationary satellite, Himawari-8. This satellite provides useful data on clouds for our region at relatively high resolution. For this reason, researchers need to know if it produced any biases, particularly around cloud-top height and cloud-top temperature, whose roles are critical in shaping Earth's climate. The majority of results agreed reasonably well with both the shipborne and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations estimates. However, some major systematic biases were identified.

In addition, we highlight our international engagement through the development and analysis of a global database of daily precipitation from multiple in-situ, remote sensing and reanalysis data sets, along with our leadership of global model intercomparison initiatives. Our research highlights the large spread in observational products comparing rainfall extremes and how products need to be carefully chosen as fit for purpose. This has important implications for model evaluation. While satellite precipitation products have the potential to supplement existing products for climate scale analysis, differences between data products, limitations in satellite-based estimation processes, and the inherent challenges of scale need to be better understood moving forward if we are to improve process understanding and model evaluation.

In the process of conducting our science we also produce data sets that directly reveal new climate insights pertinent to Australia. PhD student Kimberley Reid led research that used an automatic algorithm to objectively identify north-west cloudbands from satellite observations. These cloudbands increase the probability of extreme rainfall in some parts of Australia and reduce it in others. The research also revealed the seasonal mechanisms associated with these cloudbands and showed there had been a statistically significant increase in the number of days they appeared from 1984-2014.

Centre researchers played an important role in the creation of the Australian Operational Weather Radar data set and used this to investigate the steady accumulation of rainfall over two weeks that led to the Townsville Flood disaster, and the cloud processes that led to an extreme hailstorm event that hit Sydney on December 20, 2018. We also produced impressive animations of these two events that give considerable insight into the processes around them.

To help plan the future direction of RP1, the almost 40 members of the Extreme Rainfall program converged on The University of Melbourne Earth Sciences building on September 23 for our second program-wide workshop. The workshop featured 16 talks, organised into our four sub-questions, each generating a great deal of discussion and ideas for future research and collaboration. As usual, the excellent Melbourne weather and coffee left our interstate visitors envious.

The Extreme Rainfall team has also been conspicuous for its successes at a national and international level. Chief Investigator Lisa Alexander was awarded the Gordon Manley Weather Prize (2018) by the Royal Meteorological Society; CLEX Deputy Director Todd Lane was named as an Australian Meteorological and Oceanographic Society (AMOS) Fellow; Chief Investigator Christian Jakob was awarded the 2018 Morton Medal and presented the RH Clarke lecture. Associate Investigator Joshua Soderholm was invited by The Royal Society of Victoria to present his work on severe weather.

PhD student Pavan Harika Raavi received the John and Allen Gilmour Award from the Melbourne University Faculty of Science, which aims to highlight medical or scientific research that benefits humankind. Kimberley received an honourable mention for her presentation at the joint AMOS-International Conference on Tropical Meteorology and Oceanography conference held in Darwin. Kimberley is also the first CLEX student to have recorded their time with us, regularly blogging about her PhD and the trials and joys that every research student goes through.

Our influence continues to be felt across the research community. Lisa Alexander will be a guest editor on Compound Weather and Climate Events, a special issue of the journal *Weather and Climate Extremes*. Associate Investigator Yi Huang will be guest editing a special edition of Atmosphere, Observations and Simulations of Clouds, Aerosols, Precipitation and Radiation over the Southern Ocean.

The Extreme Rainfall program's research was also highlighted when the work of Claire Vincent featured on the cover of the NCI annual report. The image is of a high-resolution animation taken from Claire's impressive Madden Julian Oscillation study that looked at its influence on rainfall over the Maritime Continent.

We have also welcomed a number of visitors to the program who have helped extend our collaborations and added to the richness of our work. A highlight was a four-week visit by the Director of NASA Goddard Institute for Space Studies, Dr Gavin Schmidt. During his visit he collaborated with Chief Investigator Steve Sherwood, held two seminars and put on a special three-day workshop on science communication.

We have continued to add depth and breadth to our team. In 2019 we welcomed Martin Jucker, Andrew Marshall, Josephine Brown and Yi Huang as Associate Investigators; plus, two new postdoctoral researchers: Stacey Hitchcock, who is based at The University of Melbourne; and Rob Warren, at Monash.

In November and December a large number of Centre researchers participated in the RV Investigator cruise off the coast of the Northern Territory as part of the Australian contribution to the Years of the Maritime Continent field experiment.

Finally, we can't fail to mention a great outreach activity by PhD student Kimberley Reid and Master student Alex Borowiak, who were guest climate researchers as part of an immersive art installation, Enter the Plastisphere, at Coburg Carnivale in September, proving that science and art can meet.

2019 was an extraordinarily productive year and we look forward to capitalising on these successes in 2020. ■

Extreme Rainfall 2020 Statement of Intent

Project	Priority	Intent
1.1	1	Continue to develop methods to analyse rainfall extremes using a combination of gauge, satellite and radar observations
	1	Identify key synoptic regimes that contribute to rainfall extremes across Australia
	2	Constrain projections using large-scale modes of variability (link to 1.4)
	3	Analyse the large-scale regimes responsible for rainfall extremes over Australia, using sounding data and simulations using WRF and ACCESS
1.2	1	Continue to explore the WRF model representation of the transition from convective (local intense) to stratiform (widespread weaker) rain (link to 1.1)
	1	Examine organized convection and its contribution to rainfall over Melbourne
	2	Derive objective metrics of rainfall organisation, structure, and other characteristics from satellite and radar data
	1	Identify key large-scale characteristics associated with rainfall extremes
	3	Conduct a suite of idealised model experiments to determine the fundamental processes linking convective organisation to extremes.
1.3	1	Investigate water vapour transport in a hierarchy of model data sets
	2	Determine the links between rainfall extremes and the migration of the Australian Monsoon trough
	3	Determine the links between heat waves in the south and eastern parts of the continent and enhanced rainfall in the north and west of the continent (link to Heatwaves RP)
1.4	1	Examine high-resolution MIP simulations to understand extreme rainfall at multiple resolutions and parameterization configurations
	1	Examine ACCESS-S representation of rainfall extremes
	2	Examine convection-permitting climate model simulations of short-duration extreme rain
	2	Improve the simulation of clouds and precipitation through assimilation of satellite observations
	3	Evaluate climate model representation of rainfall extremes and other convective hazards with new radar and satellite observations
All RP	1	Identify and conduct high-resolution WRF and ACCESS model experiments of extreme rainfall events over Australia, including ECLs
	1	Analyse Grand Challenge high-resolution ACCESS simulation.

Priority levels: 1 = to be achieved in 2020. 2 = substantial progress in 2020. 3 = progress towards in 2020.

New dataset reveals key to Townsville flood disaster

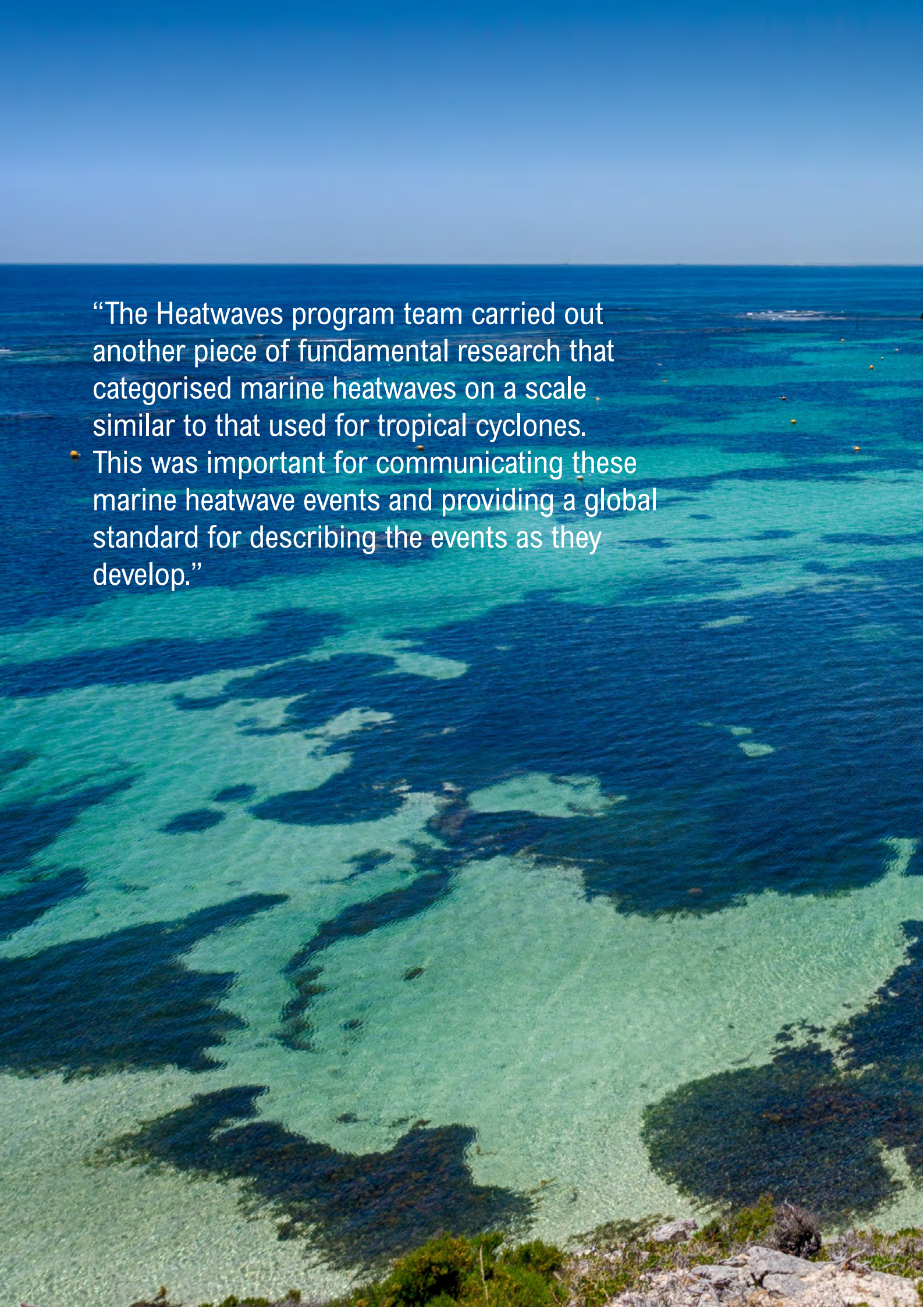
When the heavens opened over Townsville bringing massive floods at the beginning of 2019, researchers were also inundated with some of the most precise data ever recorded for this kind of event.

That data revealed that over the two weeks from January 25 to February 7, even though no single day was record breaking, enough rain fell over 260 km2 around Townsville to fill 14.4 million Olympic swimming pools or the equivalent of 72 Sydney Harbours. The highest rainfall in any one square kilometer was 2.2m. This level of accuracy is all thanks to data extracted from Australian weather radar network that has now been compiled by researchers from the ARC Centre of Excellence for Climate Extremes (CLEX) and the Bureau of Meteorology into a 20-year-long precipitation dataset, the Australian Operational Weather Radar Dataset.

Using this data, CLEX researchers created a three-dimensional animation showing the passage of severe thunderstorms and a series of large hail events that hit Sydney on December 20, 2018. In this 3D-representation it is possible to see how high the hail forms, where it forms and the trajectory from cloud top to the land surface. They have also produced an animation showing how the rainfall over Townsville steadily accumulated over the two weeks leading to the massive floods, which are estimated to have cost $1bn dollars in stock loses and damage.

The Bureau of Meteorology's real time weather radar page is already one of the most visited Australian website pages by the Australian public. But for scientists this new detailed data archive gives us an invaluable historical map of precipitation and its characteristics in Australia. The 20-years of data from the Bureau of Meteorology's radar network will help researchers understand more about rainfall processes and open many new avenues for research and education.

To encourage the use of the data, the three partners – Bureau of Meteorology, National Computational Infrastructure and CLEX – have released the complete archive for research and education use. Data from the archive is available on demand through an open access portal hosted on NCI and updated daily. ■



“The Heatwaves program team carried out another piece of fundamental research that categorised marine heatwaves on a scale similar to that used for tropical cyclones. This was important for communicating these marine heatwave events and providing a global standard for describing the events as they develop.”

RP 2: Heatwaves and Cold Air Outbreaks

Highlights

- Trends in the global occurrence of marine heatwaves show a dramatic increase over the past century
- Conditions conducive to the occurrence of firestorms (pyrocumulonimbus) were found to increase in climate projections for south-east Australia
- Springtime changes in the winds in the Antarctic stratosphere may play a role in early summer heat and in dry extremes over Australia
- AI Andrew King won the inaugural Australian Meteorological and Oceanographic Society (AMOS) Award for Science Outreach.
- CI Julie Arblaster was recognised among the most highly cited researchers in their field over a 10-year period by Clarivate Analytics
- ANU post-doc Annette Hirsch was the Centre's first-ever winner of the annual CLEX Career Development Award for Women and Other Underrepresented Groups.

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Prof Michael Reeder (Monash University)

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A/Prof Julie Arblaster (Monash University)
Prof Neil Holbrook (UTAS)
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Prof Todd Lane (U.Melb)

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Dr Harry Hendon (BoM)
Dr Reto Knutti (ETH Zurich)
Dr Gerald Meehl (NCAR)
Dr Joe Santanello (NASA-Goddard Space Flight Center)
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Over the past year, the ARC Centre of Excellence for Climate Extremes (CLEX) Heatwaves and Cold Air Outbreaks research program has produced world-leading research, clearly delineated the likely impacts of the extreme events we study, and has made many strides in improving our climate models.

In a world-first and fundamental piece of research, the Heatwaves and Cold Air Outbreaks program produced a global assessment of the drivers of marine heatwaves. It also found they have increased by 50% over the past century. The researchers revealed that often the instigator of marine heatwaves was found thousands of kilometres away and sometimes in entirely different ocean basins. The team also uncovered a range of relationships between marine heatwaves and nine well-known climate oscillations that might enhance or suppress the development of the former. This is important fundamental research that will set a baseline for future studies into marine heatwaves and potentially improve our capacity to predict these events.

The Heatwaves program team carried out another piece of fundamental research that categorised marine heatwaves on a scale similar to that used for tropical cyclones. This was important for communicating these marine heatwave events and providing a global standard for describing the events as they develop.

The importance of this work was demonstrated with a paper in *Nature Climate Change* that highlighted how ocean heatwaves were significantly altering ecosystems. These ecosystem changes persisted even after the waves had ended, creating what the authors described as an ecological-step change. The work in this area by Centre researchers continues to be at the forefront of marine heatwave research and has already produced outcomes that will help us to improve our forecasts of marine heatwaves around Australia.

Heatwave program researchers have also made their mark over land, quantifying the impact a changing climate and climate extremes have on four of the world's staple crops: wheat, maize, soybeans and rice. Their research showed that 18% to 43% of the variation in yield of these crops could be accounted for by extreme weather events. The research also highlighted that specific regions, which produce the vast majority of these crops, were particularly susceptible to extreme events. As a result of the importance of particular regions to the world supply of these staples, extreme weather impacts would be felt far beyond the borders of the countries where these crops are grown.

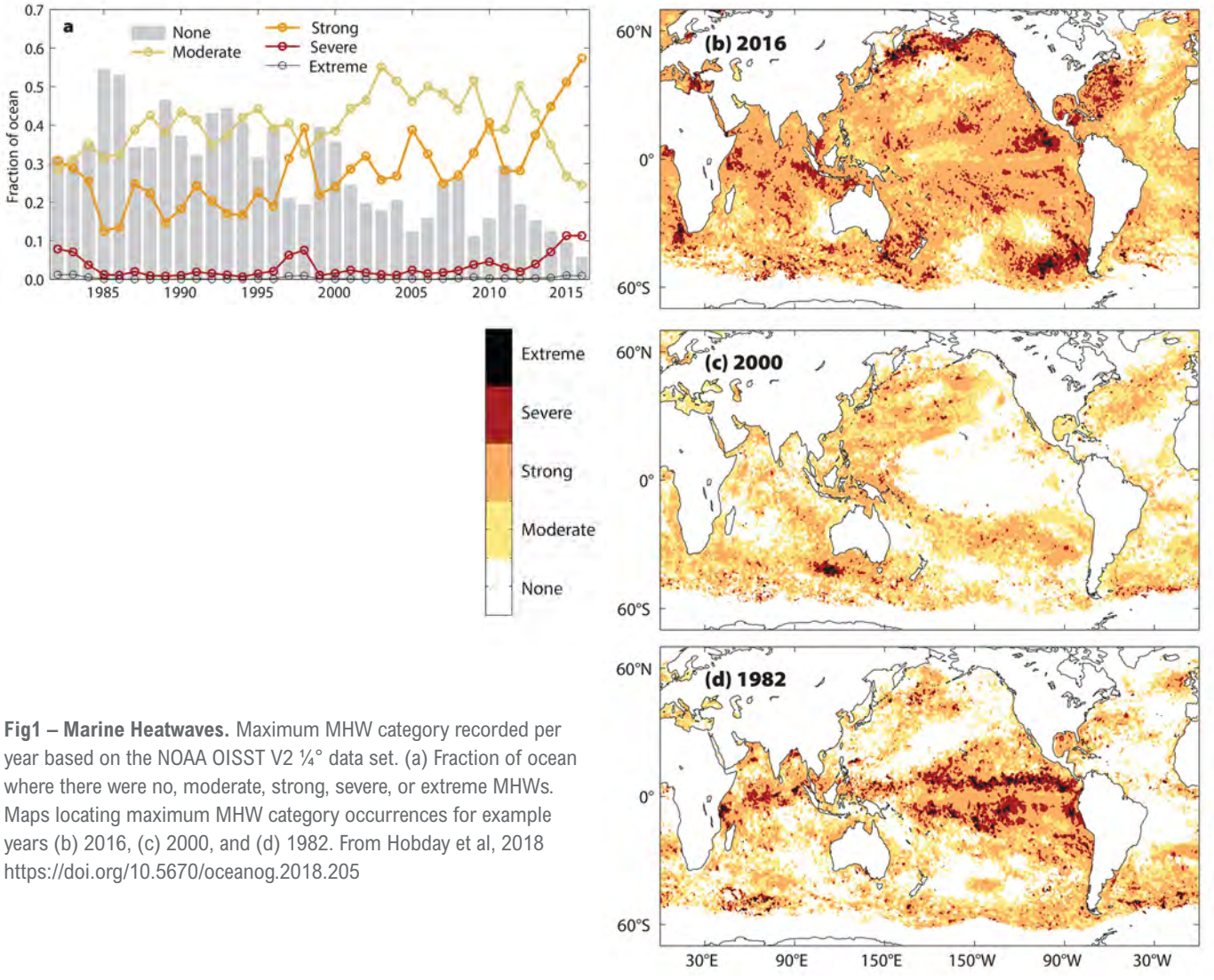


Fig1 – Marine Heatwaves. Maximum MHW category recorded per year based on the NOAA OISST V2 ¼° data set. (a) Fraction of ocean where there were no, moderate, strong, severe, or extreme MHWs. Maps locating maximum MHW category occurrences for example years (b) 2016, (c) 2000, and (d) 1982. From Hobday et al, 2018 https://doi.org/10.5670/oceanog.2018.205

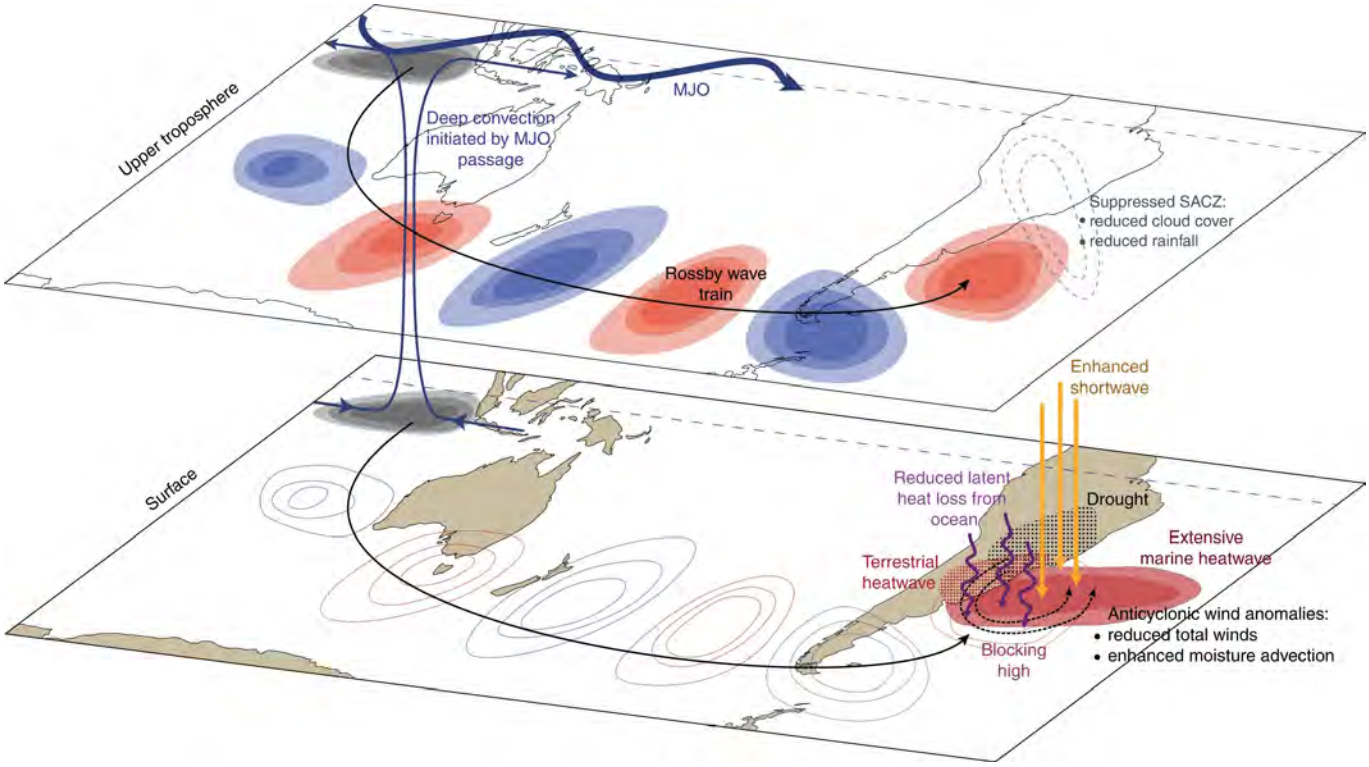


Fig 2 Rossby Wave train. Tropical deep convection, mainly in the Indian Ocean, associated with the MJO passage triggers a Rossby wave train that extends through the South Pacific to the tip of South America and turns equatorward to reach subtropical South America. From Rodrigues, et al, 2019. htpps://doi.org/10.1038/s41561-019-0393-8

The impact of one part of the world on another isn't limited to the economics of agricultural production. In climate science, we regularly see how a phenomenon in one part of the world can lead to a domino effect that has impacts on another.

A very specific piece of research, done in concert with the CLEX Variability and Teleconnections research program, highlighted the importance of understanding these distant linkages. Working with colleagues in South America, our researchers found the extreme drought over South America in 2013/14 and a particularly intense marine heat wave in the southern Atlantic were actually spawned by convection over the Indian Ocean. Importantly, the researchers isolated the mechanism and indicated that strong convection in the Indian Ocean is likely to cause a similar event in the future.

Often distant events can have an impact on extreme temperatures in Australia. This was revealed in a fascinating paper that showed how variations during spring of winds high above the Antarctic could cause hot and dry extremes in early summer over Australia. The study showed that a weakening of these winds in spring results in higher temperatures, lower rainfall and an increase in heatwave and fire-prone weather conditions (especially across New South Wales and southern Queensland) over late spring to early summer. The release of this research coincidentally followed a sudden stratospheric warming event in September that resulted in weather patterns – featuring both heatwaves and cold air outbreaks – that were very similar to those predicted by the above-mentioned paper.

Another distant phenomenon known to have an impact on Australia's weather is the El Niño Southern Oscillation (ENSO). Understanding its role in the processes that lead to heatwaves can also help us improve our forecasting around them. This was shown by research that revealed how land surface processes responded to ENSO events. The researchers found this response was most pronounced in the northern part of Australia. The ENSO relationship was less important in south-eastern Australia.

This variation in responses within the climate system also extends more broadly to future warming. Heatwaves program researchers examined why different areas of the world warm faster than others and explored whether, as global warming continues, this pattern of accelerated warming will only continue in these fixed locations. They found a slight geographical change but this change differed considerably between the climate models selected. The uncertainty uncovered between climate models appears to revolve around how they represented precipitation, making this a key focus of future research if we are to improve future projections of warming.

Focusing more closely on variations within Australia, the Heatwaves and Cold Outbreaks program looked at how heatwaves between Victoria and New South Wales differed. This was in an effort to understand the dynamics of these events. Centre researchers found that Sydney heatwaves were associated with relatively weak anticyclones in the Tasman Sea in conjunction with relatively strong cyclones south of the continent, whereas in Victoria it was the opposite.

The Heatwaves program also looked at variations within a heatwave to understand how different locations may need to adapt in the future as heatwaves intensify with climate change. Research led by PhD student Cassandra Rogers found that during heatwaves the overnight temperatures between three Australian cities and the country areas around them varied by as much as 3.3°C. The results of this investigation suggest adaption measures will need to be taken as Australian cities expand and extreme heat events become more common.

However, as the news headlines on bushfires in the latter half of 2019 can attest, there are some phenomena that are almost impossible to prepare for. Important research by our program showed how human-caused climate change will impact the most dangerous of bushfires that produce their own weather. Pyrocumulonimbus are deep convective clouds produced by bushfires. They can generate fire tornadoes and hurricane-strength winds that were at the core of the 2003 Canberra Bushfire and the 2009 Black Saturday Bushfires. Our research found the conditions that generate these pyrocumulonimbi in Australia will become more frequent as a result of climate change over the next 30 years and they will begin to appear in spring, not just summer. The research also identified key agricultural and suburban fringe areas in Australia that would see the greatest increase.

