climate extremes

ARC centre of excellence

Report 2018

Centre of Excellence for Climate Extremes Annual Report 2018

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The Centre is financed and hosted by the University of New South Wales. Collaborating partners are Monash University, the University of Melbourne, the University of Tasmania and the Australian National University. They provide significant financial support. The Centre is also financially supported by the NSW Research Attraction and Acceleration Fund, Sydney Water, NSW Office of Environment and Heritage and the Bureau of Meteorology.

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Pg 34/35: Mike Archer
Pg 36: DP (Brisbane)
Pg 50, 55: Mike Roderick
Pg 58: Stock Australian photo
Pg 65, 66, 67: Nathan Bindoff
Pg 68: Computer rendered
Pg 78: Matthias Retsch
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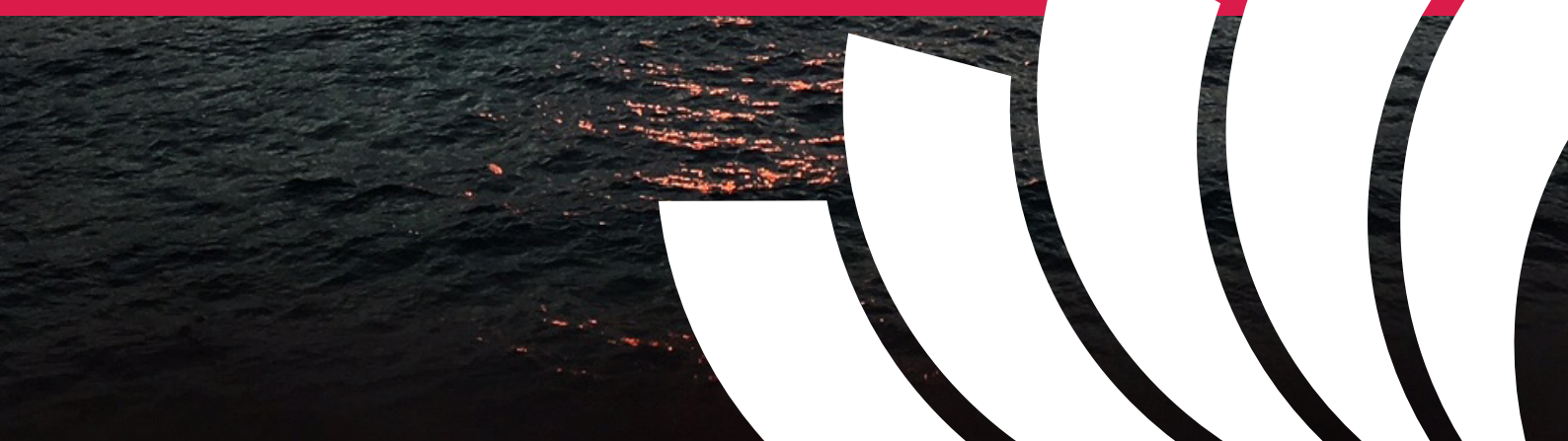
RECYCLED CONTENT
FOREST MANAGEMENT
RENEWABLE ENERGY
ECF ELEMENTAL CHLORINE FREE
EMS ENVIRONMENTAL MANAGEMENT SYSTEMS
ISO CERTIFICATION

Contents

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.



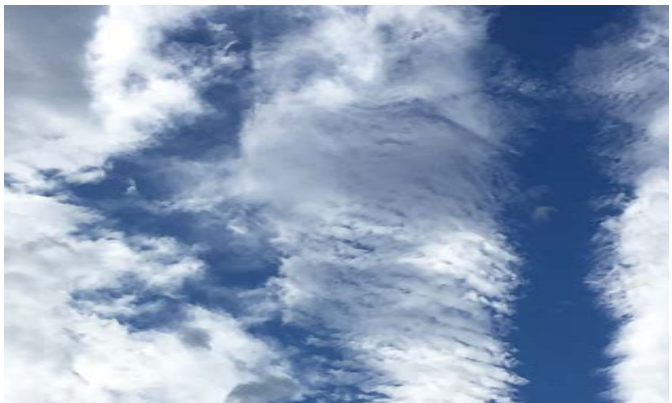
Aims and Objectives

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 large 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 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 focus on five key areas, as set out in our Strategic Plan:

World Class Research	▪ We will undertake world-class research into processes that cause, amplify or prolong climate extremes in the 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.



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.

Overview

"We aim to help reduce Australia's economic, social and environmental vulnerability to climate extremes"

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.

The Centre held its launch event at UNSW on 10 April 2018. We were honoured to have the CEO of the Australian Research Council, Prof Sue Thomas and UNSW's President and Vice Chancellor, Professor Ian Jacobs as a distinguished guests. The Hon. Craig Laundy MP officiated over the launch and plaque unveiling. Dean of Science at UNSW and President of Science Technology Australia, Prof Emma Johnston was a superb MC.

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 will focus 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 will be necessarily quantitative, 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 we will prioritise how climate extremes affect insurance risks, and via the MCV Program we will prioritise how climate extremes affect food production.