Most of this research could not be carried out without high-quality climate models that reproduce as closely as possible real-world outcomes. This is why a big part of our research focuses on testing the models to improve their performance and to understand how best to represent the natural processes in these mathematical constructs.

One of the fundamental influences on the accuracy of climate model projections is to understand which models to choose. In a *Nature Climate Change* paper, Centre authors and colleagues suggested moving away from an approach that determines models purely on their ability to successfully simulate past climates. Instead, they suggested model selection should be based on analysing the performance patterns to understand the processes that make some models more successful than others.

In a review paper for *Earth System Dynamics*, CLEX researchers, as part of a broader international team, explored how models that used almost identical parameterizations would naturally produce very similar results, known as "model dependence". The authors questioned whether these results were robust if they were based on similar parameterizations. They suggested approaches to avoid overconfidence in model outcomes, and how to avoid this model dependence to produce more robust results.

This approach was explored in yet another paper that looked at the impacts on variations in seasonal precipitation and the soil moisture/temperature response, and how these were represented in climate models. It found that where these relationships were unrealistically represented there was an overestimate on future extremes. Excluding these models reduced the uncertainties around future changes in extreme heat events.

Another area of some uncertainty has been the use of attribution studies to infer the contribution of human-caused climate change to extreme heatwave events. Centre researchers identified a range of climate model ensembles that are regularly used for attribution events and found they showed a systematic bias in the way these extreme events were represented. However, they then developed a correction method that ensured these models produced results that were more in line with real-world observations. This newly developed correction method is a major advance towards providing quantifications of climate change that are more meaningful to the real world.

Our researchers also looked at model outcomes of the Coordinated Regional Downscaling Experiment (CORDEX) to test the accuracy of its regional projections against temperature and precipitation. This experiment specifically focuses on climate change outcomes across eastern and south-eastern Australia. Our researchers noted some unique errors with individual model members but, overall, it produced a good average representation of Australia's climate.

High-quality data is vital for testing our models, meaning data sets need to be tested and corrected as often as our models. As part of this process, our researchers looked at a land cover data set, GIMMSv3.0g, in which Australian researchers identified calibration errors that had caused significant errors and trends over Australia's dryland regions. It is likely that these errors have also affected previous estimates of dryland degradation globally. A recent update to the data set, GIMMSv3.1g, was tested and appeared to remove these errors. It was recommended the research community use this latter data set, and noted that using multi-ensemble runs with different data sets produced a more comprehensive understanding of uncertainties.

Our researchers also continue to play an important role in the international community. Our Heatwaves program Co-leader, Chief Investigator Jason Evans, was a Lead Author on the desertification chapter of the recent Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Change and Land. If you had been following the mainstream media, you would have assumed that its key message was to become vegetarian, but one quick look at the headline statements will quickly disabuse you of that idea. With land temperatures rapidly outstripping the rise of the global average temperatures and constant change in land cover, this is a report that deserves time and proper consideration.

Chief investigator Julie Arblaster has also been involved in key work leading up to the IPCC's 6th Assessment Report, due to be released in 2021. She attended the Coupled Model Intercomparison Project Phase 6 (CMIP6) Model Analysis Workshop, held in Barcelona from March 25-28, 2019. It provided the first opportunity for results from CMIP6 models to be discussed and presented by the modelling community.

We have also welcomed a range of international visitors and collaborators. Caroline Bain from the UK Meteorological Office

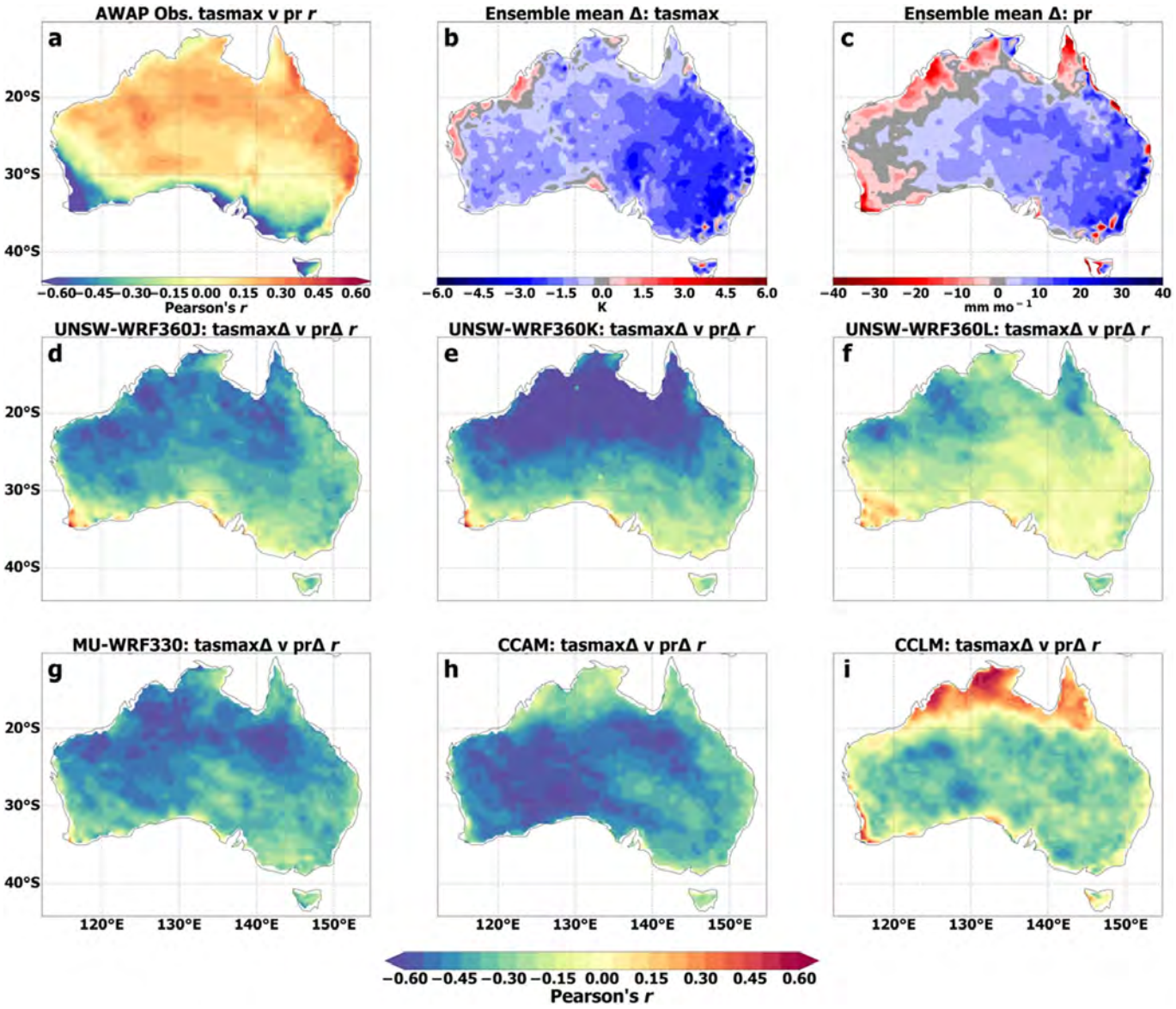


Fig 3 CORDEX: A Temporal correlations between observed mean monthly maximum temperature (tasmax) and precipitation (pr), b, c biases in modelled versus observed tasmax and pr, d–i temporal correlations between mean monthly biases in maximum temperature and precipitation. From Di Virgilio, et al, 2019. https://doi.org/ 10.1007/s00382-019-04672-w

visited the Centre of Excellence to work with Chief Investigator Michael Reeder on research into novel techniques to track high-impact weather in tropical regions. Seraphine Hauser, a student from Karlsruhe Institute of Technology (Germany), supervised by Julian Quinting (a former postdoctoral researcher in the ARC Centre of Excellence for Climate System Science), visited Michael and Associate Investigator Shayne McGregor for three months. During her visit, Seraphine worked with Michael and Shayne on a synoptic perspective on the effect of ENSO on cool season rainfall in south-eastern Australia. Joan Cuxart from the University of the Balearic Islands (Spain) visited Jason and Michael to work on determining evapotranspiration and the boundary layer role in cold snaps.

Recognition of our activities continues to be seen through a range of awards. Associate Investigator Andrew King won the inaugural Australian Meteorological and Oceanographic Society (AMOS) Award for Science Outreach. Julie Arblaster made the Clarivate Analytics list as one of the consistently most highly cited researchers in their field over a 10-year period. Associate Investigator Sarah Perkins-Kirkpatrick was recognised by the American Geophysical Union as an outstanding reviewer in 2018. ANU post-doc Annette Hirsch was the Centre's first-ever winner of the annual CLEX Career Development Award for women and other underrepresented groups.

We have also been involved in a range of outreach activities. Highlights include Michael Reeder as a panel member of a free public lecture associated with the AMOS Fire Weather Workshop, A Decade On: Lessons from Black Saturday. In this role, Michael spoke about what we have learnt in the past 10 years about the science of bushfire weather, including the development of a coupled atmosphere-fire version of the Unified Model. Associate investigator Joelle Gergis co-curated an exhibition, Water, Soil & Life, at the Charles Nodrum Gallery.

Each of the pieces on display looked at the variability of Australia's climate from settlement to today and were combined with passages from Joelle's recent book, *Sunburnt Country: The future and history of climate change in Australia*.

Finally, throughout this very packed year the Heatwaves and Cold Air Outbreaks program team continued to expand. This year we welcomed two new Associate Investigators: Eric Oliver, who specialises in marine heatwaves; and Tess Parker, who has particular expertise in the dynamics of heatwaves over south-east Australia. We also added a number of new students, including Ritwik Misra, Jemima Rama, Jingwei Zhou and Xinyang Fan. ■

Heatwaves and Cold Air Outbreaks Statement of Intent 2020

Project	Priority	Intent
2.1	1	Complete work on the difference between days with strong upper-level anticyclones but no heatwave, against heatwave days
	1	Complete work on a new technique developed to define the history of heatwave *events*, where an event is a heated region *contiguous in space and time*, parts of which satisfy the definition of a heatwave (3 consecutive days on which the maximum temperature exceeds the 90th percentile. Apply the technique to an analysis of heatwave life cycles
	2	Given the relative weakness of most climate models in producing realistic modes of tropical variability, evaluate how well current climate models describe the PV-theta (potential vorticity) structure of heatwaves and the relationship between heatwaves and tropical convection (including the MJO and ENSO). The analysis will make use of the heatwave object tool
	3	Extend the life cycle analysis to the ERA5 data set
	3	Investigate the dynamics of the mixed layer associated with heat waves
2.2	1	Use WRF-LIS-CABLE experiments with externally controlled surface energy and water budgets to quantify the impact on heatwave intensity to changes in the land surface
	1	Perform convection-permitting simulations over greater Sydney with a focus on the urban landscape and its surrounds covering summer 2016/7, to determine the role of the local land surface on the temperature differentials across the city
	2	Examine the relative influence on a heatwave's intensity and duration on the local landscape (urban form and surrounds) compared to the regional/continental conditions
	1	In combination with the back-trajectory analysis in project 2.1, determine the relative role of surface conditions and atmospheric processes in the heatwave evolution
2.3		No explicit work in this subprogram
2.4	1	Analyse high-resolution model experiment outputs to identify the key processes that caused the 2017/18 Tasman Sea marine heatwave
	1	Develop a perspective article that considers marine heatwaves, their mechanisms and potential predictability
	2	Investigate how marine heatwaves are simulated in the first set of available CMIP6 models, and compare with those in CMIP5 models
	2	Perform a set of targeted model experiments to understand the key drivers of marine heatwaves in the Australian region
	3	Further investigate the vertical scale of marine heatwaves and the important processes that underpin vertical extent
	3	Develop marine heatwave theory.

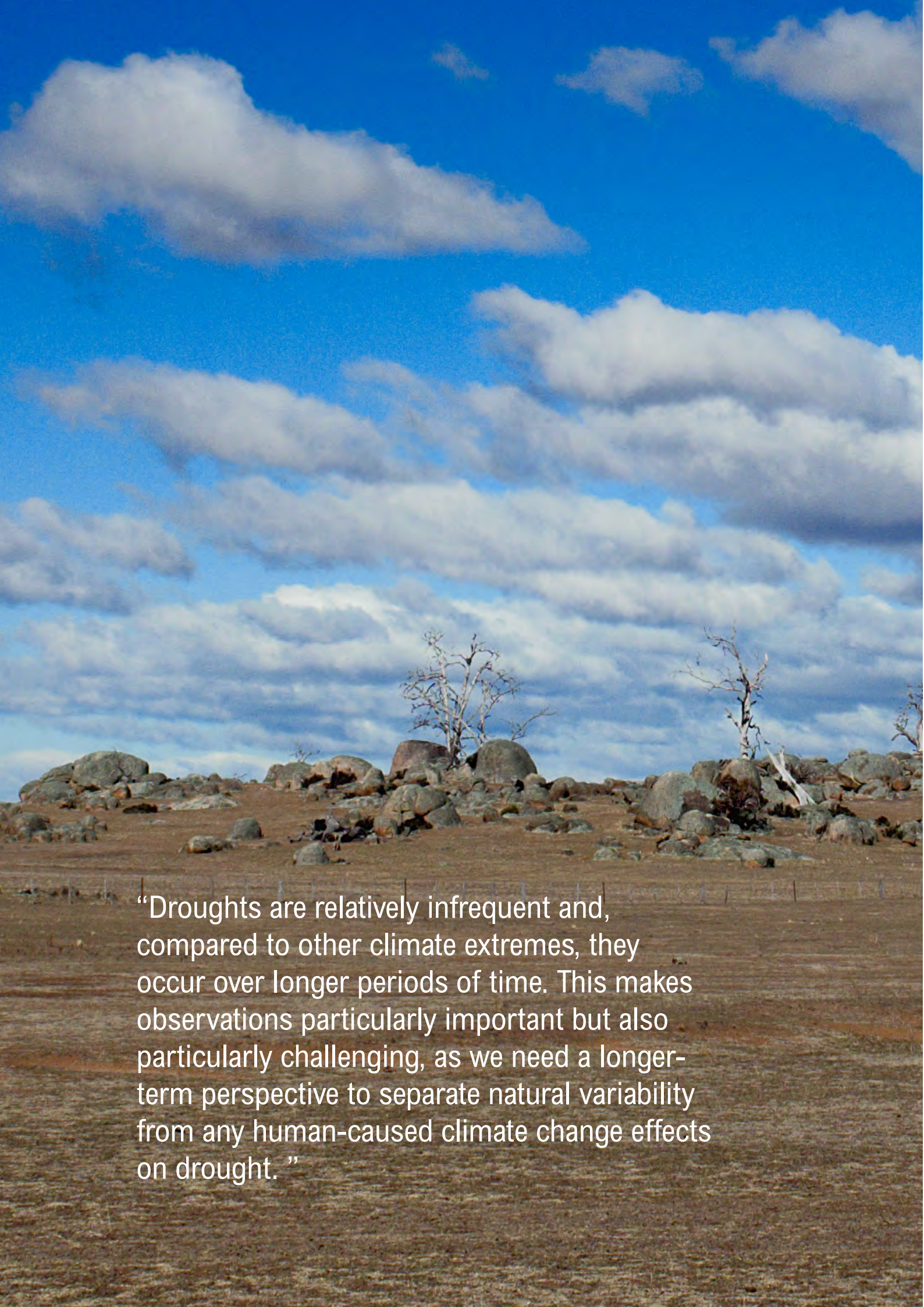
Priority levels: 1 = to be achieved in 2020. 2 = substantial progress in 2020. 3 = progress towards in 2020.

Our first winner of the CLEX Career Development Award

UNSW postdoctoral research associate, Dr Annette Hirsch was the inaugural recipient of the $10,000 CLEX career development award for women and other under-represented groups. The intent of the award is to make a meaningful investment in the careers and professional development of women and people from other underrepresented groups by addressing some of the key issues that hinder their career progression. People from other under-represented groups are defined as those who are underrepresented in the general CLEX population, particularly at senior levels, as well as those who experience bias or discrimination in the broader community. Examples include: Aboriginal or Torres Strait Islander peoples, those from an ethnic minority, people with a disability, etc.

Annette indicated that a key piece in her leadership and career development jigsaw puzzle is to gain a deeper understanding of how science is translated into policy. She therefore chose to invest much of the award in leadership and training courses addressing this issue. She also benefitted from an immersive experience working for a time within the APS at the (then named) Department of Environment and Energy. Annette reflected that this was an eye-opening and important, career-building experience, saying "I've learnt so many things as a result of this award and I'm still unpacking how to navigate the path towards effective policy engagement."

CLEX is committed to improving gender representation at senior levels within our disciplines. We are confident that investing in meaningful career and leadership development for our ECRs will aid them to become the leaders of tomorrow. ■



“Droughts are relatively infrequent and, compared to other climate extremes, they occur over longer periods of time. This makes observations particularly important but also particularly challenging, as we need a longer-term perspective to separate natural variability from any human-caused climate change effects on drought. ”

RP 3: Drought

Highlights

- Joint work with the Heatwaves RP led to new understandings of how drought, heatwaves and precipitation affect crop yields and tree mortality
- Continued to develop and enhance observational data sets that underpin much of our research
- Andy Pitman was awarded the Royal Society of Victoria's prestigious Medal for Excellence in Scientific Research
- Martin de Kauwe's research is uncovering new understanding on how vegetation responds to increased CO_2 levels in the atmosphere
- Chief Investigator Nerilie Abram was promoted to professor and awarded the Priestley Medal of the Australian Meteorological and Oceanographic Society.
- Two PhD students Manon Sabot and Sanaa Hobeichi were part of the UNSW Women in Maths & Science Champions group which won the UNSW President's Award for Embracing Diversity.

Team

Co-leads

Prof Andy Pitman (UNSW)
Prof Michael Roderick (ANU)

Chief Investigators

Prof Nerilie Abram (ANU)
Dr Gab Abramowitz (UNSW)
A/Prof Dietmar Dommenget (Monash University)
Prof Jason Evans (UNSW)

Partner Investigators

Dr Martin Best (UK Met Office)
Dr Nathalie de Noblet (LMD/CNRS)
Prof Hoshin Gupta (University of Arizona)
Dr Harry Hendon (BoM)
Dr Reto Knutti (ETH Zurich)
Dr Christa Peters-Lidard (NASA-Goddard Space flight Centre)
Prof Dani Or (ETH Zurich)
Prof Sonia Seneviratne (ETH Zurich)
Dr Ying Ping Wang (CSIRO)

Research Associates

Dr Martin De Kauwe (UNSW)
Dr Sanaa Hobeichi (UNSW)
Dr Anna Ukkola (ANU)
Dr Nicky Wright (ANU)
Dr Dongqin Yin (ANU)

PhD Students

Mustapha Adamu (Monash University)
Xinyang Fan (U.Melb)
Jessica Hargreaves (ANU)
David Hoffmann (Monash University)
Chiara Holgate (ANU)
Mengyuan Mu (UNSW)
Manon Sabot (UNSW)
Lina Teckentrup (UNSW)

In the past year, the ARC Centre of Excellence for Climate Extremes (CLEX) Drought research program has challenged some of the fundamentals of modelling drought, improved important data sets for the global community, and added key observations that underpin our climate extremes work.

Droughts are relatively infrequent and, compared to other climate extremes, they occur over longer periods of time. This makes observations particularly important but also particularly challenging, as we need a longer-term perspective to separate natural variability from any human-caused climate change effects on drought. For this reason, research by Associate Investigator Linden Ashcroft that seeks to recover centuries-old weather records is particularly valuable. Working with international weather data-rescue initiative, Atmospheric Circulation Reconstructions over the Earth, Linden was an author on a paper that described an inventory of 4583 unique entries of weather data from 2250 locations around the world. The paper highlights key goals for data-rescue groups and continues Linden's Australia work, which has led to the recovery of pre-instrumental meteorological observations from across the country that help to reveal the extent and impact of droughts in early settlement.

A perfect example of why observations matter was revealed when researchers from two CLEX research programs, the Drought program and the Heatwaves and Cold Air Outbreaks program, were able to discern the global and regional impact on the crop yield of wheat, rice, maize and soybeans as a result of gradual climate change and extreme events. Intriguingly, they found that seasonal heat extremes were more important than precipitation extremes when it came to yield impacts for these crops. The only exception to this was in south-west Western Australia, where precipitation variability played the leading role in yields of spring wheat.

Equally important is the impact of drought on our natural world. A key part of understanding these impacts now and into the future is to accurately determine at what stage droughts result in tree mortality. Working with colleagues from the Hawkesbury Institute for the Environment, Centre researchers examined eight species of eucalypt to determine how long it would take for these trees to completely dehydrate under drought conditions. The variation was considerable; between 96 and 332 hours. This research is a start on improving our ability to predict the timing of drought-induced mortality at tree and forest scales.

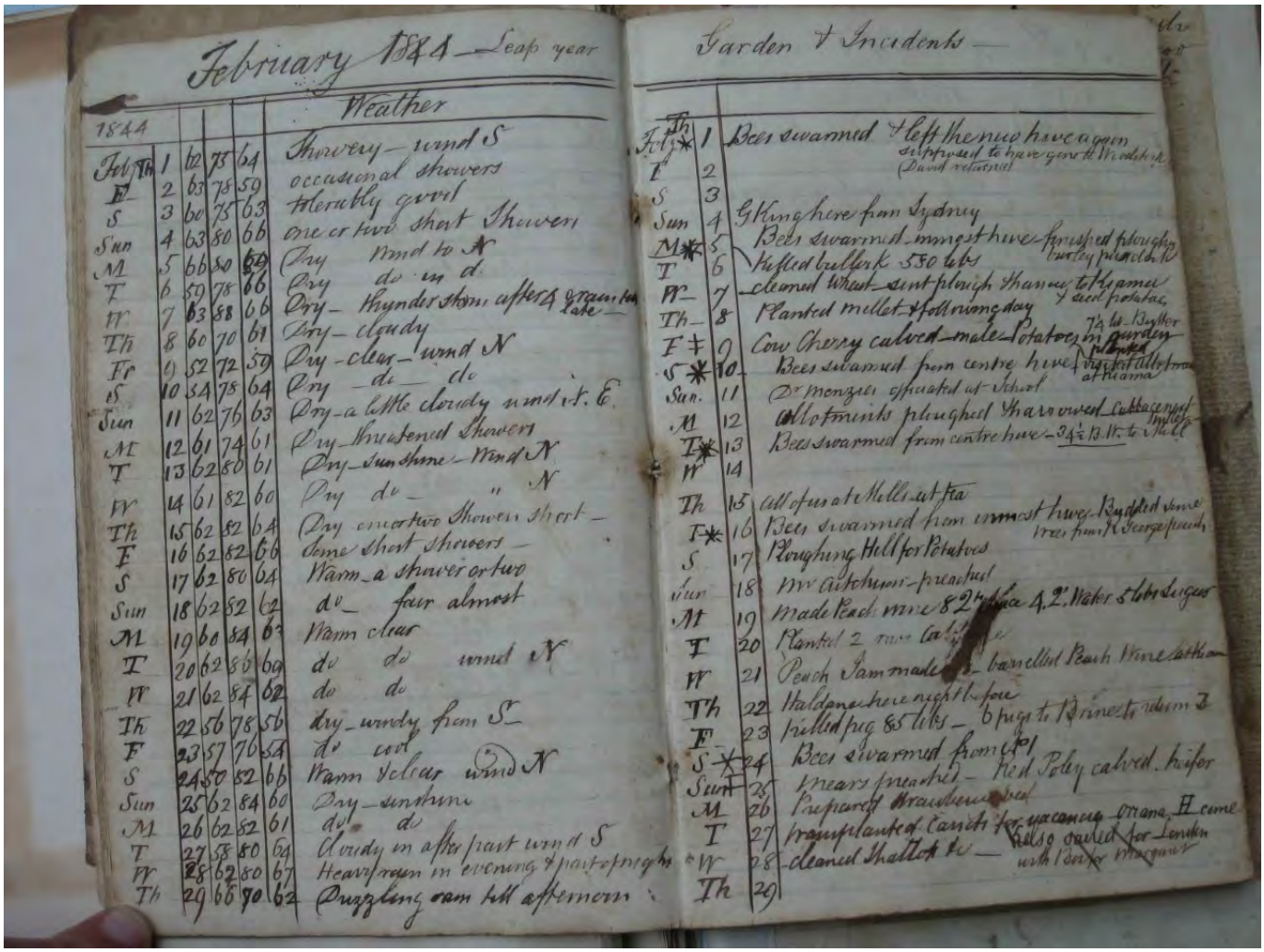


Fig 1 Excerpt from 1844 meteorological records for Jamberoo, NSW. Held at Mitchell Library. See more at http://www.met-acre.net/MERIT/AMETA.html

Our researchers have also been involved in important observational research of vegetation at a global level. CLEX researcher Martin de Kauwe is part of the international first generation of Free-Air Carbon Dioxide Enrichment (FACE) experiments that will set up observation platforms in the Amazon forest and which already has platforms in Australian eucalypt forests. These experiments reveal the response of vegetation to increased CO_2 via the stomata on plant leaves, as well as the important role that soil nutrients will have in mediating this response.

One of the key features of the Drought program is that observations like those in the FACE experiment of seemingly minor processes often can amplify the effects of climate and weather. Our drought researchers worked with colleagues in the extreme rainfall program and examined the long-asked question of whether rainfall followed wet soils. The researchers found that the amount of moisture already present in the soil could alter precipitation both in the north and south of Australia. While in the north wetter soils produced more rainfall, the opposite occurred in the south. These results further demonstrate the complexity of coupling between the land surface and the atmosphere, which add to the difficulty in providing accurate regional projections of future climate change over Australia.

To get results like these, climate researchers often have to rely on national and international observational data sets. These feed into our models and give us perspective on the historical climate. This is why an important part of our research is to improve existing data sets and to create new data sets of what sometimes seem to be small processes to help us answer many of the difficult climate questions we face.

At the land surface, energy and water are coupled via evaporation and this is central to linking rainfall and runoff with radiation, humidity and temperature. To that end, Drought program researchers produced a data set that increases the accuracy of global river flows by developing a reanalysis-type product based on assimilating available hydrologic and meteorological data. We expect to make increasing use of this important baseline data in coming years.

The Drought program team also tested and improved a data set for land degradation over Australia and found that the new data set reduced the uncertainties for Australia. A previous version of the data set had caused significant errors in trends over some of Australia's dryland regions because of problems in calibrating the satellite images. These problems have now been corrected after the researchers identified and accounted for the data artefact that caused the errors in the updated data set. This new version can now be used globally.

The recurring theme in the Drought program, namely that small changes can make a big difference, can also be found in the relationship between radiation, evaporation and surface temperature over wet surfaces, which has been an area of intense study for 50 years. This relationship is important for estimating evaporation from saturated land surfaces. To test a new formulation developed to explore this relationship in climate models, Centre researchers used newly available satellite data for radiation to investigate how radiation, evaporation and temperature interact over the largest wet surface they could find – the global oceans. The results showed that at both global and local scales the observed evaporation from the oceans occurs at the maximum possible rate. They suggest that the concept of a maximum in the evaporation from the ocean is a natural attribute of any extensive wet evaporating surface. This work has provided fundamental new insight into how radiation, evaporation and temperature are interlinked over very wet surfaces and it is hoped this will stimulate research into evaporation from saturated surfaces on land.

Continuing with work on fundamental processes that may influence future modelling work, an international team including CLEX researchers found that a process known as mesophyll conductance had a significant impact on how plants respond to increased carbon dioxide levels. This not only affects plant growth but also carbon and water exchanges. Importantly, mesophyll conductance is not currently included in climate models. Whether or not the mesophyll conductance changes how climate models project regional changes in climate remains to be seen, but this is an important first step in ensuring our models represent all of the key processes properly.

This theme of observations being used as the basis for informing and improving our climate models was also extended to studies on global aridity. The widely used Aridity Index (AI) only considers one aspect of aridity – how dry the atmosphere is – and predicts relatively drier atmospheres worldwide over the last 50 years. However, observations of other aspects of aridity (vegetation cover, river runoff) suggest a more complex interaction. With this in mind, Drought program researchers analysed climate model predictions of rainfall, runoff and plant productivity that more directly reflect landscape dryness. Their new analysis produced a very different picture. In the global average, climate models predict higher rainfall, runoff and plant photosynthesis, suggesting a globally averaged wetter future. Regionally, both increases and decreases are predicted. For Australia, climate models suggest increased plant productivity (because of elevated CO_2) and possible increases in runoff. Our researchers concluded that in the current implementation, the widely used AI was too simplistic to capture the many different perspectives that define landscape aridity, including the amount of rainfall, water resources and vegetation productivity, and that the AI is a poor indicator of future aridity changes.

Climate models themselves can also generate contradictory results that require deeper investigation. Vegetation responses to a changing climate were the key to a paper that found droughts may not increase as a result of climate change. This finding resulted from Centre researchers investigating an apparent climate model contradiction that saw climate change projections of the 21st Century showing increasing droughts at the same time as more runoff and a general greening of the landscape. This work, published in *Nature Climate Change*, showed that off-line climate impact models had not factored in how vegetation growth and water use responds to increasing atmospheric CO_2. Once taken into account, researchers found that climate impact models project a warmer future with more vegetation but little change in droughts – in line with some current climate model projections. However, as we have noted in previous work, current climate models do not simulate drought processes well, so whether droughts increase or decrease with increasing atmospheric CO_2 remains an open question.

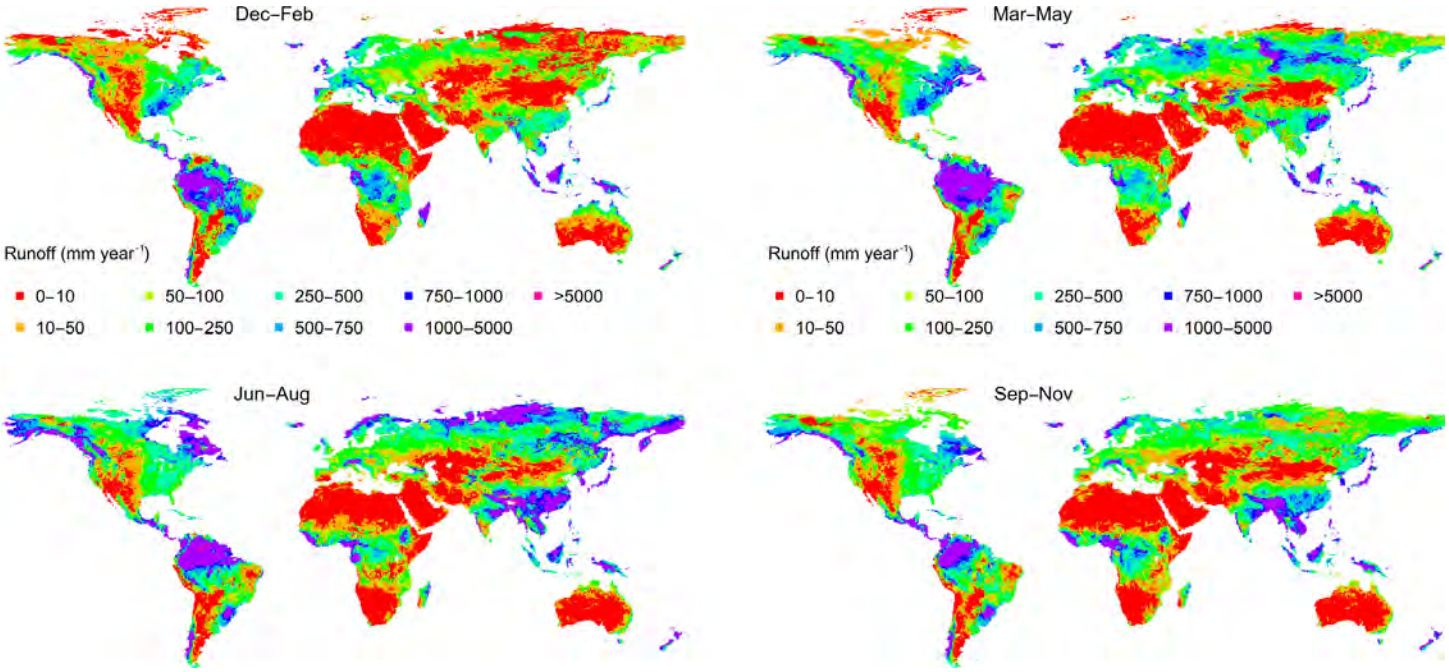


Fig 2 – Global runoff. Mean seasonal runoff (mm year^{-1}) calculated for the period 1980–2012. There is consistently low runoff in arid regions and high runoff in wet regions across all the seasons. Overall, there is a clear agreement between the spatial distribution of runoff and the different climate regimes. From Hobiechi et al https://doi.org/10.5194/hess-23-851-2019

Improving and testing climate models has been a key part of the past year's work. Research on photosynthesis processes was key to the development of a new algorithm that will help improve prediction around the function of ecosystems in the future as regions experience climate change. It has long been known that plants can adapt to variations in temperature, either permanently through genetic evolution or through short-term, reversible temperature responses. However, this ability to adapt in these two ways has proved difficult to conceptualise in an algorithm that could be used in climate model applications. A new multi-institutional collaboration involving CLEX researchers showed how to include current knowledge in a suitable algorithm. This research will help agricultural and ecosystem researchers understand future vegetation changes with global warming, and has the potential to be included in climate models in the form of a vegetation feedback.

Earlier this year, we used the Comins and McMurtrie analytical framework to determine if the influence of soil nutrients on the carbon dioxide fertilisation effect was accurately reproduced in a range of climate models. Using this framework allowed us to unlock insights into the representation of plant nitrogen uptake. Overall, our results highlighted the fact that the quasi-equilibrium analytical framework was effective for evaluating both the consequences and mechanisms through which different model assumptions affect predictions.

One important area where errors can creep into modelling outcomes is through misclassification in the assumed land cover. Our researchers examined whether simulations of air temperature and rainfall were impacted in areas where there was a low accuracy for land cover classification, with a particular focus on East Asia. The results showed that misclassification-induced land cover change does affect key biogeophysical characteristics (albedo, leaf area index, and roughness length) that modify the sensible and latent heat fluxes from vegetated surfaces at regional scales. However, we found that the impact on regional air temperature was very limited and was restricted to the Tibetan Plateau, where warming of up to 2°C occurs, associated with the replacement of barren or sparsely vegetated land with grassland. The impact on regional rainfall was negligible. Overall, we concluded that uncertainties in the reconstruction of land cover have negligible impacts over the south-east Asian region and that we can use standard satellite-based products (i.e., the Moderate Resolution Imaging Spectroradiometer land cover product) to specify the land cover in regional climate simulations over East Asia.

Getting our models right matters in real-world terms, as shown by work from Associate Investigator Ben Henley, who looked at how Melbourne's water supply may change in the future. The resulting paper, published in *Environmental Research Letters*, found that climate change was likely to put a strain on Melbourne's water supply if global average temperatures were to reach 2°C above preindustrial levels. It highlighted how the water reserve would shrink and, importantly, highlighted the critical importance of the recently constructed desalination plant that would help Melbourne maintain a secure water supply in a warmer world.

While this was a fascinating year for research there are already signs for a strong research performance in 2020 after CLEX post-doc Anna Ukkola was awarded a very competitive Discovery Early Career Researcher Award (DECRA). The goal of Anna's DECRA is to increase the predictability of seasonal droughts in the Bureau of Meteorology's seasonal prediction system.

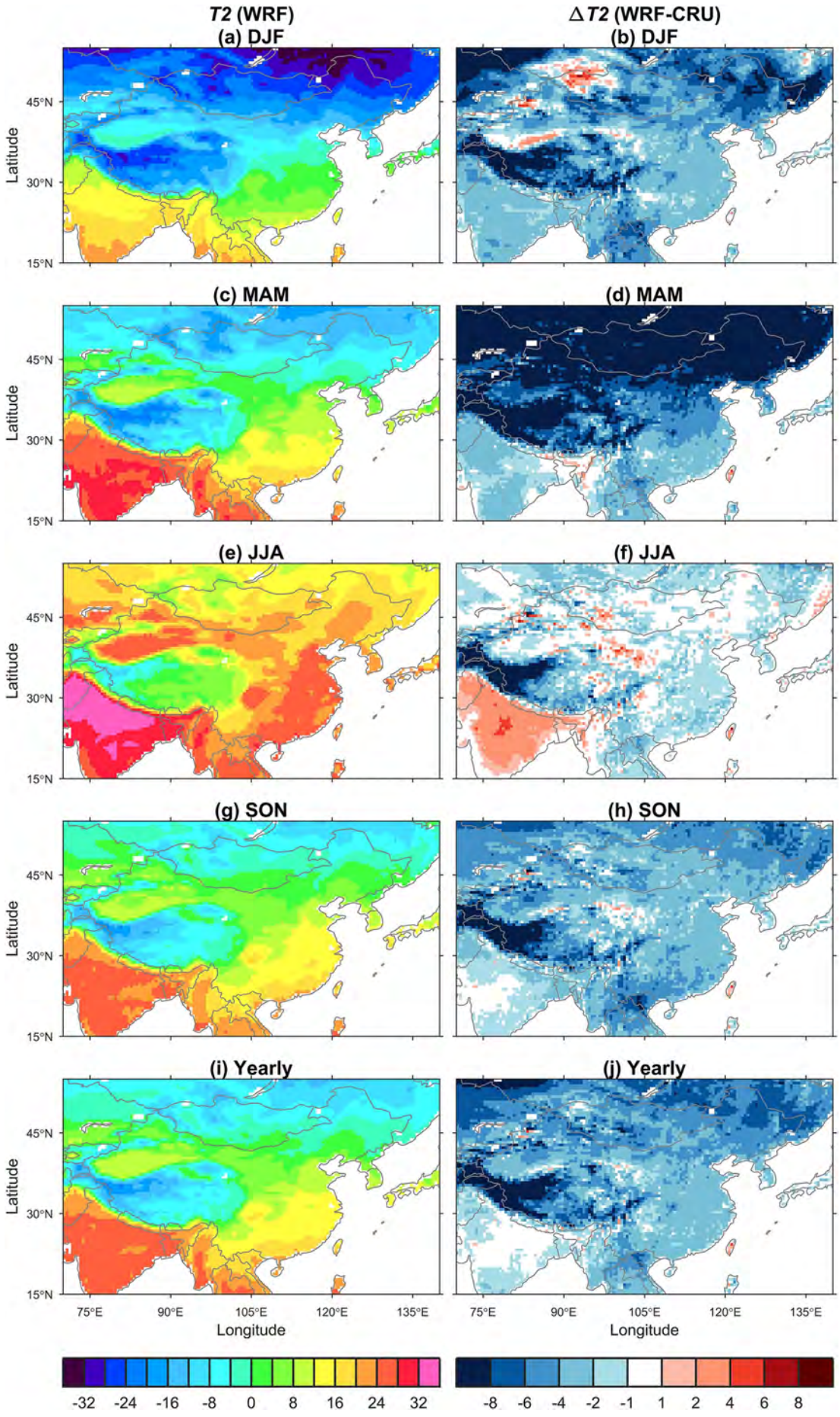


Fig 3: Two-meter air temperature (T2, °C) from Weather Research and Forecasting (WRF) control simulation (left column), and the bias in 2-m air temperature (ΔT2, °C) between WRF and Climatic Research Unit (CRU) TS4.01 (right column, WRF minus CUR TS4.01) in winter (December-January-February [DJF], a and b), spring (March-April-May [MAM], c and d), summer (June-July-August [JJA], e and f), autumn (September-October-November [SON], g and h), and averaged on annual scale (i and j). From Jun Ge, Andrew Pitman, et al 2019. https://doi.org/10.1029/2018JD029945

Meanwhile, Martin, de Kauwe along with national and international colleagues, was the recipient of two grants. The first grant for $450,000 focused on Eucalypt Futures: using functional traits to predict species distributions and responses to environmental change. The second from the US Department of Energy was for $320,000 as part of the ongoing FACE experiment. Martin and colleague Daniel Falster were also awarded $15,000 by the Australian Academy of Science to host a Boden Research conference that will promote research on the representation of eucalypt ecology and physiology in vegetation models, with the over-arching question being "What makes eucalypts distinct?"

Amid all this research we have continued to add to our Drought program team. We welcomed a new Associate Investigator, Linden Ashcroft, to our University of Melbourne node. Linden is an expert in historical weather records and will be using documentary records and paleoclimate data to explore the droughts of the past, their causes, and how they may change in the future. We also welcomed PhD student Lina Teckentrup and masters student Mustapha Adamu.

Over the past year we continued to strengthen our international connections, being visited by Partner Investigator Professor Dani Or from ETH Zurich, who collaborated with Chief Investigator Mike Roderick and Luke Parsons from the University of Washington who worked with Ben Henley.

The Drought team not only welcomed international visitors but has in turn been recognised nationally and internationally for the quality of its work. Associate Investigator Tim McVicar recently won the Chinese Academy of Sciences (CAS) President's International Fellowship Initiative Distinguished Scientist Award for 2020. The award will involve one to two weeks intensive interaction with the CAS Institute of Geographic Sciences and Natural Resources Research, CAS Institute of Tibetan Plateau Research, and CAS Institute of Remote Sensing and Digital Earth.

We were also delighted to see Drought program researchers pick up a range of national awards. CLEX Director Andy Pitman was recently awarded the Royal Society of Victoria's prestigious Medal for Excellence in Scientific Research. Chief Investigator Nerilie Abram was promoted to professor and in more or less the same week was awarded the Priestley Medal of the Australian Meteorological and Oceanographic Society. We were also delighted that PhD student Manon Sabot and research associate Sanaa Hobeichi were part of the UNSW Women in Maths & Science Champions group, which won the UNSW President's Award for Embracing Diversity. ■

Drought RP Statement of Intent for 2020

Project	Priority	Intent
3.1	1	Improved gridded observationally-based estimate of Australian surface water budget components over millennium drought period
	1	Can recent Indian and Pacific Ocean variability explain the current drought in Australia?
	1	Modelling experiments assessing the contribution of Indian and Pacific Ocean SST variability to Australian rainfall and temperature anomalies and drought
	2	Quantify how climate change is altering the modes of variability important for southern Australian rainfall, and how this is changing the odds of consecutive years of below average rainfall (drought as a compound event).
	3	Identify the climatic conditions that characterise Australia's worst droughts, including megadroughts over SE and SW Australia, and how the duration and frequency of these events might change in the future
3.2	1	Undertake an assessment of drought metrics in existing last millennium model experiments
	1	Assess drought metrics in existing historical and 21st Century experiments, in comparison with known historical droughts
	1	Examine CMIP6 simulations of the water cycle variability and drought
	2	Compare drought metrics in existing models with palaeoclimate evidence
	3	Begin new multi-century experiments to test drought variability over long and pre-anthropogenic time periods
	3	Assessment of drought indices in multi-century experiments run in previous year.
3.3	1	Improved gridded observationally-based estimate of Australian surface water budget components over millennium drought period
	1	Evaluation of soil-groundwater interactions and CABLE parameterisation in the context of heatwaves and drought
	1	Examine how well CMIP-5 models capture the characteristics of observed droughts including the Millennium drought.
	2	Using the existing UNSW WRF ensemble runs, understand the relative roles of large scale advection and local land-atmosphere coupling on surface drying throughout the Millennium drought
	2	Examine the ability of WRF and ACCESS to simulate the droughts. Then analyse them to determine the relative role of advection and local coupling on the drying as the drought evolves
	3	Compare local processes with advected processes in the context of drought
	3	Test whether new approaches to hydrology and vegetation responses to drought improve simulations and change future projections of droughts
3.4	1	Improved gridded observationally-based estimate of Australian surface water budget components over millennium drought period
	1	Improved gridded observationally-based estimate of biomass in Australia over millennium drought period
	1	Systematic assessment using observations of continental scale vegetation response to rainfall/drought
	1	Incorporate and test plant hydraulics in CABLE and use to predict where trees will die during drought
	1	Develop and test a new method for representing ecosystem drought stress in land surface models
	1	Test alternative model structures of vegetation responses to drought
	2	Systematic assessment using observations of continental scale hydrologic response to rainfall/drought
	2	Assessment of how well CABLE simulates the vegetation-hydrologic response to drought
	2	Improve the representation of key vegetation-hydrology processes in CABLE to reflect new understanding of drought, and repeat model evaluation.
	3	Systematic assessment of how well we can estimate surface (vegetation-hydrologic) feedbacks to the atmosphere.

Priority levels: 1 = to be achieved in 2020. 2 = substantial progress in 2020. 3 = progress towards in 2020.

CLEX researchers make the impossible possible

CLEX scientists developed an innovative method using cores drilled from coral to produce the world's first 400-year long seasonal record of El Niño events, a record that many in the field had described as impossible to extract.

The 400-year record revealed a clear change in El Niño types, with an increase of Central Pacific El Niño activity in the late 20th Century and suggested future changes to the strength of Eastern Pacific El Niños. This extraordinary result was made possible because coral cores – like tree rings – have centuries-long growth patterns and contain isotopes that can tell us a lot about the climate of the past. However, until now, they had not been used to detect the different types of El Niño events.

The key to unlocking the El Niño record was the understanding that coral records contained enough information to identify seasonal changes in the tropical Pacific Ocean. However, using coral records to reconstruct El Niño history at a seasonal timescale had never been done before and in fact many people working in the field considered it impossible. It was only after CLEX researchers worked on an innovative approach with a team of climate scientists and coral experts that they were able to proceed with the idea.

While the approach was considered challenging, CLEX researchers felt that it was worth a shot. After carefully refining the technique to reconstruct the signature of El Niño in space and time using new machine learning techniques, the scientists were able to compare recent coral results with the instrumental record. They found a strong agreement between the coral cores and recorded events. This confirmation allowed the team to extend the data beyond the instrumental record.

The researchers found there has been an unprecedented increase in the number of El Niños forming in the Central Pacific over the past 30 years, compared to all 30-year periods in the past 400 years. At the same time the stronger Eastern Pacific El Niños were the most intense El Niño events ever recorded, according to both the 100-year long instrumental record and the 400-year long coral record.

This world-first seasonal El Niño record and the new methodology that brought it about will likely be the basis for considerable future climate research. ■

CLEX all at sea

CLEX researchers and students have been involved in two major field trips with the RV Investigator in 2019.

The first month-long voyage left Fremantle in May and was Australia's main contribution to a large international effort: the second International Indian Ocean Expedition (IIOE 2). IIOE 2 is being conducted from 2015-2020 by numerous countries to reveal new information on the Indian Ocean, especially looking at changes since the last expedition in the 1960s.

The CLEX group on this voyage was part of the physical oceanography team led by Dr Helen Phillips. The team was responsible for preparing, guiding, sampling and analysing conductivity, temperature and depth (CTD) measurements. More than 50 CTD profiles were taken during the trip, half of which were deep CTD, down to 5000m. Using a variety of other instruments attached to the CTD, they were able to collect high vertical resolution profiles over 20 stations, which will give researchers an idea of the vertical and horizontal structure of physical and biogeochemical conditions along the 110E line. Along with being responsible for the CTD measurements, the team also deployed NOAA and BoM drifters as well as Argo and deep-Argo floats. Data collected by such devices are valuable, especially for model or satellite calibration (drifters) and measuring the ocean's subsurface (Argo).

The second major voyage that included CLEX researchers and students was a two-leg expedition. The first leg over three weeks, from October 19 – November 11, departed from Darwin and travelled to the NW shelf while the second leg five-week expedition, from November 11 – December 17, travelled from Darwin to Warruwi Station. The voyage was part of the international Years of Maritime Continent. It aimed to:

- Sample different phases of the Madden-Julian and other monsoon oscillations;
- characterise the 3D mesoscale atmospheric dynamics of a coastal locations in Northern Australia;
- characterize in detail the diurnal through monthly evolution of the upper ocean and near surface structure to advance our understanding of atmosphere–upper ocean coupling;
- and construct detailed datasets of clouds, air-sea fluxes and atmospheric turbulence and make all datasets available to the international Years of Maritime Continent (YMC) science community.

Student researchers on both voyages contributed reports to the CLEX newsletter, which went into detail about life aboard the R V Investigator and the scientific work they carried out. ■

“Changes to sea ice around Antarctica, droughts in South America, unusual weather across Australia, marine heatwaves around the world, slowing currents in the Atlantic and variations in trade winds have all been caused by events and/or climate drivers thousands of kilometres away.”

RP 4: Climate Variability and Teleconnections

Highlights

- Research using coral palaeoclimate records spanning 400 years showed El Niño events have become stronger and more diverse in recent decades
- Paper published in Science on pantropical climate interactions has important ramifications for climate prediction and projections
- We highlighted the role of the tropical Indian Ocean in driving the rapid Antarctic sea ice decline in recent years
- We showed the rapid warming of the Southern Hemisphere since 2005 is a combination of human influence in the climate system and climate variability
- Research investigated the sensitivity of marine heatwaves to ocean model resolution in ACCESS at 1°, 1/4° and 1/10° resolutions. The patterns of marine heatwaves are well represented, with the 1/10° model having the least bias.
- We showed the rapid warming of the Southern Hemisphere since 2005 is a combination of human influence in the climate system and climate variability.
- We had a strong role in the IPCC Special Report on Oceans and Crysophere Change via Nerilie Abram and Nathan Bindoff. Both played a major role in public and government briefings.
- We had a significant role in the 2nd Tropical Pacific Observing System Report. The report calls for "for an expanded motivation for and redesign of the backbone Tropical Pacific Observing System"
- Numerous awards and recognition for RP4 members including Amelie Meyer, Scott Power and Matt England, among others.

Team

Co-leads

Prof Matthew England (UNSW)
Prof Andy Hogg (ANU

Chief Investigators

Prof Nerilie Abram (ANU)
A/Prof Julie Arblaster (Monash University)
Prof Nathan Bindoff (UTAS)
A/Prof Dietmar Dommenget (Monash University)
Prof Neil Holbrook (UTAS)
A/Prof Peter Strutton (UTAS)

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Prof Nicolas Gruber (ETH Zurich)
Dr Robert Hallberg (GFDL)
Dr Harry Hendon (BoM)
Dr Simon Marsland (CSIRO)
Dr Richard Matear (CSIRO)
Dr Gerald Meehl (NCAR)
Prof Joellen Russell (University of Arizona)
Dr Peter Stott (Hadley Centre/Met Office)
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Abhishek Savita (UTAS)
Serena Schroeter (UTAS)
Shweta Sharma (UNSW)
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DongXia Yang (Monash University)
Nicholas Yeung (UNSW)
Wenhui Zhao (Monash University)

One of the striking features of this year's ARC Centre of Excellence for Climate Extremes (CLEX) Climate Variability and Teleconnections research program has been how it revealed the deep interconnectedness of the climate system. Changes to sea ice around Antarctica, droughts in South America, unusual weather across Australia, marine heatwaves around the world, slowing currents in the Atlantic and variations in trade winds have all been caused by events and/or climate drivers thousands of kilometres away.

In Australia, we have become accustomed to the powerful influences of distant teleconnections through the well-established effects of El Niño events. Research published in *Nature Communications*, led by Chief Investigator Neil Holbrook, together with numerous CLEX colleagues, showed that remote climate modes and their teleconnections, such as those connected to El Niño/La Niña, can potentially enhance or reduce the likelihood of marine heatwaves.

What we hadn't been able to discern, because the instrumental record was too short, was whether El Niños are changing. That is, until now. In what is perhaps the highlight of our research effort this year, a former CLEX PhD student who has now moved on to CSIRO, Dr Mandy Freund, produced a world-first 400-year-long observational record of El Niño events using coral cores. What made this result particularly rewarding was that many people considered such an approach to be impossible. Mandy's research showed that recent changes in El Niño activity were out of the ordinary, particularly in the past 30 years, and that there were shifts in location and potentially the intensity of recent key events.

As well as looking back, we also looked forward this year to see what may happen to El Niños in the future. A paper in Nature by Centre of Excellence researchers brought together a wide range of models to determine if there was consensus on how El Niños may change with global warming. The results across multiple models indicated a future increase in their strength and impact. But that is not the only change to El Niños. It has long been assumed that extreme heat and extreme convection coincided under very strong El Niño events. However, research by Associate Investigator Agus Santoso and colleagues has shown that as El Niños change with global warming, this may not always be the case. It is yet another indication that as the planet warms our expectations of the behaviour of seasonal events will have to change.

The current knowledge of the El Niño - Southern Oscillation (ENSO) and how it will change in a warmer world is summarised in an American Geophysical Union monograph titled "El Nino Southern Oscillation in a Changing Climate", edited by Michael McPhaden, Agus Santoso, and Wenju Cai. Several CLEX members and associates contributed to the book project, which is scheduled to be published in 2020. The book consists of 21 chapters on various aspects of ENSO and has 98 contributing authors. Notably, Neil Holbrook, along with Associate Investigators Andrea Taschetto and Shayne McGregor, led some of the chapters. Coordinating the book was a massive effort, involving a meeting of authors at CSIRO Hobart in February 2019, led by Agus Santoso.

A strong influence on the development of El Niño is Pacific Ocean trade winds. New research has extended the influence

of these winds on the world's climate even further. The strength of trade winds as they blow across the Pacific was found by our researchers to have the capacity to accelerate or decelerate global warming. Intriguingly, the strength of the trade winds was linked to a low-frequency climate phenomenon, the Interdecadal Pacific Oscillation, which is now entering a positive phase. This suggests Pacific trade winds could slow, leading to accelerated global warming.

The influence of the Pacific Ocean on global climate is also felt below the surface. A paper by Ryan Holmes and colleagues showed how the heat taken up in this ocean influences major currents in the Atlantic Ocean, including the Atlantic overturning circulation, which is a key climate driver for regions around North America and Europe.

A paper led by student Jiale Lou, together with Neil Holbrook and Associate Investigator Terry O'Kane, demonstrates the importance of the Pacific Decadal Oscillation (PDO) and the upper layers of the South Pacific Ocean to decadal climate variability, and how it is driven by much higher frequency forcing via the Pacific-South America pattern. This is analogous to the relationship between the Aleutian Low as a driver of the PDO in the Northern Hemisphere. Centre researchers found the South Pacific relationship to be even stronger.

Much of the heat taken up by the Pacific Ocean and other ocean basins that goes on to influence the world's climate is derived from the tropics. The importance of the tropics is why researchers from the Variability program team have called for an improvement to the Tropical Pacific Observing System (TPOS). This observing system is crucial in monitoring and

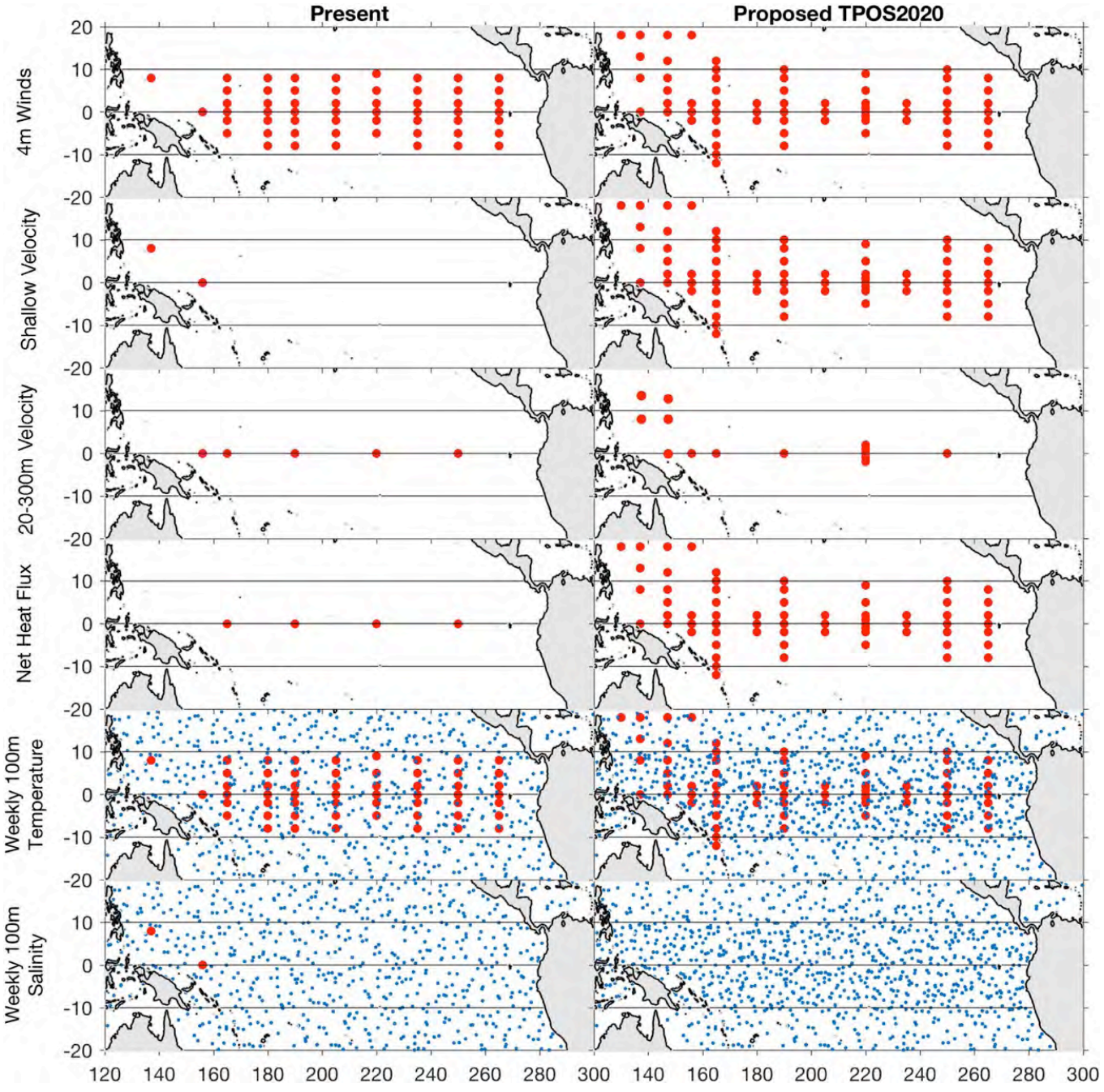


Fig 1: Tropical Observing system. Proposed Tropical Observing System. Schematic showing data from moorings (red) and profiling floats (blue) for key variables of interest between the present observing system (left) and the proposed tropical Pacific observing system (right).

forecasting the development of El Niño and La Niña events. A paper by Centre researchers and colleagues called for four important changes to TPOS, and also looks ahead at future requirements. It is a vital investment for Australia, the Pacific Rim and beyond.

A key tropical region with significant climate influence is the Indo-Pacific – an area that includes the Indian Ocean and the Central and West Pacific Ocean. This is an important region of intraseasonal variability characterised by the Madden-Julian Oscillation (MJO). Neil Holbrook and Associate Investigator Eric Oliver, together with international colleagues, demonstrated the importance of the MJO on wet season rainfall over Iran and its influence on the Costa Rica midsummer drought. This research demonstrates the far-reaching climatic teleconnections across two key ocean basins and rainfall changes that potentially are predictable. Neil, Eric and their PhD student also demonstrated the potential seasonal predictability of tropical cyclone tracks and landfall into North Indian Ocean rim countries, using a statistical forecast model that employs an index of the stratospheric Quasi-biennial Oscillation.

The importance of the Indian Ocean to the world's climate is why Centre researchers contributed to an observing system design for the Indian Ocean. As we discovered in 2019 with a record-strong Indian Ocean Dipole (IOD), this ocean basin also has a powerful influence on Australia's climate. The strongly positive IOD reduced rainfall across much of the country, adding to the precursors that brought about our dangerous bushfire season experienced in the summer of 2019/20.

Research by Chief Investigator Nathan Bindoff and colleagues has also uncovered new insights into how heat moves from the Indian Ocean to the atmosphere, which will improve how this is represented in climate models. Another study, by former CLEX honours (and current PhD) student Annette Stellema, also projects a slowing of Indian Ocean circulation in a future warming world. These changes matter because the Indian Ocean's influence can extend to the other side of the world. Work by Andrea Taschetto and fellow AI Alex Sen Gupta, with South American colleagues, revealed that strong convection over the Indian Ocean was responsible for the 2013/14 drought in South America and the accompanying marine heatwave. The research indicated this was not the first time Indian Ocean convection had played a role in droughts over South America, and that it was likely to occur again.

The influence of the Indian Ocean also extends far to the south. Its influence on distant global climate was seen again when Centre researchers, including Chief Investigator Julie Arblaster and PhD student Dongxia Yang, in collaboration with national and international partners, found that it likely played the lead role in the rapid decline of Antarctic sea ice in 2016 – a loss that has yet to see a recovery. Postdoctoral researcher

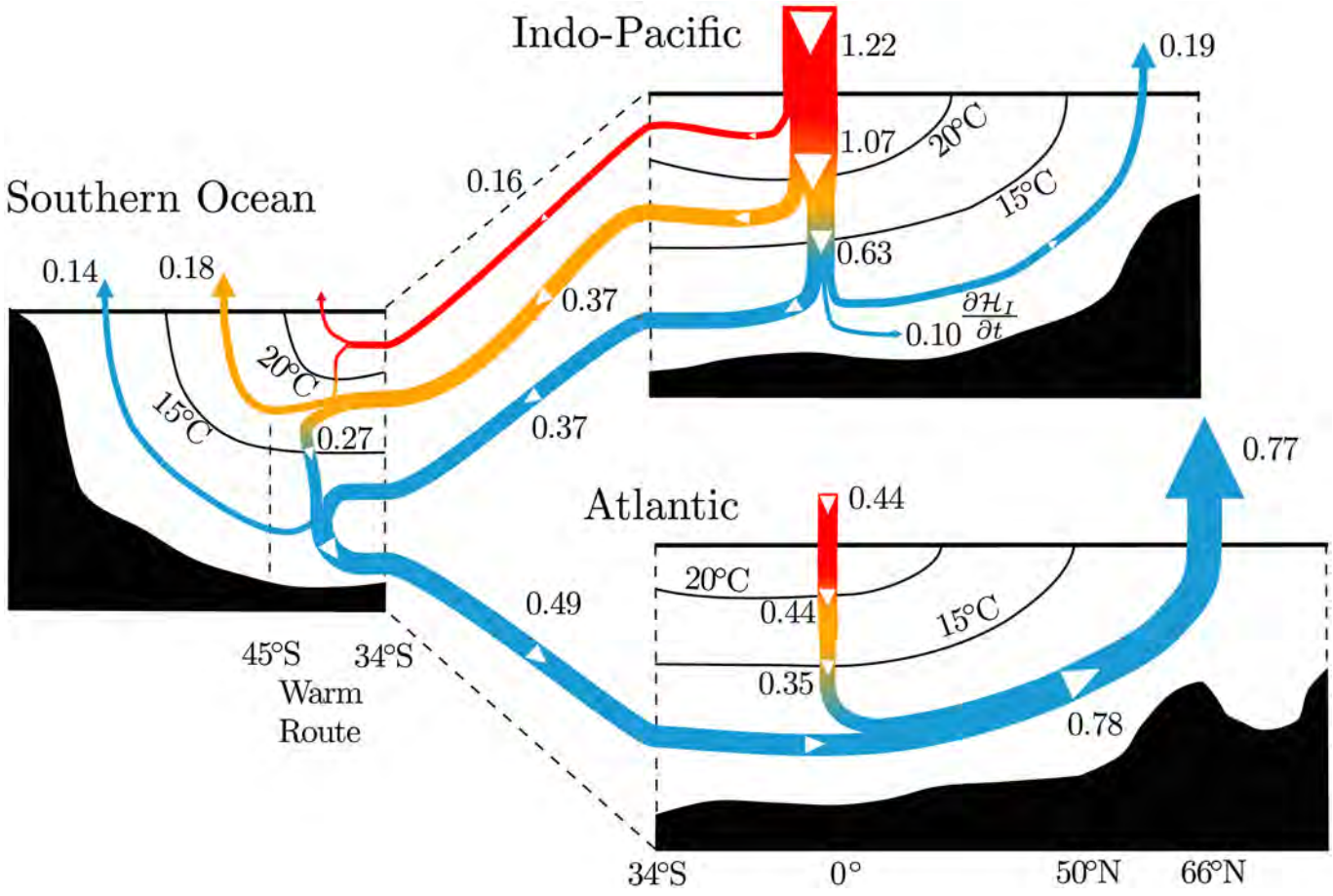


Fig 2: Ocean Heat transport. Summary of the internal heat content transports (in PW, with proportional line thickness) above, below, and across the 15 and 20 °C isotherm from MOM025 Control. From Holmes, et al, 2019. https://doi.org/10.1029/2019GL085160

Ariaan Purich and Chief Investigator Matthew England then quantified this effect using Australian Community Climate and Earth System Simulator (ACCESS) coupled model experiments. However, the wide range of variation in sea ice found during these model runs suggested this sharp decline was the result of natural variation rather than climate change.

The power of ocean currents to influence the atmosphere, absorb carbon and distribute heat makes them a vital part of the research of the Variability program team. The deep, hard-to-reach ocean currents play a particularly important role over the long term. The strongest of these is the Antarctic Circumpolar Current (ACC), which powers much of the oceanic circulation. It is considered to be the single most important current in the ocean when it comes to understanding how our oceans may respond to climate change and how ocean heat moves from the surface to the depths and vice-versa. Understanding its processes and characteristics is vital work. However, it exists at the abyssal depths of the Southern Ocean, making it very hard to observe. One way of tracking this deep current is by using synthetic tracers; however, we have little understanding of how they disperse at these depths and therefore how effective they may be. Using an ocean model, CLEX researchers were able to simulate how these tracers would behave on or near the ocean floor and to test their usefulness at depth. This gave an insight into the capacity and limitations of such an approach.

Another issue at these extreme depths is the influence the ocean floor has on the ACC. Fascinating research by ANU research associate Navid Constantinou and Chief Investigator Andy Hogg found that, in certain regions, the strength of the ACC was predominantly affected by the topography at the bottom of the ocean. This adds further complexity to the eddy-wind-current relationships in the Southern Ocean that play key roles in climate processes.

While the ACC drives deep Southern Ocean circulation, above the surface, extreme winds play an important role in how the ocean responds to climate change. New research by Centre researchers with US colleagues has found that the increase in wind speeds across the Southern Ocean, and the shift of these wind tracks towards Antarctica, will have an impact on how well this ocean absorbs heat and carbon from the atmosphere. The results revealed that the Southern Ocean's capacity to store heat and carbon increased with a strengthening of the winds, but the southward shift of these wind tracks had little effect. The observed increase in wind speeds in this region has seen more energy enter the ocean. This additional energy has expressed itself as high-frequency motions, but it has been unclear until now how the vortices in this part of the world have responded. The response of these vortices is important because they play a key role in controlling climate. Using satellite measurements, CLEX researchers found that the energy went into increasing the strength of these vortices rather than increasing their number.

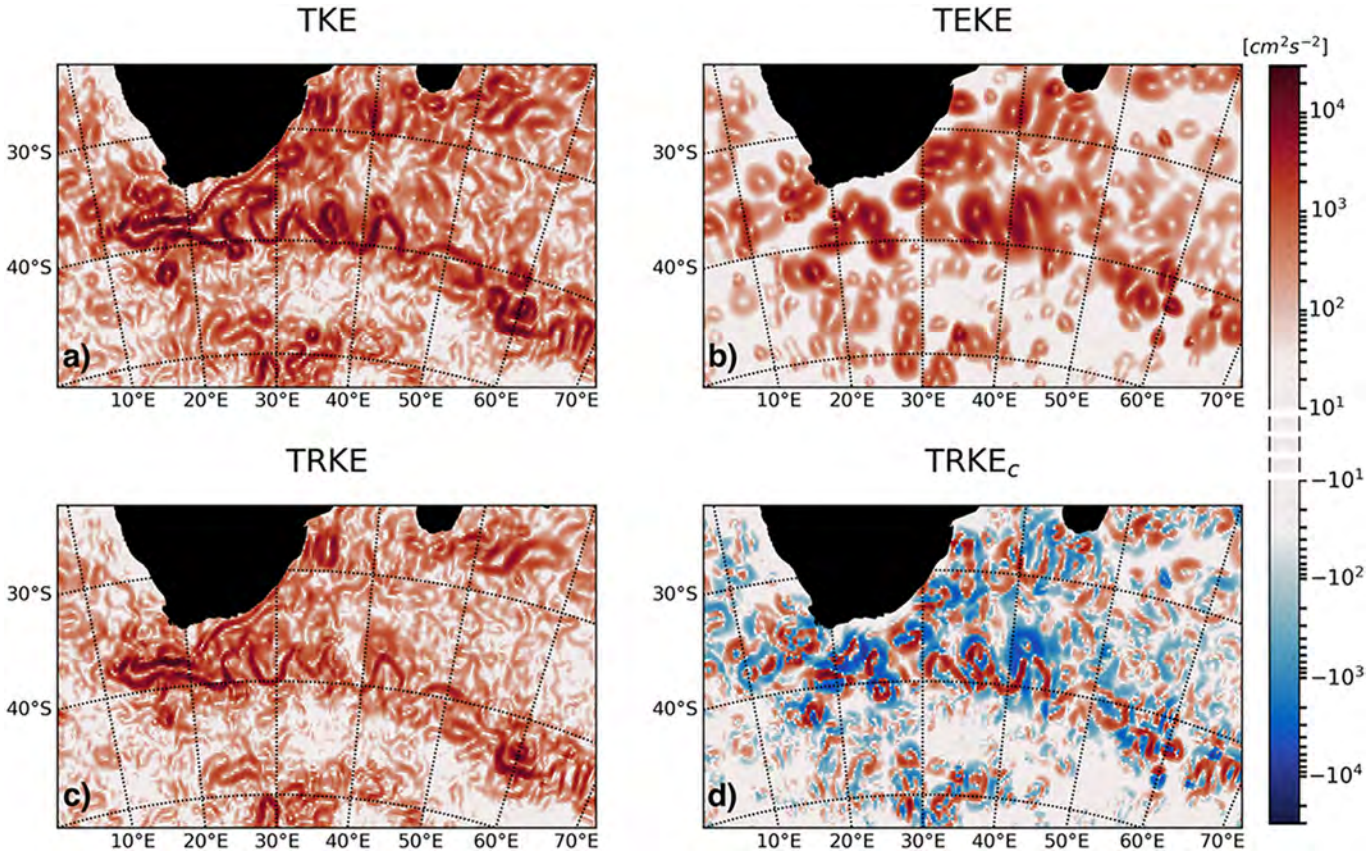


Fig 3: Magnitude of Transient Kinetic Energy and its decomposition in the Agulhas Current for a snapshot on January 1st 2016. a) Transient Kinetic Energy, b) Transient Eddy Kinetic Energy or the energy of eddy processes, c) the Transient Residual Kinetic Energy or energy of jets and waves, and d) the cross terms which correspond to the overlap between processes. From Martinez Moreno, et al 2019. https://doi.org/10.1029/2019MS001769

Centre researchers also took observations during a voyage into the Southern Ocean. These observations revealed cold eddies carried heat into the Subantarctic Zone at a rate 2.6 times greater than previously estimated. Combining these observations with satellite measurements, the researchers estimate that 21% of the heat carried across into this zone comes from these cold eddies.

Another area of strong scientific interest is the movement of circumpolar water from the Antarctic ice shelf to the depths. This has important implications for the speed of ice melt around the frozen continent and also for global ocean circulation. Taking a novel approach, Centre researchers and colleagues tagged seals with observational instruments that allowed them to track temperature changes through the water column close to these ice shelves. The research found that eddies played the most important role in this transfer of heat, salt and high-density water.

The atmosphere above the Antarctic also plays an important role in Australia's climate. At the time of writing, New South Wales is blanketed with smoke amid unseasonably hot weather, while further south, Tasmania and the Victorian Alps are experiencing late-season snowfalls. It sounds like a wildly unpredictable weather pattern but research published by the Variability program team, led by BoM researcher Dr Eun-Pa Lim, in early October, forecast the likelihood of this type of weather following a stratospheric warming event over Antarctica. It's yet another example of how seemingly unrelated distant events can have a powerful impact on Australia.

Not every link in the climate system is so clear-cut. In some cases, a correlation does not necessarily equate to causation. PhD student Zoe Gillett and a team of international researchers discovered this when they investigated a correspondence between Antarctic ozone hole observations during spring and extremely hot summer temperatures in Australia. The researchers found that ocean temperatures were key to simulating the variations of the spring ozone hole and the consequent warmer summers in Australia. So, while the ozone hole didn't necessary cause the warmer summers, as some suspected, its correlation with ocean temperatures may help us improve seasonal predictions.

As proof that Centre of Excellence research spans the globe, far to the north, the decline of sea ice in the Arctic has been strongly linked to human-caused climate change. Working with colleagues from Norway, UTAS postdoc Amelie Meyer found that the disappearance of old ice in this region wasn't just caused by summer melting; winter storms and warm-water intrusions from the Atlantic Ocean were playing an important role, too. Her research found winter storms over the Arctic leave a legacy that breaks up the ice, melts it from beneath, and has led to constant ongoing decline in old ice that far exceeds the period of the storms. Meanwhile in another area of the Arctic, and working with another team, Amelie and colleagues found limits on these warm-water intrusions. Using ocean gliders to capture observations of the warm-water intrusions of the West Spitsbergen Current (WSC), they found small, very cold eddies formed by melting freshwater acted to prevent deeper penetration of these currents, rapidly cooling the WSC.

While these observations reveal important insights, much of the work that helps reveal climate connections is performed in climate models. For this reason, part of our research effort is dedicated to improving these tools. As part of these investigations, Centre researchers found that optimising a climate model ensemble to perform well in one variable not only degrades estimates in other variables but results in uncertainty estimates that are too narrow. It is only when several variables are optimised independently, and the results from each optimisation are merged, that we can achieve both improved ensemble performance and improved uncertainty estimates. This research has informed our practice.

Model improvements can also reduce computing time and consequent cost. Work by Chief Investigator Craig Bishop and colleagues will help reduce this time after they developed a new technique for an Ensemble Kalman Filter that also improves its results.

The work we do on modelling and understanding ocean processes can have unexpected but very useful outcomes. For instance, research led by research associate Dr Gabriela Pilo, together with Neil Holbrook, Andy Hogg and Associate Investigator Andrew Kiss, investigated the sensitivity of marine heatwave metrics to ocean model resolution in the ACCESS ocean model - at 1°, 1/4° and 1/10° resolutions. They showed that while model-simulated marine heatwaves are weaker, longer-lasting and less frequent than in observations, the broad-scale patterns of marine heatwaves are well represented, with the highest-model resolution having the least bias.

Outside of the immediate research outcomes, the Variability program has been involved with a wide variety of ventures. Associate Investigator Helen Phillips led a multidisciplinary team aboard the RV Investigator that left Fremantle to investigate changes in the eastern Indian Ocean since the 1960s. The voyage was the Australian contribution to the Second International Indian Ocean Expedition, led by Prof Lynnath Beckley of Murdoch University. CLEX students Maxime Marin (UTAS) and Earl Duran (UNSW) were part of Helen's team. Chief Investigator Dietmar Dommenget spent six months at the Max-Planck Institute working on a variety of projects, including the evaluation of tropical rainfall in state-of-the-art climate models and helping in the development of the next generation of climate models. The Consortium for Ocean-Sea Ice Modelling in Australia community, founded by Variability program team members, continues to expand, with its fourth annual meeting held at ANU in early September. It was great to see that for the first time the two-day workshop was streamed live – an innovation we hope to see more of in the future.

We had two chief investigators who led the chapter teams for the latest IPCC Special Report on Oceans and Crysophere Change. Chief Investigator Nerilie Abram led Chapter 1 (Framing and context of the report) and Nathan Bindoff led Chapter 5 (Changing ocean, marine ecosystems and dependent communities). Both were heavily involved in the government approval session for the report, and in media duties and government briefings following its release. This report is now published. Chief Investigator Peter Strutton, along with Associate Investigator Shayne McGregor and Partner Investigator Harry Hendon, were Lead Authors on the second Tropical Pacific Observing System Report. The report calls for "for an expanded

motivation for and redesign of the backbone Tropical Pacific Observing System".

Matthew England was named as a 2019 Highly Cited Researcher by Web of Science, based on citations over the past decade. Julie Arblaster was named on this same list in 2018.

UTAS postdoc Amelie Meyer has had an outstanding year, winning the Young Tall Poppy Science Award for Tasmania and being awarded a DECRA fellowship from the Australian Research Council. PI Scott Power received an Innovation and Research Contribution Award from the Pacific Meteorological Council "in recognition of outstanding, innovative and exceptional climate change and climate variability research" and "for empowering the next generation of researchers". PhD student Sarah Jackson was awarded a fellowship from the Scientific Committee for Antarctic Research (SCAR). The fellowship will allow Sarah to collaborate with researchers from the British Antarctic Survey. This will complement her PhD research where she is applying this same technique to the Mount Brown South ice core from East Antarctica, which will provide a 1000-year long record of climate variability in the Indian Ocean sector of Antarctica. We also saw Annette Stellema and Rishav Goyal receive honourable mentions among a packed field for best poster at AMOS-ICTMO. U.Melb student Dom Thorn received the AMOS Melbourne Chapter Regional Award for his master's thesis. Many of our Associate Investigators also took out prizes in 2020. The best published paper by an honours, masters or PhD student went to Sonja Neske. The prize for best published paper by an early career researcher was won by Navid Constantinou and the CLEX Director's Prize went to Amelie Meyer. This is a great result for the program and for three very deserving winners. ■

Variability and Teleconnections Research Program Statement of Intent for 2020

Project	Priority	Intent
Tropics	1	Understand the drivers of global and Pacific SST variability on decadal time scales
	1	Investigate tropical Atlantic and Pacifc interactions on decadal time scales using idealised pacemaker experiments
	1	Quantify the role of physics and productivity in driving tropical Pacific air-sea CO2 flux
	1	Analyse tropical Pacific variability and change in mean-state corrected coupled simulations
	1	Do flux corrections of land surface temperatures for coupled model simulations
	1	Conduct review of palaeoclimate perspectives on the IOD
	1	Carry out assessment of modern-day climate signals at Christmas Island, eastern Indian Ocean
	1	Conduct review of ENSO atmospheric teleconnections with focus on seasonality using CMIP models
	1	Produce a representation of Indian Ocean variability in climate models and interactions with the tropical Pacific
	2	Explore the interactions between ENSO and the MJO, and impacts on current and future rainfall extremes in tropical Australia
	2	Study volcanic eruptions and IOD events
	2	Carry out reconstruction of tropical rainfall variability in the eastern Indian Ocean over the last 200 years
	3	Conduct perturbed physics experiments with corrected mean states to study tropical climate variability and change
	3	Develop a diagnostic model for large-scale tropical circulation changes.
SAM	1	Assess SAM response to solar forcing in last-millennium simulations
	1	Use AMIP simulations to look at tropical Pacific influence on SAM and the eddy-driven jet
	2	Investigate rapid declines in Antarctic sea ice using various model ensembles
	1	Conduct ocean-sea ice model simulations with SAMx forcing from extreme years
	1	Use idealised CESM experiments to understand what controls zonal wave 3 pattern of atmospheric circulation in the Southern Hemisphere
	1	Write SAM review paper stemming from 2019 workshop
	1	Examine the impacts of the seasonal dependence of SAM upon sea ice
	2	Study Antarctic sea ice effects on the stratosphere using CM2.1, aiming to connect ice variability with sudden stratospheric warming events
	1	Investigate SAM trends in the CMIP6 model output
	1	Write a paper on the impact of the SAM and ENSO on Southern Ocean productivity
	2	Investigate SAM extreme states over the last millenium.

Project	Priority	Intent
Oceans	1	Study intrinsic and forced variability of the Southern Ocean using OCCIPUT ensemble
	1	Compile climatology of global eddy kinetic energy
	1	Explore tropical teleconnections to Subantarctic Mode Water in observations and models
	1	Investigate drivers of warm water volume changes during El Niño and La Niña events
	1	Quantify projected changes in Circumpolar Deep Water circulation in CMIP6 models
	1	Understand physical drivers of interannual variability in Mertz Polynya productivity
	1	Use existing model runs to investigate projected changes in marine heatwaves and their impact on biogeochemistry
	1	Conduct data and model inter-comparison of standing waves in the ACC
	1	Seek to explain high heat uptake in the Southern Hemisphere
	2	Investigate whether low frequency variability in the Southern Ocean is stronger in higher-resolution ocean models
	2	Use ACCESS-OM2 to conduct simulations that include ocean and sea-ice biogeochemistry
	2	Use BGC-Argo floats in the Southern Ocean to understand (1) seasonal drivers of phytoplankton blooms and (2) biogeochemical signatures of eddies
All RP	1	Do flux corrections of land surface temperatures for coupled model simulations
	3	Investigate whether we should invest in an ACCESS-CM2-025
	3	Develop ACCESS coupled model correction scheme for land and ocean.

Priority levels: 1 = to be achieved in 2020. 2 = substantial progress in 2020. 3 = progress towards in 2020.

Computational Modelling Support

Highlights

- Configured ACCESS-ESM 1.5 for paleoclimate simulations for contribution to the CMIP6 data set
- CABLE in WRF now functional; a first paper studying the model's performance was published in 2019
- NCI installed a new supercomputer at the end of 2019; CMS helped CLEX researchers with this transition, limiting negative impacts
- We contributed strongly to facilitating the use of the CMIP6 data including improving the CleF tool which is now available in the public conda environments,
- We created a data set of climate indices for CMIP6 using Climpact2
- An initial version of the European Centre for Medium-Range Weather Forecasts release of the ERA5 climate reanalysis has been made available
- A new, improved version of DMPonline is now available to the Center's researchers to create data management plans, based on the Data Curation Center Roadmap
- ModelEvaluation.org, designed to evaluate model performance is progressing and will shortly be applied for benchmarking with land surface models.

ACCESS

A Grand Challenge simulation is among the proposals put forward by the Centre of Excellence for Climate Extreme's (CLEX). Additionally, the National Computational Infrastructure (NCI) is interested in simulations to stress-test the new supercomputer, Gadi,(STRESS2020) and has invited the Centre to submit such a simulation. Consequently, Computational Modelling Support (CMS) has helped the Centre design and implement this simulation, which will fulfil both of the aforementioned goals. It is planned to run an atmospheric simulation using the Unified Model (UM) version 11.4 at 400m resolution over the whole of Australia over a couple of days during the landfall of Tropical Cyclone Debby. Scott Wales has put together a feasibility study looking at the scalability of the model and the handling of the outputs to manage the storage requirements.

ACCESS-ESM1.5

The Earth system modelling version of the Australian Community Climate and Earth System Simulator (ACCESS), namely ACCESS-ESM1.5, is a coupled model using UM 7.3 – including the Community Atmosphere-Biosphere Land Exchange (CABLE), Modular Ocean Model (MOM)5.0 and the sea ice model, CICE 4.1 -- and coupled using the coupling software, OASIS-MCT. It was originally developed by CSIRO for Coupled Model Intercomparison Project - Phase 6 (CMIP6) modelling.

CSIRO is running ACCESS-ESM 1.5 using KSH scripts, but Holger Wolff, Aidan Heerdegen and Scott converted it to be run using the payu workflow management tool. This creates several advantages for the researchers, including more intuitive configuration, automatic configuration history using a git repository, and the ability to bundle several runs into a single submit, a feature that has been requested -- especially during times when submitted jobs would hang in the queue for a long time. Tests have been performed to ensure that the model output is bit-identical to the version produced by the KSH scripts.

ACCESS-ESM1.5 via payu has been used at the Centre of Excellence to model paleoclimate runs (PMIP4), currently Last Interglacial (lig) by Nicholas Yeung and Mid-Holocene (mh) by Josephine Brown. These runs require a modification of the orbital parameters, which in this old version of the UM need a code-change and recompilation. Preparations are being made for a model run of the last millennium. The configuration work needed for the paleoclimate runs is being done by Holger in collaboration with the researchers involved in the projects.

In December Holger was also at CSIRO, where he worked with the ACCESS-ESM team to port ACCESS-ESM1.5 to Gadi and to develop a more robust and user-friendly environment to compile ACCESS-ESM1.5. ACCESS-ESM wasn't yet available on Gadi at the end of 2019; it should be ready in the first few months of 2020.

MOM Code Harmonisation

The Consortium for Ocean Sea Ice Modelling in Australia (COSIMA) group has developed a suite of ocean/sea ice model configurations, with a hierarchy of resolutions, that are under active use by the Centre. These ACCESS - Ocean Model 2 (OM2) models utilise the latest MOM5 codebase, which has transitioned to a community-supported model. Along with members of COSIMA and CSIRO, Aidan is part of the team that supports the MOM5 model. CSIRO has developed a new coupled model configuration (ACCESS - Coupled Model 2 (CM2)) which it is using for a CMIP6 submission, but it was using an older version of the MOM5 codebase. Through a significant combined effort, particularly from Russ Fiedler at CSIRO, the MOM5 code in ACCESS-CM2 was upgraded to the most recent version at the time of harmonisation, so ACCESS-CM2 and ACCESS-OM2 are using the same MOM5 code. Also, the source code is being pulled directly from the main git repository for both projects, which makes it much easier to track code divergence and add updates when required. Harmonisation of the ACCESS-ESM-1.5 configuration is ongoing, but could not be finished in time to be included in the ACCESS-ESM-1.5 model that has been used for a CMIP6 submission.

JaC

The JaC project involves integrating the Australian-developed CABLE land surface model into the code repository of the Joint UK Land Environment Simulator (JULES) land surface model developed by the UK Meteorological Office. Doing so will provide potential benefits for the development of both models.

Work on the JaC project has involved setting up CABLE's distinct I/O requirements within the Rose-Cylc framework in which JULES runs. Danny Eisenberg introduced some of the CABLE input parameters to the JULES trunk previously, and completed that process this year. He also made modifications to the CABLE science code in collaboration with Jhan Srbrinovsky and Dr Ian Harman at CSIRO, enabling it to work within Rose-Cylc. Further changes to the science code will be required in order for it to be in line with changes that are currently being made to the JULES science code by the UK Met Office. As a result, the CABLE science code is likely to be added to the JULES trunk only next year.

Gadi

NCI replaced its supercomputer at the end of 2019. The CMS team has helped the Centre of Excellence to plan for the change and to port essential infrastructure to the new supercomputer, Gadi. Dr Claire Carouge, as the Scheme Manager for CLEX, has attended information meetings with NCI. Those helped the CMS to send tailored information about the upcoming changes to the Centre researchers. It also allowed CMS to develop strategies and processes to deal with the upcoming changes. CMS identified which versions of ACCESS, Weather Research Forecasting (WRF) and CABLE models were needed by the Centre, and started porting those to Gadi from December 2019.

A major change with Gadi is the move to a proper scratch disk space for simulation outputs. This space will not have quotas by projects but will have a time-based purging. In effect, this meant projects lost some permanent disk space between Raijin and Gadi. The CMS organised and scheduled the necessary cleanup effort. We also helped researchers to deal with their data where necessary, and archived forgotten data from former ARCCSS researchers.

Analytics

The move to Gadi was an opportunity to clean up CLEX's data spaces at NCI. To help Centre members with the clean-up, we implemented a resource monitoring service using the open-source dashboard software, Grafana. The service provides charts of NCI disk and computer resource usage for Centre projects over time, and these let both CMS and project managers see where our resources are being used. Aidan adapted existing Python monitoring tools to store data from NCI's queue and disks in the Grafana database. Scott wrote and deployed an efficient disk monitoring tool (dusql) that also uploads daily disk usage data for Centre storage to the Grafana database.

NUWRF-CABLE

The NASA Unified Weather Research and Forecast (NUWRF) model is based on the regional atmospheric model, WRF. NUWRF is distributed with additional utilities, in particular, the Land Information System (LIS) Framework. In previous years, we have used LIS to couple the CABLE model to WRF.

This year we have continued working on NUWRF-CABLE. Firstly, Claire upgraded the NUWRF version to version 9 patch 2. Then she integrated CABLE to this version. This work resulted in a research paper led by Dr Annette Hirsch on the skill of NUWRF-CABLE to simulate key elements of both the mean climate and some extremes. NUWRF-CABLE appeared to have more skills than WRF with the Noah land surface model which is extensively used around the world.

Work is now under way to update the CABLE version in NUWRF-CABLE to the version of CABLE used in ACCESS-Coupled Model version 2 (ACCESS-CM2) for its contribution to CMIP6.

Model outputs analysis

Interestingly, this year the CMS had less work helping researchers using climate models. At the same time, we received more and more help requests for data analysis. There is currently a trend to higher spatial resolution models and/or higher time frequency in data. This results in challenges in the data analysis due to the size of the data sets. Many people need to write and use parallelised codes. Although there has been a lot of development for parallelisation in popular languages such as Python in recent years, there still are subtleties and changes in the way to code that researchers need to learn. As such, CMS has spent a significant amount of time helping researchers with their analysis code but also developing and giving training. In the coming years, CMS wants to spend some time developing specialised parallelised codes to cover the most common needs of our Centre's researchers.

Data Sets

CMIP6

The second round of the Data Enhanced Virtual Laboratory (DEVL) project around CMIP6 has now concluded. CMS contributed by continued participation in the technical and steering committees, providing feedback, and with improvements to the CleF tool. CleF is now available in the public conda environments, accessible by anyone, as well as in a development environment. We added a new local query, which can also be loaded directly in a Python session, and an option to do more complex queries – both importing the module and on the command line. Results can now be saved to a CSV file or in a summary format following the user's request. We improved the documentation, and users can access a CleF demo notebook to learn how to use it. We also ran two training sessions during our regular Wednesday sessions, one of which was run by NCI at the Australian Meteorological and Oceanographic Society conference.

Additionally, Scott Wales has created a data set of climate indices for CMIP6. This was done by running Climpact2 on all the CMIP6 data available at that time. The data set also includes the indices calculated for the Australian Water Availability Project data set. This is available to all Australian researchers at NCI but is not open access. Please contact CMS or Margot Bador at UNSW for access.

ERA5

The European Centre for Medium-Range Weather Forecasts released the official version of ERA5 climate reanalysis. Currently, both monthly and hourly data is available for the main model, the wave model and for ERA5 Land. Not all years are yet available but will be released soon. It was important to provide a temporary replica of ERA5 while the Centre is waiting for storage associated with a recent LEIF grant.

We decided in consultation with the community to host a partial replica, based on users' requests. Some rules to limit what could be requested were put together, to ensure that we were prioritising the storage and time involved. Paola Petrelli then adapted the code she previously used to download ERA-interim to work for ERA5. The script automates most of the process but running it on Raijin or the VDI posed some limits. Matt Nethery from NCI helped Paola with this. Together they set up an automated download workflow that allows creating, locally, a download request that can be picked up by a remote server where the files can be downloaded more efficiently.

Publication Workflow

A new, improved version of DMPonline is now available to the Center's researchers to create data management plans. It is based on the Data Curation Center Roadmap. The tool has a new interface that is more user-friendly. Paola also added new features so that plans and storage requests can be traced back to any of the CLEX research programs. Reports on published data are now easier to create and there is a new template to produce plans to publish data sets, as well as one to publish software.

Plans can be exported in different formats, including XML. The plan in XML format can then be processed by another script to produce one Geonetwork XML file for the NCI publication process and one XML file following Australian National Data Service conventions to upload to the Research Data Australia repository. A user can also get more information on their storage requests – including an estimate of their usage, which is regularly updated.

To enable our researchers to publish their codes, in addition to a DMP template, we started a Zenodo CLEX community collection. While the software can be made public on services like Github, a repository on Github will keep on changing and, as such, doesn't provide a good, persistent identifier. Zenodo allows users to attach a DOI to a specific release of a repository and also to add metadata information. Collecting the codes in one community can also facilitate discovery.

In collaboration with CLEX Chief Investigator, Professor Andy Hogg, Aidan Heerdgen has developed splitvar, a new tool to help with the data publication process. It converts netCDF model output in multiple files of heterogeneous temporal extent, with many variables per file, and outputs the data organised in a way that it is suitable for publication by standard data services. It has been designed with the ACCESS-OM2 model output in mind but should be usable for netCDF data from other models.

ModelEvaluation.org

ModelEvaluation.org is a web application designed to evaluate model performance by comparing model simulation results to observational data. Application development has been ongoing for several years, most recently by Danny Eisenberg, and this year the application has started to be used for benchmarking intercomparison with land surface models.

Further development of the system has been ongoing. As more users provided feedback about the application, new features were introduced to make the application more user-friendly and robust. The permissions system for different kinds of users was redesigned. More thorough application tests were set up. Development of additional functionality has also been planned for next year.

Training

Weekly Wednesday training sessions continued through the year. Where appropriate, training sessions are recorded and uploaded to our Youtube channel. There has been a 50% increase in traffic on the channel (over three and a half thousand views) and an even larger (167%) increase in watch time. After consulting with Centre researchers at the winter school, we have also tried some "flipped" training. We create short information-rich training videos and upload those prior to the training, and then set some problems to solve based on the content of the videos. Then we work through the problems in the training in a tutorial-style approach.

Conferences

Aidan and Claire attended the Collaborative Conference on Computational and Data Intensive Science 2019, in Canberra. This year, one of the conference themes was Understanding the Earth. This conference provided a view of the current trends around machine learning and cloud computing in particular. We also gained additional insight into the PANGEO initiative (an open source software ecosystem), with talks and a one-day workshop. PANGEO aims to develop solutions and foster collaboration for analysis of Big Data in geosciences.

CMS Wiki

Our wiki, which hosts information on how to run models and access data we support at NCI, moved to a new platform this year: climate-cms.wikis.unsw.edu.au. With Wikispaces — which hosted the old wiki — closed down, we moved to UNSW's new Mediawiki service. This gave us a chance to redesign the front page and clean up old pages on the wiki. ■

Computational Modelling Support Team - Statement of Intent for 2020

Level	Intent
1	Finish upgrade to NU-WRF (i.e. CABLE-LIS-WRF coupled model) to version v9p2. Update the simulation work-flow system for NUWRF. Develop benchmarking suite with modelevaluation.org
2	Model updates and maintenance at NCI for WRF, MOM and ACCESS
2	Continue integration of CABLE in JULES in compliance with the UM and LFRIC requirements. Work on CABLE benchmarking suite
1	Develop optimised functions for common data analysis needs at the Centre
3	Deliver major data sets and associated tools, including data quality, for ▪ CMIP6 ▪ ERA5 ▪ CleF
1	Publish new data sets
1	Reorganise data sets at NCI. Continue linking with NCI, BoM and CSIRO to ensure CLEX needs are considered and help communicate the changes to users
1	Make data procedures and access more automatic
3	Improve data workflows
3	Maintain Python conda environments
1	Provide support to CLEX researchers and ACCESS users via the CWS help desk
1	Document outcomes on the CMS wiki for future reference, and report outcomes
1	Provide training opportunities in tools such as Fortran, Python and visualisation tools that researchers can take with them beyond CLEX to enhance their future research
2	Participate more actively in research programs. Establish relationships at relevant level, identifying possible improvements to workflows.

Priority levels: 1 = to be achieved in 2020. 2 = substantial progress in 2020. 3 = progress towards in 2020.

Researcher Development Program

Highlights

- A successful winter school on modelling the climate system
- Regular technical training delivered virtually by our CMS team
- A professional development workshop on developing a research profile
- Professional development training organised by and for our ECRs, including guidance on becoming a balanced researcher and dealing with 'impostor syndrome'
- Two successful science paper writing workshops
- 10 students completed their degrees in 2019
- Our students were authors on 13 journal articles in 2019, 11 as first author
- 20 undergraduate students were introduced to climate science research via our undergraduate research scholarship initiative.

The ARC Centre of Excellence for Climate Extremes (CLEX) Researcher Development Program develops national capacity in climate science by training and mentoring the next generation of researchers. It equips them with the intellectual and technical capacity required to take on the research challenges of the future. The graduate program includes fundamental research and communication skills, professional development, mentoring and leadership opportunities, and involves all Centre of Excellence researchers.

Our students and early career researchers (ECRs) are represented in the Centre via our ECR committee (ECRC). The ECRC provides formal and informal communication channels between ECR members and the CLEX Executive Committee. The ECRC's mission is to facilitate, encourage, and contribute to the development of all Centre researchers undertaking postgraduate study or who are five years post-PhD.

In 2019 we welcomed six honours students and 30 graduate students to the Centre. All have been actively involved in our graduate activities. We had 10 students submit this year (one PhD and nine honours/masters) and they have been moving on to positions in a variety of sectors.

Our graduate program recognises that climate scientists come from a variety of undergraduate backgrounds, and come to us with a varying range of skills and knowledge. Therefore, the program offers important breadth and depth of climate science knowledge, technical and communications training, and professional development, including detailed career advice. In 2019 we started running regular Alumni Sessions. These are professional development seminars delivered by Centre alumni, in which they share advice and strategy on life post-CLEX. Speakers come from a broad range of industries and career paths.

Researcher development activities include virtual and in-person training covering the knowledge, skills and resources our researchers will need to succeed in their research and successfully move on to the next step in their career. In collaboration with our Computational Modelling Support team, technical training opportunities this year have included weekly technical training sessions delivered via our videoconferencing system.

The CLEX Media and Communications Manager, Alvin Stone, has run regular communications and media training workshops in collaboration with other Centres of Excellence.

Our students and ECRs continue to be supported in their writing via our science paper writing workshops. The success of these can be seen in successful research publication, with 13 papers published by Centre students this year (11 as first author). Included in this impressive publication list was a first-author paper in Scientific Reports by Annette Stellema, three first-author papers in Journal of Climate and two first-author papers in Journal of Geophysical Research.

Professional development of our students continued via an ECR Day developed by and for our ECRs. This year we concentrated on the skills for becoming a balanced researcher and

dealing with the dreaded 'impostor syndrome'. We also ran an interactive workshop, in collaboration with the National Environmental Science Program's Earth Systems and Climate Change Hub and the Monash Climate Change Communication Research Hub, on developing researcher profiles. This workshop identified exactly who our ECRs want to be noticed by, and then provided the basic tools to increase their profile with that audience. These potential audiences included schools, employers, mainstream media, stakeholders and peer networks. The ECRs then produced short videos targeted at these audiences, with the aim of helping researchers see how they present themselves and how this may differ depending on the target audience.

Winter School

The likelihood of a graduate student moving on to a position in exactly the same research area of their PhD thesis is slim. Therefore, we need to graduate PhDs with not only a depth of knowledge in their own research area, but also vital breadth of knowledge across the discipline. This is where our annual winter school comes in. The theme of the winter schools changes each year, and shifts from broader, relevant-to-everyone topics, to more focused topics requiring prerequisite knowledge. This year's theme, Modelling the Climate System, fell into the former category. In all, this year's winter school had 70 participants from across the five CLEX universities.

Lectures were delivered by Centre researchers from our universities and Partner Organisations CSIRO and the Bureau of Meteorology (BoM). All lectures were recorded and will soon be available on our website. We ran an ambitious, practical program this year, with students setting up and running models, both Mk3L and Australian Community Climate and Earth System Simulator - Ocean Model 2 (ACCESS-OM2), and then analysing output and presenting. Participants were engaged throughout, and presented some really impressive analyses for the short amount of time they had.

Undergraduate Scholarships

Climate science students come from a range of quantitative undergraduate degree backgrounds. To ensure undergraduate students are aware of the opportunities within the climate sciences, we offer undergraduate scholarships. These scholarships are highly competitive and provide the students with an introduction to cutting-edge climate science research at one of our five CLEX universities, or our national Partner Organisations, including CSIRO and BoM. In addition, the Department of Environment and Energy has supported a scholarship focused on ozone science. Undergraduate students are supervised by our ECRs, giving them vital supervisory experience. Scholarships are offered throughout the year and can be undertaken either full time during semester breaks, or part time during the academic year. In 2019 we welcomed to the Centre 20 undergraduate students from six universities, to work with us on research projects.

Travel

Many of our students had the opportunity during 2019 to spend significant amounts of time embedded in international research institutes, including many of our international Partner Organisations, or to attend Northern Hemisphere summer schools. Our students are also actively involved in cross-node collaborations and often spend time visiting nodes other than their home institution. Being mindful the environmental footprint of air travel and working within our travel budget, the Centre's strategy is to favour travel that will lead to meaningful and deep engagement over longer visits to partners and collaborators. We are able to minimise the number of shorter trips via extensive and effective use of videoconferencing facilities to facilitate group meetings and one-on-one engagement between researchers at different institutions.

Prizes

Our students were extremely successful in winning both national and international prizes this year, including:

- **Rishav Goyal** - AMOS-ICTMO Best Poster Award: honourable mention
- **Chiara Holgate** - AMOS-ICTMO Conference Best Student Presentation
- **Sarah Jackson** - Awarded 2019 SCAR Fellowship to visit British Antarctic Survey/Cambridge University
- **Stephy Libera** - Runner-up in Science in the Pub's Inspiring Women in STEM grant at UTAS
- **Ruth Moorman** - Recipient of a 2020 John Monash Scholarship to undertake PhD studies at GFDL, Princeton
- **Manon Sabot** - UNSW Science Showcase Overall Poster Prize
- **Ewan Short** - Uni. Melb Rowden White Merit Scholarship and Puzey Merit Scholarship
- **Annette Stellema** - AMOS-ICTMO Best Poster Award: honourable mention. ■

Researcher Development Program – Statement of Intent for 2020

Priority	**Intent**
1	Run a student-focused winter school with a focus on atmosphere and ocean dynamics
1	Work in collaboration with CMS team to deliver regular virtual training sessions
1	Offer regular researcher development virtual seminars
1	Expand undergraduate scholarship program into additional national Partner Organisations
1	Support leadership training and mentoring opportunities for ECRs, and offer in-Centre opportunities for ECRs to lead projects and initiatives
1	Expand the library of virtual resources available via the Centre's website
1	Develop researcher development opportunities purely for Centre postdoctoral researchers that identify priority areas for development based on individual needs and career objectives
2	Provide a formal certification on completion of the Researcher Development Program
2	Develop a formal alumni network, including exit surveys, and opportunities for alumni to be involved in Centre mentoring and events
3	Explore industry placements and/or industry mentoring opportunities for students and ECRs.

Priority levels: 1 = to be achieved in 2020. 2 = substantial progress in 2020. 3 = progress towards in 2020.

2019 Early Career Researchers Workshop

This year's ECR workshop informed by a pre-workshop poll focused strongly on how to maintain a healthy work/life balance as a researcher and the best approach to overcome some of the common challenges every researcher faces.

The first part of the day was taken up with The Balanced Researcher program produced by Thinkwell. A brief synopsis of this workshop program over three hours included learning the art of saying 'no'; how to time manage more effectively by finding the balance between writing papers, teaching, writing code, preparing talks, writing grants, family, writing newsletter items and more. One powerful take home our ECRs learnt is that they only have so much time available, there is no magic genie who can create extra hours in the week for an ECR to agree to every opportunity that comes their way. Our ECRs learnt that it's better to pause, buy time (e.g. don't reply to emails immediately) and reflect: *"How long would it take me to do this and do I have the time?"*. It is far better to turn down an opportunity if you don't have the time than agree to something and fail to deliver.

The second part of the workshop focused on imposter syndrome presented by Dr Kim Norris Imposter syndrome is sadly a circumstance that a large proportion of researchers experience at some point in their careers. It can involve moments of feeling *"I'm not cut out for this"*, *"I'm only here because of luck"* or *"I don't deserve to be here"*. What researchers experiencing these moments often forget is all the hard work and time they have invested in themselves to get to where they are today and the evidence of their own success. Kim encouraged ECRs to consider a few approaches to overcome imposter moments'? First, she suggested giving it a name. This is a clever way to acknowledging the imposter feelings when they emerge. Second, take the time to celebrate successes. This is important to remind yourself of the evidence that you are not an imposter. Finally, if you need help internalising your proof of competence, write a sentence about how awesome you are including notable achievements (we all have them) and stick this above your computer. Every time you take a break from that screen, read that sentence and remind yourself of the qualities that show you deserve to be where you are.

These six hours were incredibly valuable for CLEX ECRs. In that time, they gained some tools and confidence to help them manage our time better and a note of warning to be wary of the words *"this will not take long to do"*. ■

Student Profiles

Abhishek Savita

Who in CLEX are you working with?

I am a CSIRO-UTAS QMS PhD student in association with CLEX, based in CSIRO at Aspendale. My supervisory team from UTAS is Will Hobbs, Violaine Pellichero and Catia Domingues, and from CSIRO, Simon Marsland and Peter Dobrohotoff. I also work closely with Jan Zika (UNSW), Gwyn Evans (National Oceanography Centre, UK), the Consortium for Ocean-Sea Ice Modelling in Australia (COSIMA), the CSIRO Coupled Climate Modelling teams and the National Environmental Science Programme (NESP), as part of the Earth Systems and Climate Change Hub.

Tell us a little about your background, how did you get here?

I have a background in mathematics/physics (BSc, Master of Science) and in physical oceanography (Master of Technology), from the Indian Institute of Technology (IIT) Kharagpur. My master's thesis focused on the "Role of the equatorial wind forcing on the interannual variability of the tropical Indian Ocean". I did that thesis at the Indian Institute of Tropical Meteorology (IITM), Pune. Just before coming to Australia in 2017, I worked as a project fellow at CORAL, IIT Kharagpur, investigating physical mechanisms driving the Seychelles Dome in the Indian Ocean and its connection with the monsoons.

Tell us a little about your project

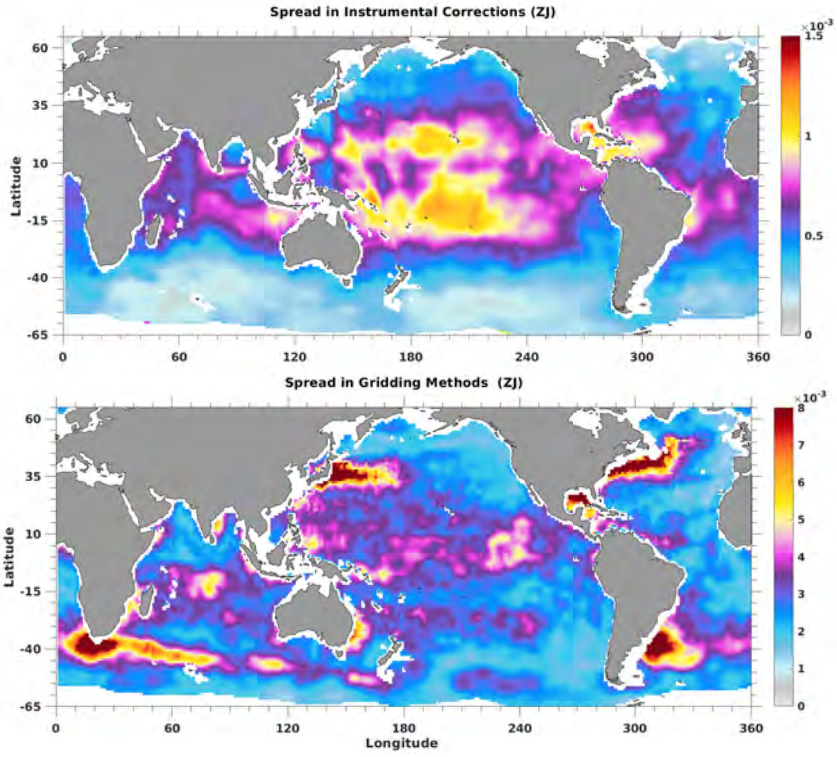
I investigate uncertainty in geographical changes of ocean heat uptake and physical mechanisms, using a combination of in-situ observations and model simulations, as part of larger, internationally coordinated efforts, with the goal of placing more rigorous constraints on the likelihood of future warming and sea level rise. For the observations, I am collaborating with seven groups – in the USA (NASA, NOAA, PMEL, Woods Hole), UK (Met Office), Japan (MRI) and Germany (Univ. Hamburg). I am performing model sensitivity experiments using the Australian Community Climate and Earth-System Simulator (ACCESS), as part of the Ocean Model Intercomparison Project (OMIP) and the Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP), both endorsed by the World Climate Research Programme. I am also involved in CMIP6 simulations with the CSIRO ACCESS team.

What opportunities has the Centre of Excellence offered you?

The Centre provides several valuable opportunities that contribute to my research skills and networking. I have participated in winter schools, CMS training, writing workshops, and also visited my CLEX collaborators from other nodes.

What are your hopes/plans for after you graduate?

My ultimate goal is to be a climate ocean modeller so I will be looking for postdoc fellowships and/or academic/researcher positions where I can continue my career in the field of physical oceanography and climate change. ■



Uncertainty in the estimation of global patterns of ocean heat uptake (1 ZJ=10^{21} J) for 1970-2004 due to instrumental bias corrections (top) and gridding methods (bottom).

Dongxia Yang

Who in CLEX are you working with?

I'm a third-year PhD student working with Julie Arblaster on the Southern Hemisphere midlatitude circulation at Monash University.

Tell us a little about your background, how did you get here?

I got my bachelor's degree in science from Sun Yat-Sen University and my master's degree in meteorology from the Chinese Academy of Sciences, which offers me a solid foundation in atmospheric dynamics to further my doctoral study at Monash University.

Tell us a little about your project

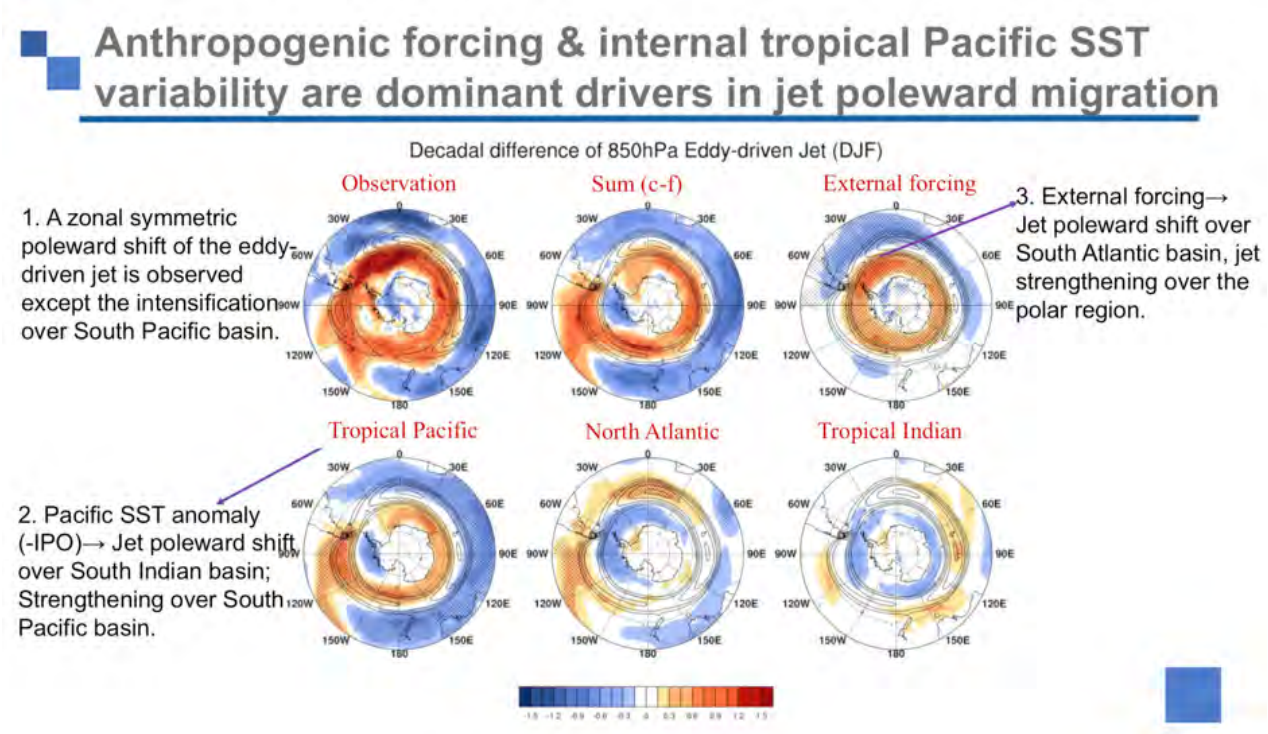
My PhD project aims to understand the influence of tropical sea surface temperature (SST) variability on the Southern Hemisphere atmospheric circulation change at a multi-decadal time scale. The answer to this question has been partly approached using some state-of-the-art climate models, including the Community Earth System Model (CESM) Large Ensemble and pacemaker experiments. We found that during the recent satellite era, both the anthropogenic forcing and the climate interval variability from tropical Pacific SST are dominant factors driving the jet poleward migration and positive SAM phase. Recent studies have shown a connection between changes in the SH extratropical circulation and SH rainfall and temperature trends, thus my research would provide references on agriculture and sustainability policy suggestions.

What opportunities has the Centre of Excellence offered you?

As a PhD student in the ARC Centre of Excellence, I felt grateful to be provided with the world-class super computational resource via the Australian National Computational Infrastructure (NCI), the travel grants to visit and collaborate with established scientists, and the opportunities to present my work in public media to make a broader impact. I also found it beneficial to be offered the winter school courses on climate modelling, workshops on academic writing and seminars on project-management skills.

What are your hopes/plans for after you graduate?

I'd love to continue to do research jobs on climate modelling or climate predictions after my doctoral study completion. Climate change has been such an urgent concern globally, it would be a good way to make my own contribution by providing professional references for policymakers and educating the public through research works. ■



Jemima Rama

Who in CLEX are you working with?

Callum Shakespeare and Andy Hogg at ANU.

Tell us a little about your background, how did you get here?

I completed an integrated master's degree in oceanography at the University of Southampton, England. Throughout my first degree I developed an interest in the different processes responsible for energy transfer within the ocean, from the larger-scale features, such as eddies, down to smaller, dissipative scales. My undergraduate project, for instance, focused on the interaction of tidal flows with the topography, while my master's project aimed at inferring the processes responsible for dissipating eddies off the Western Boundary. Both projects delved into the role of internal waves as an intermediate pathway from large-scale flows to mixing in the ocean interior, and have been a good motivation for my PhD research topic.

Tell us a little about your project

Internal waves generated by the winds at the ocean's surface contain a significant portion of energy available for mixing in the ocean. However, the ultimate fate of these internal waves remains unknown. Up until the last decade, the common consensus was that wind-generated internal waves could not propagate deep enough to sustain mixing in the ocean interior, but recent high-resolution numerical models have demonstrated that eddies can enhance internal wave propagation, acting as conduits into the interior.

My project will make use of numerical simulations to study the propagation of wind-generated internal waves. The main goals are to determine the fraction of theses waves that can make it to the deeper ocean and to identify the mechanisms that allow such propagation.

What opportunities has the Centre of Excellence offered you?

While enabling me to attend the annual CLEX conference, the Centre has also allowed me to attend the Fluid Dynamics of Sustainability and the Environment summer school at École Polytechnique in Paris this past year. During the summer school I was able to engage with leading researchers in the field of fluid dynamics and participate in lectures/workshops that consolidated my understanding of the same topic. It was also an opportunity to meet fellow early-career scientists from all over the world and increase my research connections. As a whole, this experience has been highly beneficial in my first year as a PhD student.

What are your hopes/plans for after you graduate?

Ideally, I would like to be in a position whereby I could implement my skills learnt from ocean modelling and use it in conjunction with the study of real ocean observations. ■

Lina Teckentrup

Who in CLEX are you working with?

I work with Andy Pitman and Martin De Kauwe at UNSW .

Tell us a little about your background, how did you get here?

I studied the bachelor's and master's in meteorology in Hamburg. Throughout my studies, I worked on a summer project in ecosystem modelling in Canada and decided to stay within the broad field after that. I was then based at the Max Planck Institute for Meteorology, a partner institution of CLEX, where I wrote my master's thesis, working with global fire models. Towards the end of my studies, I began to look for PhD positions and eventually reached out to Melissa Hart to enquire about opportunities within CLEX. She got me in touch with Andy Pitman who shortly after visited the Max Planck Institute – we chatted for a while and he offered me to come study in Sydney.

Tell us a little about your project.

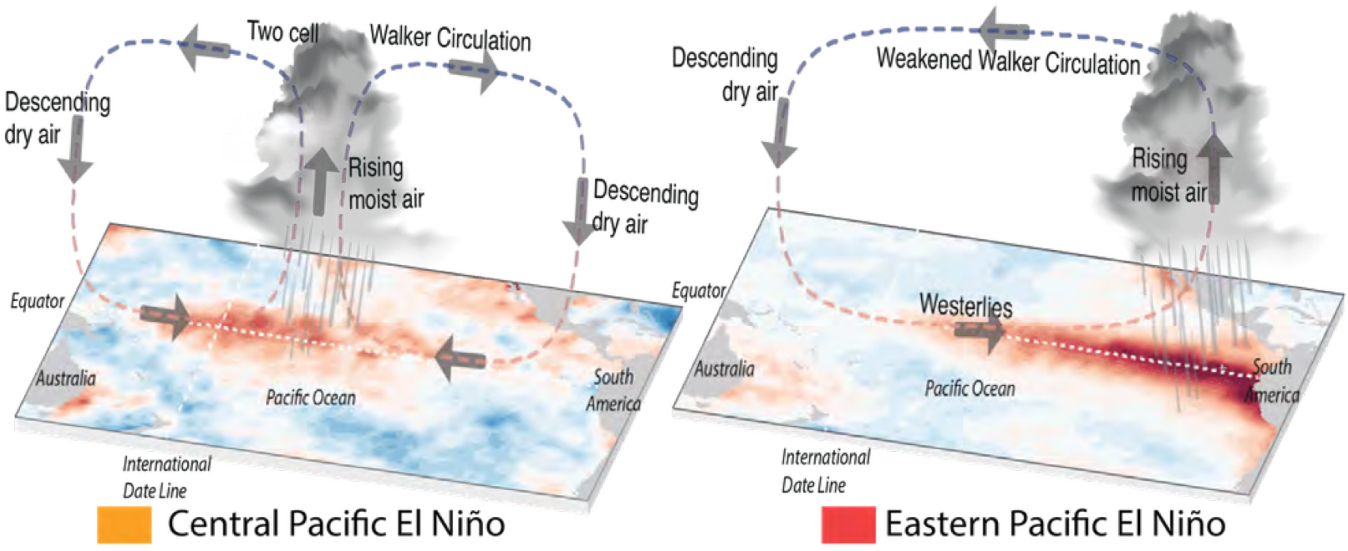
Oceanic variability influences the terrestrial ecosystems through climate variability. The most prominent example is the El Niño Southern Oscillation (ENSO): During El Niño events, the Walker circulation is weakened or reversed, resulting in altered precipitation and temperature patterns and consequently affecting the vegetation over Australia and South America, as well as ecosystems in parts of North America, through teleconnections. Further, based on the location of the positive sea surface temperature anomalies, two different expressions of El Niño are distinguished. Both types change the Walker circulation in distinct ways, leading to different ecosystem responses. For my PhD, I aim to understand how different climate modes influence the ecosystems, using a dynamic global vegetation model.

What opportunities has the Centre of Excellence offered you?

First of all – to do a PhD here, of course. Apart from that, CLEX is very supportive and offers a lot of networking opportunities. For example, I participated in the annual winter school in Melbourne and the workshop in Hobart. On these occasions I got to know a lot of other PhD students from other nodes and was able to talk to researchers during the poster sessions. In addition, CLEX funded me to take part in a summer school in Colorado to learn about measuring and modelling terrestrial ecosystems fluxes, which was a great opportunity to network with international students and researchers from that field. In addition, I will visit AMOS in Freemantle next year to present some of my research.

What are your hopes/plans for after you graduate?

I only started my PhD this year, so my future plans are pretty vague. For now, I'd like to stay in science and find a postdoc position, but where is very open. There will certainly be some travelling in-between finishing the PhD and starting a new chapter in my life. ■



Maurice Huguenin

Who in CLEX are you working with?

My supervisors are Professor Matthew England and Dr Ryan Holmes at UNSW.

Tell us a little about your background, how did you get here?

In 2016, I completed my undergraduate program in Earth sciences at the Swiss Federal Institute of Technology, Zurich. My bachelor's thesis on the modelled thermosteric contribution to sea level rise sparked my interest in oceanography and climate models. To learn more about our climate system, I enrolled in my university's masters program in atmospheric and climate science. After a year of lectures, I wanted to broaden my knowledge abroad. I contacted Prof England at UNSW and asked if I could come to Australia and work with him on my next thesis. To my surprise that actually worked out! My master's thesis on ocean heat changes during the El Niño-Southern Oscillation (ENSO) answered many questions and raised even more. I am fortunate that I can continue working with Prof England and Dr Holmes and investigate some of the open questions from my master's during my PhD research.

Tell us a little about your project.

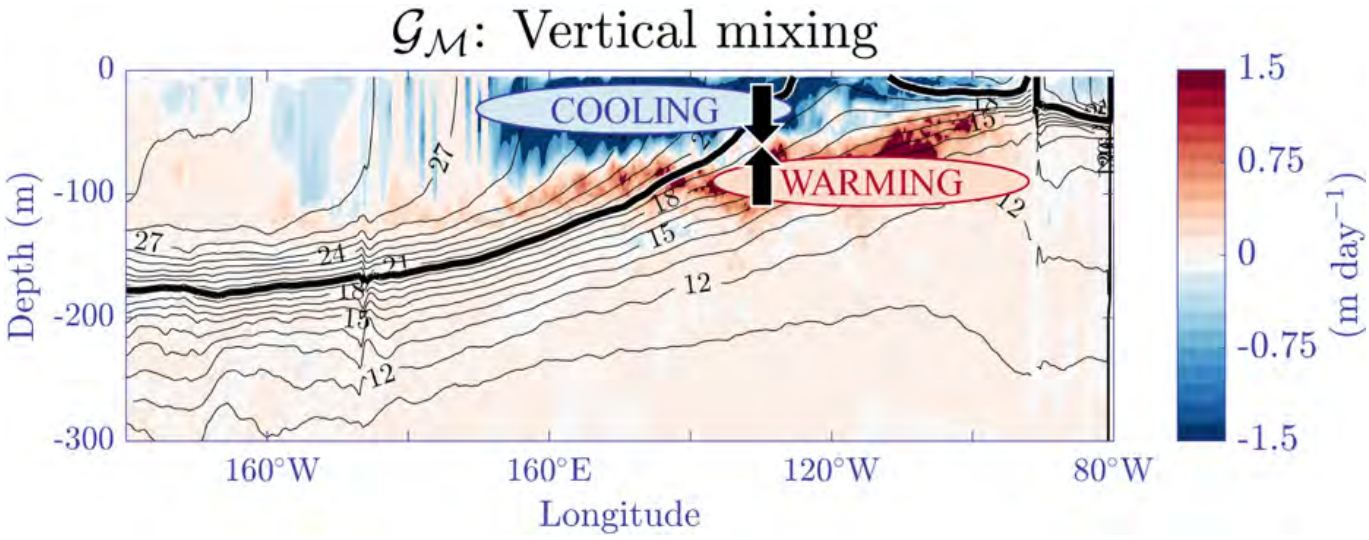
ENSO is the dominant mode of variability in the Earth's climate system on interannual time scales. To forecast ENSO events, we commonly use a metric called warm water volume – the volume of water above 20°C in the equatorial Pacific. To increase our predictive skill of ENSO beyond six months, a better understanding of the processes changing warm water volume is therefore necessary. With the help of the water mass transformation (WMT) framework, we are able to investigate heat and volume fluxes in temperature instead of the more commonly used Cartesian coordinates. Surface forcing and vertical mixing (Fig. 1) are the primary diabatic processes changing a water parcel's heat content. They also have a global significance as they allow large-scale heat transport from the tropics to higher latitudes, essentially closing the global heat balance. Investigating these diabatic fluxes will thus give us valuable insight into natural changes in the ocean's heat content and emergent changes caused by human-induced climate change.

What opportunities has the Centre of Excellence offered you?

CLEX has given me the opportunity to attend annual workshops as well as this year's winter school. This allowed me to meet other PhD students and researchers from across Australia. The regular training sessions and seminars through zoom are a great way to keep in contact with other members of CLEX.

What are your hopes/plans for after you graduate?

High up on my list of goals is joining a research program heading for Antarctica. I am certain such an experience would be very insightful and help me better understand the nature of this cold, windy and dry continent. Alongside continuing my academic career with a postdoc, I would also like to gain experience in politics to help shape important future decisions.



Equatorial transect of the vertical mixing WMT velocity (m day-1) during La Niña in a global ocean model. Vertical mixing cools water near the surface and warms water below. This leads to heat/volume exchanges between these regions as cool water sinks and warm water rises.

Zeya Li

Who in CLEX are you working with?

I am working with Prof Neil Holbrook from UTAS. Neil is my primary supervisor (both honours and PhD projects).

Tell us a little about your background, how did you get here?

I was an undergraduate student of the 2+2 program between Ocean University of China and UTAS and spent my honours year at UTAS. Since my honours project was about MHW, one of the focused topics of CLEX, I followed Neil's suggestion and joined CLEX at the start of my honours year.

Tell us a little about your project.

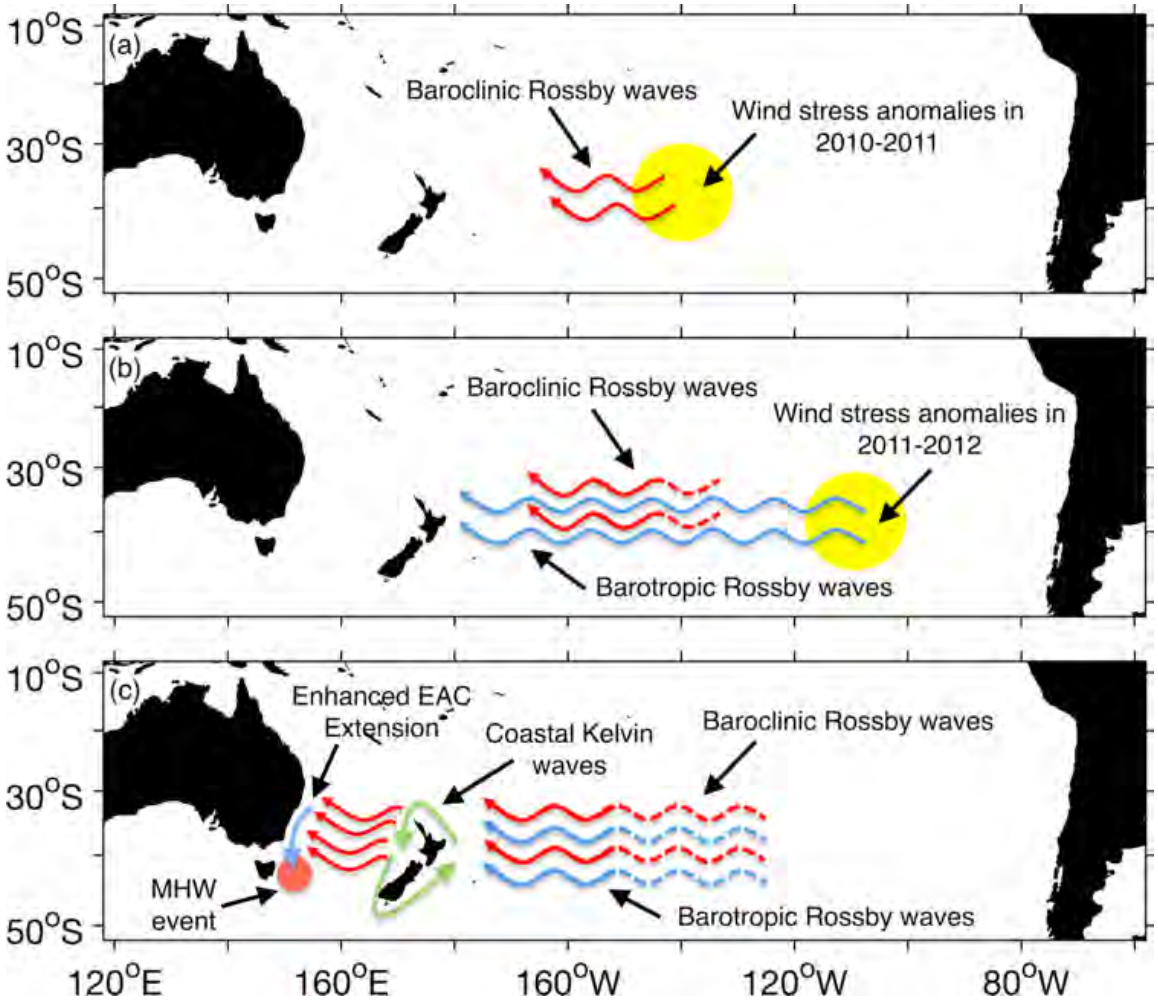
During my honours project, I investigated the large-scale forcing mechanisms of the extreme and prolonged 2015/16 Tasman Sea MHW. After finishing the honours project, I started my PhD in UTAS at the end of 2018. During the first PhD year, I chose to continue my honours study and further investigated the large-scale forcing mechanisms of historical MHW events in the Tasman Sea. My findings suggest that wind-forced Rossby waves in the South Pacific can potentially enhance or reduce the likelihood of MHW occurrences in the Tasman Sea. During the rest of my PhD, I will keep studying MHWs occurring in other regions around Australia and the world. I will mainly focus on the large-scale forcing mechanisms of these extreme events and their teleconnections with ENSO.

What opportunities has the Centre offered you?

I attended several great workshops and schools held by CLEX, including CLEX annual workshops, the writing workshop, the Tasmania modelling school and the 2019 winter school. These workshops and schools help me to gain a better understanding about climate and ocean science (especially extreme events), as well as improve my research and scientific writing skills.

What are your hopes/plans for after your graduate?

After finishing my PhD, I plan to seek a postdoc position and continue my study of MHWs and their forcing mechanisms.



Zijie Zhao

Who in CLEX are you working with?

I work with Dr Claire Vincent and Prof Todd Lane at the University of Melbourne

Tell us a little about your background, how did you get here?

I finished my honours at the program between University of Tasmania and Ocean University of China in 2018, working on a statistical model to predict marine heatwaves off eastern Tasmania, and then moved to the University of Melbourne to start my PhD study. My current research focuses on mesoscale response to the Madden-Julian Oscillation.

Tell us a little about your project.

The Madden Julian Oscillation (MJO) is a tropical disturbance associated with an extensive region of cloud cover and convection that propagates from the Indian Ocean to the Pacific Ocean over a period of 30 to 90 days. It is the dominant mode of intraseasonal variability in the Maritime Continent region, and it has been shown to have an important influence on global circulation patterns and extratropical weather patterns. Despite its global importance, the MJO is often poorly represented in climate models. Hypotheses for why the MJO is particularly difficult to model include the impact of low-level heating from unresolved shallow convection and the impact of mid-level moistening. My project will seek to answer the research question: "What is the role of unresolved mesoscale cloud processes in simulating a realistic MJO?". In particular, the impact of these unresolved mesoscale cloud processes on diabatic heating and moistening will be explored in depth. In contrast to previous work, this study will directly quantify the simulated latent heating, moistening, and cloud structures associated with large-scale environments that arise as the MJO propagates eastward. The study will employ climate-scale and high-resolution data, to be applied in idealised frameworks, and will be informed at all stages by a broad range of observational data sets. To resolve issues found in previous data, the sensitivity of diabatic heating and moistening to model resolution and other pertinent aspects of model physics will also be quantified, providing robust evidence for the impact of mesoscale processes on future climate predictions.

What opportunities has the Centre of Excellence offered you?

CLEX gives me fantastic supervision, funding for academic travelling, and the chance to visit other universities overseas for academic research (I will go to University of Reading next year to be a visiting scholar for three to four months).

What are your hopes/plans for after you graduate?

I plan to find a postdoc position which is associated with my PhD study.

CLEX students organise ocean modelling school

In 2019, Centre of Excellence students, Madi Rosevear and Wilme Huneke with IMAS PhD student Ole Richter put together their own ocean modelling workshop that ran from April 29 to May 3 after recognising they needed to know more about how to develop ocean models. The students pitched and received funding from the Centre of Excellence and its partners the ACE CRC and IMAS to hold the workshop in Tasmania.

Twenty-eight PhD students and early career researchers from Australia and New Zealand came together in Strathgordon to learn from some of the world's leading ocean researchers.

"We wanted to be able to develop and improve models, not just use them," said CLEX student and co-organiser of the workshop, Wilma Huneke.

Co-organiser Madi Rosevear said another goal of the workshop was to create a close and productive community of young ocean modellers in Australia.

The principal lecturer at the workshop was Prof Stephen Griffies, whose book, *Fundamentals of Ocean Climate Models*, is a foundational resource for ocean modellers. Prof Griffies is also a key developer behind the Modular Ocean Model (MOM), which is one of the most popular ocean models in the world.

Other lecturers included Prof Andy Hogg, Prof Max Nikurashin as well as participants Dr Navid Constantinou and Dr Ryan Holmes who shared their knowledge in their fields of expertise.

In all there were around 35 hours of lectures, that were described as dense but accessible. The expertise and engagement of the lecturers was very much appreciated as was their pedagogical expertise and flexibility in adapting to student feedback throughout the week. The students said the most rewarding part of the school came from the questions asked during the lectures and the depth and breadth of the discussions that followed.

But it wasn't all hard work, with the students taking part in social activities to build the links between this future community of ocean modellers. These activities included walks, a running crew, visits to Strathgordon Dam, kayaking and various games. Madi Rosevear said the workshop, which received very positive feedback, was a one-off event but that it was an example of what other students could do.

"I encourage students to take learning into their own hands if they feel something is missing. Organising a workshop like this is certainly more rewarding, but also considerably more effort, than buying a textbook." ■

Media and Communications

Highlights

- Combined media training courses have now engaged 10 Centres of Excellence
- Instagram page initiated with team of young ECRs and students across all nodes
- Significant growth of website visits and in social media numbers
- Marked increase in number of news stories compared to 2018.

Introduction

Following 2018, in which we encountered a number of headwinds and spent a lot of time building the foundation for our media and communications, 2019 has been a year of strong growth. We have seen more than a doubling of the number of visits to our website and more time being spent on our pages once those visitors have arrived. Our researchers have also significantly increased their engagement with media organisations. This steady growth of interest in our work has also led to the development of an extended mailing list for our Weekly Update, taking the latest news from the ARC Centre of Excellence for Climate Extremes (CLEX) to others beyond our traditional stakeholders.

The Combined Centre of Excellence training courses that we initiated last year have taken off. We ran three more this year, with the most recent including participants from five Centres of Excellence. Other Centres are now using that template to create their own media workshops. This year has also seen the Centre of Excellence communications community engage more closely with each other than ever before, which has allowed us to share ideas and bring together guest experts to our monthly meetings who can enhance our skill sets.

CLEX has continued to expand its social media presence and we were delighted this year to engage early career researchers (ECRs) and students as part of a new Instagram team. This team made its first post in June and has steadily grown this new social media outlet for our Centre.

Meanwhile, the Knowledge Brokerage Team (KBT) has continued to produce a range of impressive briefing notes aimed at policymakers and stakeholders that have garnered significant interest while building new relationships. You can read more about the activities in Dr Ian Macadam's KBT Report on page 95.

In total, this has been an exceptionally busy year that has seen growth in nearly every aspect of our media and communications portfolio.

CLEX Website

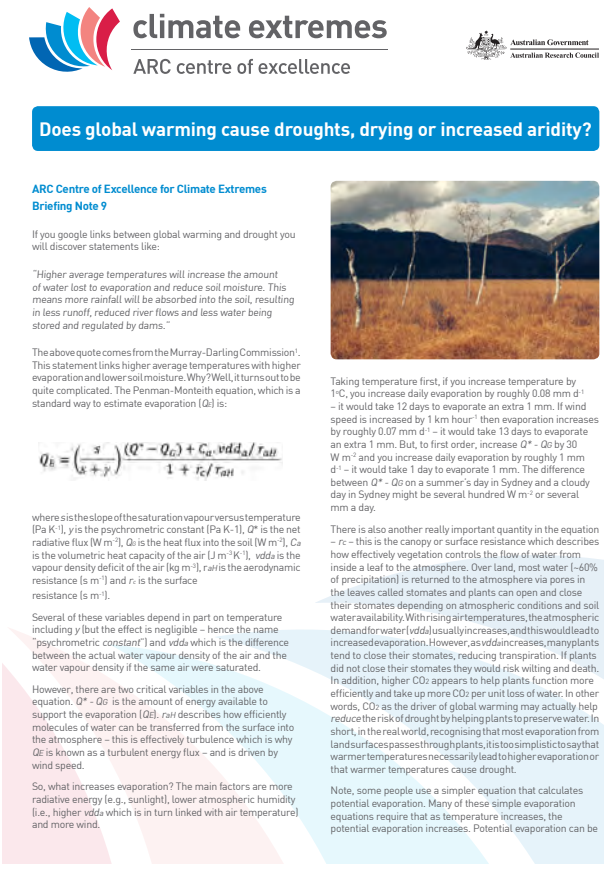
This has been the first full year for the CLEX website, with close to 100% growth across every aspect. In 2019 we have seen:

- 30,502 unique users
- 48,190 sessions
- 93,684 page views
- Top 5 countries — Australia (50.4%), US (18.6%), India (3.78%), UK (3.31%), China (2.06%)
- Most popular pages: landing page (17.42%), Briefing Note 09 : Drought (13.26%).

The growth in visits to our website echoes the growth in content. Over the past year we have almost doubled the available content. The website now contains 408 posts and 144 pages. However, this is not just a story about quantity but also quality. We are seeing more time spent on our pages, particularly the pages containing research briefs (plain English summaries of our research), briefing notes (summaries for stakeholders and policymakers concerning important research), media releases and newsletter items. The most popular posts this year were:

- Briefing Note 09, which focused on the relationship between droughts and climate change
- A media release highlighting how bushfires will become more frequent with climate change
- An evergreen article that describes the process for students to become climate scientists.

It has become clear over the past year that the 2018 initiatives, which aimed to make the work of Centre researchers more accessible to the public and decision-makers, have been successful. In the coming year, the website will continue to be a key part of our communications strategy as we use it to deepen and develop relationships with other organisations in our area of science.



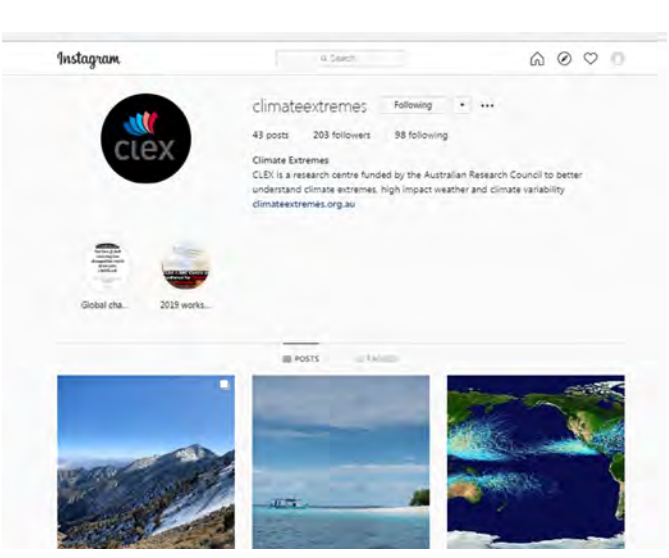
Social Media

As noted last year, dramatic changes to the Facebook algorithm saw considerable uncertainty around how effective it would be in sharing our achievements. By contrast, Twitter's ability to reach into new groups and attract followers was unchanged. We were fortunate in that our Facebook page was primarily created as a way of improving our internal communications, so the focus here was not on growth and driving web traffic so much as it was on maintaining our internal networks. This has meant that, unlike other organisations that relied on Facebook to drive website traffic, we have been less affected by these changes. Meanwhile, between the increase in our website content and using Twitter as the social media mainstay of our external focus, we have been able to achieve consistent strong growth.

Our Twitter presence has grown markedly. We added 664 followers, bringing our end-of-year total to 1534. Our above-average engagement rate also continues. More than half a million people saw our tweets, with the most popular tweet coming from research into past temperatures by Associate Investigator, Ben Henley. Our audience remains evenly balanced between male and female.

Our Facebook page grew by a modest amount in 2019 and now stands at 1372 followers. However, as noted above, it is primarily for sharing news and triumphs internally and by that standard it remains very effective, especially when it comes to reaching our students and ECRs.

One of the highlights of this year for social media was the creation of an Instagram feed that aims to reach a younger audience. Instagram skews towards teenagers and those in their early 20s, and is a highly visual medium. This is why a team made up of ECRs and students is the main driver. We have been particularly delighted by the way they have organised themselves, so that posts are regular but are not individually taxing in terms of time or effort. It is interesting to note that the team seriously thinks about the fundamentals of communication on a regular basis and it is likely this will hold them in good stead for future public engagement. While still in its early days, our Instagram feed already has 181 followers and is getting responses from groups and individuals that we have previously struggled to engage.



Media Engagement and Training

Once again, the outstanding success of 2019 in terms of media engagement rests very heavily on the foundational work that we did in 2018. This year we have seen our research featured in 411 stories, up from 253 in 2018. Our researchers have featured in all major national media outlets and have also had a very strong presence in the international media, including *The Washington Post*, the *New York Times*, *Die Spiegel*, *The Independent (UK)*, *The China Post*, NBC News, the BBC and a wealth of other outlets that span every continent.

Perhaps most impressively, our researchers are being contacted directly as a result of earlier media work, which suggests the profile of individuals and CLEX has now gone international.

This focus on our researchers and the work that we do has increased the importance of media training. Over the past year, the combined Centre of Excellence workshop has gone from being a pilot program to establishing itself as a key part of our training process. During 2019 we held three workshops, led by Alvin Stone, the Media and Communications Manager at CLEX; Samantha Snowden and Anne Meyer from the ARC Centre of Excellence in Convergent Bio-Nano Science & Technology; and Timothy Macuga from the ARC Centre of Excellence for Mathematical and Statistical Frontiers. We saw some almost-instant benefit from these workshops when a number of our finishing PhD students found themselves in front of major media for the first time. They were able to employ the practical tools taught at the workshop to successfully handle live-to-air interviews. The post-workshop feedback continues to be outstanding, with 100% of attendees saying that the workshops clearly benefited them. A large number said these were the best workshops they had ever attended. Further combined Centre of Excellence workshops are being organised for 2020, with a range of new Centres of Excellence already prepared to participate.

At the same time, Alvin was able to visit all nodes in 2019, with the exception of the University of Tasmania. A workshop and visit to Tasmania has been scheduled for mid-2020.

Our newsletter has now been set at three issues per year and it continues to be well read. We currently have 419 subscribers and a more-than-double industry average opening rate of around 40%.

In terms of our citizen science outreach activities, 2019 has seen a considerable amount of foundational work put in place. With the help of the KBT we were able to get further funding for the WeatheX app and look forward to version 2 appearing late in 2020. Meanwhile, we are close to launching the Schools Weather and Air Quality (SWAQ) citizen science project, which will improve weather and air quality measurements around Sydney by placing meteorological and air quality sensors at schools. The final tests of the equipment are currently underway. SWAQ will not only have research benefits but its integrated structure will directly engage students in curriculum-related activities.

Looking ahead

As we look to 2020, it is clear that we have a formidably busy year to come. We expect to see an extension of the WeatheX capabilities and consequent accompanying media. This is likely to be preceded by the official launch of SWAQ and media activity at local and regional levels.

Our Combined Centre of Excellence workshops will be expanded over the coming year and will likely be further developed for other Centres of Excellence. This will play an important role in our future activities because, while it is true we have had a high number of media stories, the majority of these have featured more senior researchers. It is our intention to swing more of the spotlight back on to ECRs and those PhD students completing their degrees, who will have research results to share with the public.

Our website continues to grow at rapid speed and, now that the majority of researchers have engaged with the research brief template, we are seeing an acceleration in the number of posts and follow-up social media related to our research.

It is worth nothing that the past year has also seen a rationalisation of major media outlets for the first time in almost a decade. This suggests we will now be able to maintain and deepen long-term contacts with key reporters, news managers and editors, so some effort will go into this.

With so much to come already, it is our expectation that we will tentatively explore new initiatives with a view to introducing these towards the end of the year or in early 2021. However, on the whole, 2020 will be a year for bedding down the expected outreach activities and consolidating the continuing growth of the media and communications portfolio. ■

SWAQ – Citizen science meets urban climate research

Schools Weather and Air Quality (SWAQ) is a citizen science project that brings together our outreach program, the deepening links with our stakeholders being developed by our knowledge brokerage team, and industry players. This project is the first of its kind in Australia.

It is primarily funded by the Australian Government's Department of Industry, Innovation and Science as part of its Inspiring Australia – Citizen Engagement Program, which has allowed the SWAQ team to partner with equipment supplier Vaisala, the NSW Smart Sensing Network, CSIRO through its Smoke Observation Gadget, data visualisation specialists Small Multiples, and design firm Tobias.

SWAQ will equip schools across Sydney with research-grade meteorology and air quality sensors, enabling students to collect and analyse research quality data through curriculum-aligned classroom activities. The data will be freely available to the public, students and researchers alike, helping to maintain awareness of local weather and air quality conditions, and to contribute cutting-edge research into cleaner and healthier cities.

Currently there are insufficient meteorological and air quality observation sites to adequately monitor the effects of increased urbanisation on local-scale weather and air quality in most Australian cities. The SWAQ project provides a pilot for how citizen science could potentially enhance monitoring networks, increase STEM engagement and give the public more agency in their daily decision making through access to localised, high temporal-resolution weather and air quality data.

The SWAQ network will allow, for the first time, detailed spatial analyses of the impacts of urbanisation on Sydney's weather, climate and air quality. The foundation work for the project has been carried out throughout 2019, with the first instruments moving into schools scattered across the Sydney basin in the latter half of the year. These instruments are currently undergoing testing and it is expected that the SWAQ project will be officially launched by mid 2020.

Similar networks have been implemented in other countries (e.g., Birmingham UK, Victoria BC Canada), however, a point of difference for SWAQ is the provision of a large network of higher quality research-grade sensors in order to optimise the use of data for high quality discovery and applied research. It is out hope that SWAQ Sydney provides a successful pilot scheme and that the network can expand to other major capital and regional cities around Australia. ■

“the WeatheX app... was developed by Monash University to allow members of the public to report extreme weather events in real time. It can be used to capture data that could ultimately contribute to performance assessments of forecasts of extreme weather...”

Knowledge Brokerage Team

Highlights

- Nine briefing notes released to stakeholders
- Continued enhancements to the Weathex app
- Deepening ties with high school teachers associations

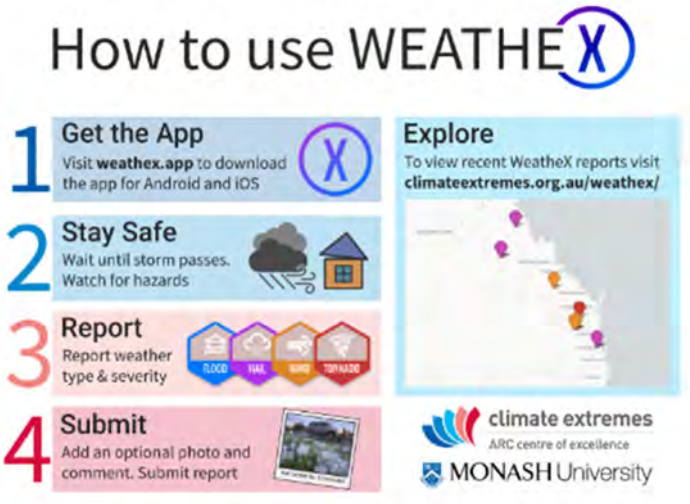
The Knowledge Brokerage Team (KBT) at the Centre of Excellence for Climate Extremes works closely with the Centre's Outreach Committee and the its Media and Communications Manager to enhance the impact of the Centre beyond academia. In 2019 the KBT added to its initial member, Dr Ian Macadam, based at UNSW, Sydney, with the arrival of Dr James Goldie in a joint position between CLEX and the Monash Climate Change Communication Research Hub in Melbourne. Ian and James help to:

- ensure relevant Centre research is communicated, and accessible, to government departments and the private sector
- facilitate collaboration between the Centre's researchers and stakeholders in government departments and the private sector
- support the teaching of climate and weather science in high school STEM subjects.

A key tool the KBT uses to communicate the Centre's research is its series of briefing notes (https://climateextremes.org.au/briefing-notes/). These cover subject matter on many aspects of Centre science and are distributed in Australia to relevant individuals, governments, businesses and climate information providers (for example, CSIRO, the Bureau of Meteorology (BoM)). As at the end of 2019, the series comprised 10 briefing notes written by Ian and Centre Director, Professor Andy Pitman.

James's focus in 2019 has been on the development of the Gridded Temperature and Precipitation Climate Extremes Indices website, which is due to be released in 2020. This will enable researchers and climate information providers with an interest in climate monitoring and/or model evaluation (for example, the World Meteorological Organization, actuarial organisations in the US and Canada) to more easily access global data sets on extremes of daily temperature and precipitation.

Another data-related project involving the KBT is the WeatheX app. The app was developed by Monash University to allow members of the public to report extreme weather events in real time. It can be used to capture data that could ultimately contribute to performance assessments of forecasts of extreme weather by forecast providers and to the timely assessment by insurers of insurance claims due to extreme weather. The KBT supported engagement with potential users of the app's data, resulting in the signing of an MOU between Monash University, the BoM, IAG (Insurance Australia Group), the NSW Government and Risk Frontiers to fund and guide the development of version 2 of the app.



Throughout 2019, Ian has been working to develop a network of contacts with expertise in the high school curriculum, including teachers and other individuals in teachers' associations (e.g. ASTA, STANSW), curriculum authorities (e.g. VCAA) and providers of teaching resources (e.g. TROP ICSU, Cool Australia) as a foundation for supporting the development of teaching and learning resources on climate and weather science. To this end, the KBT and other Centre staff and affiliates are co-convening a lesson plan development workshop at the AMOS 2020 conference in February 2020. This will bring academics, including Centre researchers, and teachers together to generate ideas for lesson plans that simultaneously help teachers teach the curriculum and give school students greater understanding of climate and weather science.■

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Prizes, Outreach and Engagement

Prizes and Awards

Abram, N. AMOS Priestley Medal

Abram, N. Part of team awarded the Vice-Chancellor's Award for Impact and Engagement for their communication of IPCC reports

Abram, N. Distinguished Lecturer at 2019 Asia-Oceania Geosciences Society meeting in Singapore

Alexander, L. Elected Fellow of AMOS

Ashcroft, L. MSSI Climate Transformation Seed Funding Grant

Ashcroft, L. Nominated one of 60 STA Superstars of STEM

Constantinou, N. CLEX Prize for the Best paper published by an Early Career Researcher 2019

England, M. Royal Society of NSW's 2019 James Cook Medal

England, M. Prof Matthew England has been named a 2019 Highly Cited Researcher by Web of Science, based on citations over the past decade

Gergis, J. 2019 AMOS Science Outreach Award

Goyal, R. AMOS-ICTMO best poster award: honourable mention

Hirsch, A. 2019 CLEX Career Development Award for women and underrepresented groups

Hobeichi, S. UNSW President's Award "Embraces Diversity" for my team of UNSW Women in Maths & Science Champions

Holgate, C. AMOS-ICTMO Conference best student presentation

Jackson, S. Awarded 2019 SCAR Fellowship to visit British Antarctic Survey/Cambridge University

Jakob, C. Invited to present the annual AMOS R.H. Clarke Lecture

Jakob, C. AMOS Morton Medal

King, A. AMOS Science Outreach Award 2019

Lane, T. Elected a Fellow of AMOS

Law, R. Elected a Fellow of AMOS

Libera, S. Runner up in the Science in the Pub's "Inspiring Women in STEM" grant at UTAS

Meehl, G. University Corporation for Atmospheric Research 2019 Distinguished Achievement Award

Menviel, L. Australian Academy of Science Dorothy Hill Medal for 2019

Meyer, A. CLEX 2019 Director 's Prize

Meyer, A. 2020 Discovery Early Career Researcher Award by the Australian Research Council

Meyer, A. 2019 Tasmanian Young Tall Poppy Science Award

Meyer, A. CLEX Director's Prize 2019

Moorman, R. 2020 John Monash Scholarship to undertake PhD studies at GFDL, Princeton

Morrison, A. Meyers Medal

Neske, S. CLEX Prize for the Best Paper published by a student 2019

Nicholls, N. 2019 Zillman Medal - AMOS awards

Pellichero, V. Thesis Prize Albert de Monaco from the Oceanographic Institute of Monaco

Perkins-Kirkpatrick, S. Recognised as an AGU Outstanding Reviewer

Pitman, A. 2019 Royal Society of Victoria's Medal for Excellence in Scientific Research

Pitman, A. Order of Australia (AO) for distinguished service to science as a leading researcher, particularly of climate systems and the environment

Purich, A. AMOS Uwe Radok award for best PhD thesis

Sabot, M. UNSW Science Showcase Overall Poster Prize

Santoso, A. Editor's Prize from the American Meteorological Society for consistently high-quality reviews on various topics in tropical climate dynamics

Short, E. UniMelb Rowden White merit scholarship and Puzey merit scholarship

Stellema, A. AMOS-ICTMO best poster award: honourable mention

Thorn, D. AMOS Melbourne Chapter Regional Award for his thesis on "Climate and weather influences on Antarctic sea ice"

Ukkola, A. 2020 Discovery Early Career Researcher Award by the Australian Research Council

Vreugdenhil, C. Uwe Radok PhD award for best PhD thesis

Editorships and Committee Memberships

Abram, N. National Committee for Earth System Science

Abram, N. National Committee for Antarctic Research

Abram, N. ANU Climate Change Institute advisory board member

Abram, N. Antarctic Science Foundation: scientific sub-committee member

Abram, N. Editor, *Climate of the Past*

Abram, N. CLA for the IPCC Special Report on the Ocean and Cryosphere in a changing climate

Alexander, L. AIMES Scientific Steering Group

Alexander, L. Chair, WMO Expert Team on Sector-specific Climate Indices

Alexander, L. Member, WCRP JSC

Alexander, L. Editor in Chief, *Weather and Climate Extremes*

Arblaster, J. National Committee for Earth System Science

Arblaster, J. National Climate Science Advisory Committee

Ashcroft, L. Editor in Chief, *Geoscience Data Journal*

Bishop, C. Co-Chair, WMO Working Group on Predictability, Dynamics and Ensemble Forecasting

England, M. Member, WCRP/CLIVAR/GEWEX Drought Interest Group

Evans, J. Lead Author for IPCC Special report on climate change and land

Evans, J. Member, WCRP CORDEX Science Advisory Team

Evans, J. Editor, *Journal of Climate*

Gray, S. Member, ARC Major Investments Working Group

Hart, M. Chair - AMOS equity and diversity committee

Henley, B. Invited to join the Queensland Flood and Drought project in an advisory role

Hogg, A. Editor, *Geophysical Research Letters*

Huang, Y. Special issue guest editor, *Atmosphere*

Jakob, C. Member, WCRP GEWEX Science Steering Committee

Lane, T. Member, WMO Monsoon Panel Expert Team on Severe Monsoon Weather

Perkins-Kirkpatrick, S. Editor, *Scientific Reports*

Perkins-Kirkpatrick, S. Editor, *Weather and Climate Extremes*

Pitman, A. Member Monash Foundation Scholarships committee

Pitman, A. National Committee for Earth System Science

Pitman, A. Associate Editor, *International J. Climatology*

Reeder, M. International Advisory Board Member, Norwegian Research School on Changing Climates in the coupled Earth System

Reid, K. AMOS Melbourne Chapter Committee Member

Reid, K. Unimelb representative for Australian Meteorological and Oceanographic Society Melbourne branch

Reid, K. President of the Unimelb Earth Sciences Student Society

Ridder, N. Regional representative for the South West Pacific, Young Earth System Scientists Community (YESS).

Santoso, A. Associate Editor, *Journal of Climate*

Schofield, R. Member, International Ozone Commission

Schofield, R. Chair, Australian Meteorological and Oceanographic Society's Expert group on Atmospheric and Oceanic Composition

Schofield, R. Associate Editor, *Atmospheric Measurement Techniques*

Sen Gupta, A. National Committee for Earth System Science

Sherwood, S. Steering Committee member, WCRP Grand Challenge on Clouds, Circulation and Climate

Strutton, P. Steering Committee Member for the Tropical Pacific Observing System 2020

Strutton, P. Chair, TPOS2020 Biogeochemistry Task Team.

Briefings/Presentations to Industry, Government and NGOs

Abram, N. Meeting with Senator Larissa Waters on climate change, including IPCC SROCC report

Abram, N. Presentation to DoEE (Canberra, and streamed to AAD) on IPCC SROCC report

Alexander, L. Risk Frontiers Seminar 2019: Using climate observations in actuarial assessments of risk

Gergis, J. Climate risk briefing to Councillors and staff, Byron Shire Council (NSW),

Gergis, J. Mick Dark Talk for the Future, presented by Varuna

Gergis, J. Keynote speaker, Australian Actuaries Institute conference

Henley, B. Invited to join the Queensland Flood and Drought project in an advisory role

Henley, B. Seminar to scientists, engineers and managers at Snowy Hydro

Henley, B. Panelist on future water security in Victoria, G21 regional alliance of councils' annual event

Holbrook, N. Work with Secretariat of the Pacific Regional Environment Programme (SPREP)

Huang, Y. Presentations / expert advice to Hydro Tasmania on Tasmania rainfall research

Huang, Y. Presentations to Bureau of Meteorology Tasmania Regional Office on Tasmania rainfall and Southern Ocean atmospheric research

Lane, T. CLEX Delegation meeting with DEWLP to discuss future opportunities

Macadam, I. Lunch meeting on compound events with Risk Frontiers

Macadam, I. Visit to IAG with Christian Jakob (Monash) and Alain Protat (BoM). I gave a brief overview presentation describing CLEX and the Knowledge Brokerage Team

Macadam, I. Presentation and meetings to DPIE on urban climate work

Macadam, I. Attended briefing of NSW Chief Scientist by Andy Pitman on ACCESS

Macadam, I. Organised OEH-CLEX seminar at UNSW

Macadam, I. Meeting at DELWP with Lane, Jakob and Arblaster to introduce CLEX

Pitman, A. Attended the ANZ climate risk round table briefing in Sydney

Pitman, A. Keynote talk at the 2019 Australasian Leadership Computing Symposium, Canberra

Pitman, A. Risk Frontiers Seminar 2019: Do climate models tell us about future extremes?

Pitman, A. Independent Planning Authority on climate change and climate risk

Pitman, A. Presentation to Climate Research Strategy for Primary Industries Group

Pitman, A. Ethical Partners Funds Management - briefing to business

Pitman, A. Briefing to Matt Kean, NSW Minister for Energy and Environment

Pitman, A. Briefing to a collection in candidates in the Federal election on climate science

Pitman, A. NSW Chief Scientist on ACCESS and on CLEX

Pitman, A. Greater Sydney Water Strategy - climate change information sharing session, NSW Government Dept. of Planning and Environment

Pitman, A. Briefed the board of APA (a leading Australian energy infrastructure business) on climate change risk

Santoso, A. Invited talk to Swiss Re Group

Schofield, R. Meeting The Lung Health Research Centre, University of Melbourne and Environmental Justice Australia

Public Talks and science outreach

Abram, N. Public event on IPCC SROCC Report

Abram, N. Lecture for adult education course on climate change, run by ANU Climate Change Institute.

Bador, M. French School, introduced climate change to students, round table with older students

Ballis, N. "Water and Climate Science Day 2019", organised by DELWP

Bindoff, N. Presentation on the IPCC at the UTAS School of Health.

Brown, J. Gave lecture to Year 10 Work Experience students on my career path as climate scientist.

Ellis, B. Girls into Earth and Marine Science outreach event at RSES, ANU

England, M. Symposium of Climate Variation, Prediction and Application

England, M. Workshop on Future Climate Change, Nanjing China

England, M. ARC CoE for Coral Reef Studies Postdoc Development Day: "Career progression from postdoc positions to academia and research"

England, M. Presentation to UNSW Shanghai Alumni Summit

Gergis, J. In discussion at Quantum Words Science Writing Festival, Perth

Gergis, J. Public talk at the Coral Reef Futures symposium of the ARC Centre of Excellence for Coral Reef Studies

Gergis, J. Exhibition co-curator: ART+CLIMATE=CHANGE 2019 Festival art exhibition

Goldie, J. Presented to the Healesville Community Watch Inc. on climate change communication and MCCCRH programs

Henley, B. Public talk at Gothenburg University, Sweden, invited by GMV, Chalmers University and Gothenburg University

Henley, B. Panel member for a public discussion after the screening of "The Hottest August" at the Environmental Film Festival

Henley, B. Seminar to Brunswick English Language Centre at Brunswick Secondary College. Students included refugees and recent immigrants

Hirsch, A. National Science Week Event: Living With Climate Change Panel Discussion

Hitchcock, S. Year 10 Work Experience presentations

Hitchcock, S. Assisted with UniMelb Open Day

Huang, Y. Engaging with general public on behalf of the School

Jakob, C. Presentation on climate and climate change to the University of the Third Age, Stonington Chapter, Melbourne

Jakob, C. Presentation on: "Climate Change: What can we do in response?" to Monash Scholars program. This program consists of 200 yr 11 students

Meijer, J. With Ram Patel and Saurabh Rathore, gave spin-tank demonstrations at Taroona High School

Meyer, A. Roving Scientist' at the Tasmanian Museum and Art Gallery 'BeakerStreet' event

Meyer, A. Gave a talk about my career pathway and current research to a group of students from the French Telopea Park School in Canberra

Meyer, A. Met with school children from Grade 1 at Goulburn Street Primary School in Hobart to talk about sea ice, land ice and sea level rise with small experiments set up.

Meyer, A. Part of the panel for the AMOS 'Meet the Scientists' event during the AMOS 2019 conference in Darwin.

Petrelli, P. Weekly 0.5 -1 hr school visit to help running a python coding course with grade5-6 students. At Albuera St Primary School, Hobart

Pitman, A. Gave talk to Pacioli Society at University of Sydney - "The emerging role of climate science in the measurement of business risk"

Pitman, A. Australian Fire and Emergency Management Conference and Bushfire and Natural Hazards CRC Research Forum

Rathore, S. Gave spin-tank demonstrations at Taroona High School

Reeder, M. AMOS Public Lecture and Forum. A decade on: lessons from Black Saturday

Reid, K. Gave a talk on the science of climate change at the Diamond Creek Hotel Politics in the Pub

Roderick, M. Member of a 3-person climate change panel discussion with ANU undergraduate students at Burgmann College (ANU residential college).

Sabot, M. Poster for the Day for Women in Mathematics at the University of Adelaide

Sabot, M. ASPIRE outreach event with Year 10 students at UNSW

Semolini Pilo, G. I wrote a blog piece for a space research consultancy - InnovaSpace

Sen Gupta, A. 10 days teaching at Brawajaya University, East Java as part of 3 in 1 program

Sen Gupta, A. Science Week Panel discussion at Hornsby Library

Sherwood, S. Spoke as part of a panel on climate change to high school UNYouth group at U Western Sydney, Parramatta.

Wadlow, I. Skype interview and discussion with year 6 students at Alamanda College about climate change and working in Antarctica.

Wadlow, I. Skype call with students at a high school in Germany about climate science, and how students can take action to combat climate change. ■

2019 Key Performance Indicators

Performance Measure	Reporting	Target 2019	**Achieved 2019**
Number of research outputs	Annually		
Journal articles		40	138
Book chapters		4	2
Software modules published		2	5
data sets published,		2	10
social media@facebook posts		52	247
social media via Centre website updates		25	>50
Science explainer videos		2	0
Quality of research outputs	Annually		
Percentage of publications in journals with impact factors greater than 2.0		80	97.1
Percentage of publications in journals with impact factors greater than 4.0		60	58.6
Number of papers in journals with impact factors greater than 10		6	18
Number of training courses held/offered by the Centre	Annually		
Professional development training in gender equity and diversity		1	1
Professional training for ECRs in engaging with government and decision makers		1	1
Computational skills workshops/tutorials		3	15
Science fundamentals workshops		1	1
Leadership and professional development workshops		1	4
Communications/writing workshops		1	4
Number of centre-wide virtual lectures/seminars		5	28
Percentage of students/ECRs attending researcher development activities		90%	83.4%
Number of workshops/conferences held/offered by the Centre	Annually		
National workshop		1	1
International conference/workshop		1	1
Topical/Research Program workshops		3	7
Number of additional researchers working on Centre research	Annually		
Postdoctoral researchers		14	6*
Honours students		10	9
HDR students		20	29
Associate Investigators		28	14**
Number of PhD completions	Annually	0	1
Number of Masters by Research completions		2	2
Number of Honours student completions		10	8
Percentage completing PhD students submitting within 4 years (FTE)		0	100%
Number of mentoring programs offered by the Centre We have an integrated researcher development program for HDR students and early-mid career researchers. It includes a personalised skills needs assessment and induction, an annual calendar of workshops and training opportunities, an annual winter school covering science fundamentals, cross-node and partner organisation supervision, and a mentoring circle initiative involving all centre researchers and students allowing a range of mentoring and networking opportunities.	Annually and at mid-term review	1	1
Number of presentations/briefings	Annually		
To the public		10	28
To government		10	16
To industry/business/end-users		5	17
To non-government organisations		5	3
To professional organisations and bodies		5	4
Number of new organisations collaborating with, or involved in, the Centre	Annually	-	-

Additional CLEX-specific performance measures	Reporting Frequency	Target 2019	Achieved 2019
Percentage of female graduate students	Annually	50%	53%
Percentage of female research fellows		50%	55%
Percentage of senior female research fellows		50%	50%
Percentage of Centre leaders who are female#		50%	27%
Percentage of administration team who are female		50%	88%
Percentage of board members who are female		50%	22%
Percentage of keynote speakers at workshops and conferences who are female		50%	66%
Computational Modelling Support	Annually		
New/refined/enhanced software modules for the climate models developed and served to the community.		2	0
New/refined/updated software tools for data analysis developed and served to the community.		2	2
New/refined/updated data sets served to the community.		2	14
Monthly bulletin to all researchers on CMS-related updates		12	10
Explainer videos on key CMS issues		4	6
Percentage of students with cross node and/or partner organisation supervision	Annually	70	40%
Percentage of students/ECRs making a research visit to other nodes and/or Australian partner organisations	Annually	60	23%
Student / ECR internships in industry/government		2	2
Percentage of students/ECRs making a research visit to international partner organisations or organisation with a collaborative relationship	Annually	30	11%
Number of undergraduate summer scholarships offered	Annually	15	16
Regular Research Program videoconference meetings p/a	Annually	10	151
Media KPIs	Annually		
Media Releases		15	14
Website – Unique Hits		25000	30,502
Website – Page Views		35000	93,684
Stories in media		300	255
Social Media – Twitter (followers)		200	664
Social Media – Facebook (followers)		150	213
Knowledge Brokerage Team	Annually and at mid-term review		
Establishment of significant partnerships		1	0***
Data sets provided to stakeholders		1	1
Strategic advice provided to stakeholder		1	9
Demonstrated examples of model improvements available for use in national modelling systems	Annually and at mid-term review	2	2

*6 new research associates joined the Centre in 2019. The total number employed at 31/12/2019 was 18.

**14 new associate investigators joined the Centre in 2019. The total number affiliated at 31/12/2019 was 61.

***This metric is difficult to quantify as partnerships take time to establish. Out KBT leader was busy throughout 2019 building linkages between CLEX and a number of public and private organisations that we expect will lead to formalisation of partnerships in 2020 and beyond.

Financial Statements

Executive Summary

The Australian Research Council Centre of Excellence for Climate Extremes (CLEX) formally commenced operations on 4 August 2017. The Centre's financial affairs are conducted within the established procedures, controls and delegations of the relevant universities, and as set out by the Australian Research Council (ARC). This statement provides an analysis of the income and expenditure of the Centre of Excellence.

In 2019, CLEX received $6,011,406 (100%) income compared to the full-year budget of $6,011,406. In terms of the Centre's expenditure, $5,574,244 (89%) was spent compared to the full-year budget of $6,255,127. This was due to the late commencement date and delays in personnel appointments.

In 2019, personnel accounted for the highest proportion of expenditure of $4,243,104 (76%), followed by travel expenditure of $732,637 (13%). Overall, the Centre's cash balance in 2019 is $437,162.

Financial Management and Performance

Quarterly financial reporting monitors institutional income and expenditure against the Centre-wide budget. The Centre's Finance Manager prepares consolidated financial statements for review by the Director. The Centre-wide finances are discussed at Centre Executive meetings, and financial statements are tabled at Centre Advisory Board meetings.

The Centre meets its annual reporting requirements to the ARC and meets all other reporting obligations set by Partner Organisations that provide financial support.

2019 Income

Cash income totalled $6,011,406 from all sources. The Centre derived its income from the ARC, participating universities, the Bureau of Meteorology (BoM), the former NSW Office of Environment and Heritage – now Department of Planning, Industry and Environment (DPIE), the NSW Department of Industry's Research Attraction and Acceleration Program (RAAP), the Sydney Water Corporation and the Department of the Environment and Energy. Income is summarised by the source in detail in the tables that follow.

1: Australian Research Council Funding

The Centre received indexed income from the ARC of $4,461,645. This was distributed to the institutions following the inter-institutional agreement and was used for payroll, scholarships, consumables and events, equipment and maintenance and travel.

2: Government Funding

2.1 Bureau of Meteorology

BoM committed $30,000 in year three of the Centre's operations. This cash contribution was targeted at PhD top-up scholarships for students working collaboratively with BoM.

2.2 NSW Department of Planning, Industry and Environment

The cash investment from DPIE is specifically intended to support pathways-to-impact by supporting an improved understanding of climate extremes in NSW and by making this knowledge available to the community and decision-makers in the form that they need. The Centre received $100,000 in 2019.

2.3 NSW Department of Industry RAAP

RAAP funding invests in appointing a research fellow to focus on high-resolution modelling of processes relating to climate extremes (for example, hail, drought processes, vegetation-climate extremes). The Centre received $142,857 in 2019.

2.4 Sydney Water Corporation

Sydney Water targeted a research associate/climate modeller to focus on the impact(s) of climate change on their operations in the Sydney basin. The total cash contribution was $200,000 to be spent in 2018 and 2019. The total amount was received in 2018.

2.5 Department of the Environment and Energy

Funds were provided to deliver one annual Ozone Science Summer Scholarship per year over 3 years, A commitment of $4,523 in 2019 was received from researching ozone science.

3: Collaborating Organisation Funding

Cash contributions to the Centre of Excellence from the Administering Organisation and the Collaborating Organisations amounted to $1,253,234, detailed as follows:

$518,695	UNSW
$162,604	ANU
$158,947	University of Melbourne
$164,450	University of Tasmania
$248,538	Monash University

4: In-kind Contributions

In-kind support totalled $7,791,063 in 2019. The Centre is grateful for $5,524,356 of in-kind contributions provided by the Administering Organisation and the Collaborating Organisations. The contributions are primarily personnel-related and consist of the apportioned salary, on-costs and burdens of faculty members and other university staff members who contribute towards the Centre. Partner Organisations provided additional in-kind contributions of $2,266,707. Again, this was mainly personnel time.

Organisation	In-Kind Budget	In-Kind Actual
ANU	814,037	860,637
BOM	141,916	141,916
CSIRO	325,500	330,579
LATMOS CNRS/INSU/ IPSL	13,400	13,400
Max Planck Inst. For Meteorology	45,000	45,000
Met Office UK	150,000	150,000
Monash	847,262	944,947
NASA Goddard Space Flight Center	40,697	40,697
NCAR	110,032	110,032
NCI	892,000	892,000
NOAA	30,000	30,000
OeH	312,785	312,785
Risk Frontiers Grp	42,000	42,000
Swiss Federal Inst of Tech	82,192	82,192
UMEL	873,246	806,128
Uni of Arizona, USA	56,790	76,106
UNSW	1,799,538	2,094,972
UTAS	510,561	817,672
TOTAL	7,086,956	7,791,063

2019 Leverage

The Centre's 2019 cash income of $6,011,406 and in-kind support of $7,791,063 totalled $13,802,469, with ARC funding accounting for $4,461,645 of the total income. The Centre's leverage of $9,340,824 equates to $2.09 of external funding and in-kind contributions for each $1.00 received from the ARC.

2019 Expenditure

In 2019 the Centre expended $5,574,244, analysed below:

Personnel (including on-costs)	$4,243,104	76%
Scholarships	$304,753	5%
Equipment and Maintenance	$79,541	1%
Consumables and Events	$214,209	4%
Travel	$732,637	13%

2019 Income Vs Expenditure

Income and Expenditure are based on cash and derived from the institutions' general ledgers. The Collaborating Organisations certify income and expenditure by formally acquitting all grants as of 31 December 2019.

The Centre's cash expenditure of $5,574,244 was below income of $6,011,406 by $437,162.

The Centre will carry over a balance of $437,162 to 2020. The carry-over by institution is as follows:

University of New South Wales	$173,413	surplus
Australian National University	$28,735	deficit
University of Melbourne	$94,920	surplus
University of Tasmania	$57,244	surplus
Monash University	$140,320	surplus

In summary, as at 31 December, 2019, the financial position for the life of CLEX after its third year of operation is as follows:

Total Cash Income	$6,011,406
Total Expenditure	$5,574,244
Surplus carried forward to 2019	**$437,162**

CLEX Cash Income & Expenditure

	Actual			Budget/ Forecast					TOTAL
	2017	2018	2019	2020	2021	2022	2023	2024	
1. Cash Income									
Australian Research Council- Centre of Excellence	4,350,000	4,250,000	4,250,001	4,300,000	4,300,000	4,300,000	4,300,000	0	**30,050,000**
Australian Research Council- Centres of Excellence Indexation	65,250	128,456	211,645	0	0	0	0	0	**405,351**
Bureau of Meteorology	10,000	20,000	30,000	30,000	30,000	20,000	20,000	0	**160,000**
NSW Office of Environment and Heritage	100,000	100,000	100,000	100,000	100,000	100,000	100,000	0	**700,000**
NSW Department of Industry/ RAAP	143,000	143,000	142,857	142,857	142,857	142,857	142,857	0	**1,000,285**
University Node Cash Contributions	1,103,142	1,285,737	1,253,234	1,236,879	1,227,652	1,227,635	1,227,635	0	**8,561,914**
Other (Interest Distribution)	0	15,871	19,146	0	0	0	0	0	**35,017**
Department of the Environment and Energy			4,523						**4,523**
Sydney Water Corporation	0	200,000	0	0	0	0	0	0	**200,000**
Total	**5,771,392**	**6,143,064**	**6,011,406**	**5,809,736**	**5,800,509**	**5,790,492**	**5,790,492**	**0**	**41,117,091**
2. ARC Expenditure									
Personnel	114,662	1,941,921	3,354,377	2,072,069	2,103,814	2,129,608	2,144,459	2,224,172	**16,085,081**
Scholarship	6,358	90,723	158,714	194,434	194,434	194,434	194,434	191,061	**1,224,591**
Equipment and Maintenance	0	5,105	33,216	1,506,105	1,580,578	1,555,087	1,598,398	1,473,347	**7,751,836**
Consumables and Events	16,369	165,632	160,379	128,920	128,920	128,920	128,920	71,956	**930,018**
Travel - Conference, workshops and meetings (Staff, AI)	12,634	133,395	210,647	280,919	198,119	198,119	198,119	165,590	**1,397,542**
Travel - Conference, workshops and meetings (Postdocs and Students)	0	40,497	178,653	165,537	174,059	172,466	171,143	168,715	**1,071,070**
Travel - Visitor travel to the Centre and other	1,336	38,236	31,324	185,051	191,021	190,621	191,551	135,699	**964,841**
Travel - New staff relocation expenses	0	0	0	74,777	74,777	74,777	74,777	67,433	**366,540**
Travel - Research Visits (Staff, AI)	0	9,585	34,451	95,471	95,471	95,471	95,471	25,107	**451,030**
Travel - Research Visits (Postdocs and Students)	1,341	380	3,484	48,216	48,216	48,216	48,216	14,731	**212,802**
Total	**152,701**	**2,425,476**	**4,165,244**	**4,751,500**	**4,789,410**	**4,787,720**	**4,845,489**	**4,537,811**	**30,455,351**
3. Nodes Expenditure									
Personnel	65	311,556	615,789	507,358	504,549	510,555	517,628	336,078	**3,303,578**
Scholarship	10,706	61,092	132,039	151,638	168,638	168,638	168,638	170,000	**1,031,389**
Equipment and Maintenance	6,182	48,972	46,325	92,695	115,094	42,896	37,117	35,043	**424,324**
Consumables and Events	4,575	43,568	53,831	210,169	261,900	272,055	272,055	279,376	**1,397,528**
Travel - Conference, workshops and meetings (Staff, AI)	12,901	49,055	67,758	25,353	25,353	25,353	25,353	26,298	**257,426**
Travel - Conference, workshops and meetings (Postdocs and Students)	2,969	60,341	104,294	99,100	105,173	110,246	99,321	103,283	**684,727**
Travel - Visitor travel to the Centre and other	0	9,570	41,971	133,832	153,838	153,838	149,477	141,931	**784,459**
Travel - New staff relocation expenses	7,354	55,163	22,719	78,576	89,074	79,074	69,074	63,276	**464,310**
Travel - Research Visits (Staff, AI)	5,132	8,979	22,952	24,000	24,000	24,000	24,000	24,302	**157,365**
Travel - Research Visits (Postdocs and Students)	0	10,981	13,860	14,000	4,000	4,000	4,000	5,967	**56,808**
Total	**49,885**	**659,276**	**1,121,538**	**1,336,722**	**1,451,619**	**1,390,656**	**1,366,664**	**1,185,555**	**8,561,914**

	Actual			Budget/ Forecast					TOTAL
	2017	2018	2019	2020	2021	2022	2023	2024	
4. Others									
Personnel	61,192	192,341	272,939	328,556	335,127	341,830	348,666	84,651	**1,965,302**
Scholarship	0	10,000	14,000	30,000	30,000	20,000	20,000	10,000	**134,000**
Equipment and Maintenance	0	0	0	0	0	0	0	0	**-**
Consumables and Events	0	0	0	0	0	0	0	0	**-**
Travel - Conference, workshops and meetings (Staff, AI)	0	0	0	0	0	0	0	0	**-**
Travel - Conference, workshops and meetings (Postdocs and Students)	0	0	523	0	0	0	0	0	**523**
Travel - Visitor travel to the Centre and other	0	0	0	0	0	0	0	0	**-**
Travel - New staff relocation expenses	0	0	0	0	0	0	0	0	**-**
Travel - Research Visits (Staff, AI)	0	0	0	0	0	0	0	0	**-**
Travel - Research Visits (Postdocs and Students)	0	0	0	0	0	0	0	0	**-**
Total	61,192	202,341	287,462	358,556	365,127	361,830	368,666	94,651	**2,099,825**
5. Summary Income Vs. Expenditure / Carry Over									
ARC									
Total Income	4,415,250	4,378,456	4,461,646	4,300,000	4,300,000	4,300,000	4,300,000	0	**30,455,351**
Total Expenditure	152,701	2,425,476	4,165,244	4,751,500	4,789,410	4,787,720	4,845,489	4,537,811	**30,455,351**
Income less Expenditure	4,262,549	1,952,980	296,402	-451,500	-489,410	-487,720	-545,489	-4,537,811	**0**
Nodes									
Total Income	1,103,142	1,285,737	1,253,234	1,236,879	1,227,652	1,227,635	1,227,635	0	**8,561,914**
Total Expenditure	49,885	659,276	1,121,538	1,336,722	1,451,619	1,390,656	1,366,664	1,185,555	**8,561,914**
Income less Expenditure	1,053,257	626,461	131,696	-99,843	-223,966	-163,022	-139,029	-1,185,555	**0**
Other									
Total Income	253,000	478,871	296,526	272,857	272,857	262,857	262,857	0	**2,099,825**
Total Expenditure	61,192	202,341	287,462	358,556	365,127	361,830	368,666	94,651	**2,099,825**
Income less Expenditure	191,808	276,530	9,064	-85,699	-92,270	-98,973	-105,809	-94,651	**0**
Carry over surplus / deficit	**5,507,614**	**2,855,971**	**437,162**	**-637,042**	**-805,647**	**-749,715**	**-790,327**	**-5,818,017**	**0**

Australian Government
Australian Research Council

UNSW SYDNEY

Australian National University

UNIVERSITY of TASMANIA

MONASH University

THE UNIVERSITY OF MELBOURNE