With national and international partners, we will apply new understanding to our national prediction systems and improve predictions of climate extremes. By linking with key economic sectors we will 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

CLEx is committed to communicating its science to policymakers, industry and the wider public

It gives me great pleasure to endorse the second Annual Report of the Centre of Excellence for Climate Extremes (CLEx). As Chair of the CLEx Advisory Board I have been able to see the important work of this Centre develop and unfold.

The report provides a snapshot of the many accomplishments made during 2018. As you turn the pages you'll see highlights of impressive scientific advances; details of how the Centre is successfully partnering with leading Australian and overseas organisations; and how CLEx is investing in the development of our next generation of climate researchers.

Researchers across the Centre have collaborated with each other and with partners from around the world in multiple disciplines. Despite 2018 being the Centre's first full calendar year since establishment, CLEx researchers published 65 papers. It's not only the volume of published research that is impressive, but also the quality of that research as evidenced by the prestigious journals much of the Centre's work is published in and further evidenced by emerging citations.

In November I was honoured to be able to attend the Centre's annual workshop in Wollongong. I was very impressed by the enthusiasm, engagement and energy of participants, the quality of the presentations and the importance of the research. One of the most important aspects of the work of CLEx was reflected in the large number of early career researchers and graduate students who made up the majority of workshop attendees. CLEx is making a significant contribution to the next generation of scientists. The future of climate research in Australia is in good hands.

Of course all this effort is to no avail if it merely contributes to the swelling body of academic publishing. CLEx is committed to communicating its science to policymakers, industry and the wider public. The members of the Advisory Board have been active in seeking opportunities for this science to be used to inform policy and decision making.

I commend the hard work of all involved in the Centre in 2018 and look forward to seeing continued success as 2019 unfolds.

Dr Tony Press
Chair, CLEx Advisory Board

Director's Report, 2018

Through 2018, the Centre of Excellence for Climate Extremes (CLEx) established its full capacity to engage in our research and outreach strategies. Our full range of postdoctoral positions are now filled, our Computational Modelling Systems team is established, we have a Knowledge Brokerage Team (KBT) leader in place, and likewise our Researcher Development Program is well established under the leadership of our Graduate Director. We have grown our graduate student numbers, and embedded them into the Centre via winter schools and workshops. We have progressed our research agenda, and are well under way in terms of planning for 2019.

Our 2018 annual report documents many of our early achievements. While a Centre of Excellence has its eye on the longer term, there are of course achievements to celebrate and acknowledge along the way and this report documents many of these. I will briefly highlight a few of our 2018 achievements but encourage you to read about these in more detail later in this report.

In terms of our research, the Extreme Rainfall program has been examining processes at very high spatial detail. Ongoing work on the tropics has examined links between cold pools and thunderstorms and how heat is released by thunderstorms. Links with planetary waves were identified – this is problematic as many interactions between these waves and orography, coastlines and the time of day are poorly resolved in our climate models. This is one of many pieces of evidence pointing to the need for our climate models to take a leap forward in terms of spatial resolution in order to capture the interactions that trigger rainfall extremes.

Extreme rainfall happens at a variety of spatial scales, but intense rain is often very small scale and can be missed by rain gauges. We have two initiatives to help with this. First, CLEx is working closely with the Bureau of Meteorology (BoM) on the development and analysis of extreme rainfall from the radar and gauge observations, with a goal to develop a national radar archive in 2019. Second, the Centre helped with an initiative led by Monash University and BoM to develop a citizen science project that allowed anyone to provide reports of extreme rainfall in real time via a phone app called WeatheX. There is more later in the report on WeatheX and links to how to use the app, where to get it from and so on.

The Heatwaves and Cold Air Outbreaks research program has led new research on both the land-atmosphere system and the marine system. Policy-relevant research focused on global warming targets of 1.5°C and 2°C levels above pre-industrial conditions was also published. Another paper with policy significance examined how inversion layers may change with global warming along Australia's east and south-east regions and what this would mean for air pollution. Centre researchers have also examined the atmospheric conditions that produce heatwaves over Brisbane, to demonstrate that a low-pressure system just off the south-east corner of Australia could be important to explaining heatwaves in Brisbane (https://climateextremes.org.au/research-brief-summertime-heatwaves-in-brisbane).

In the marine environment, research on the now-familiar marine heatwaves has developed well. Using observations, the strength of marine heatwaves in some regions have been linked to the East Australian Current and part of the Leeuwin Current. Researchers also examined the role of human-caused climate change in the Great Barrier Reef heatwave of 2016 and an Alaskan marine heatwave in the same year.

The Drought research program has collaborated on a number of projects with the Heatwaves and Cold Air Outbreaks program. Work has linked land processes with temperature extremes and with soil-moisture proxies, via both observations and modelling. It is unclear if models accurately capture the amplification of heatwaves during hot and dry conditions in what are normally wet regions. Our researchers compared the outputs of climate models with observations for hot and dry periods and found models overestimated the interaction between hot and dry days in wet regions, thus over-amplifying heat extremes. This has opened the way for further model and forecasting improvements. In other work, we evaluated global climate models for common drought metrics over the past 55 years. The different climate models produced very different simulations of drought, related to how the models represent the land-atmosphere interactions at the surface. The study pointed to a clear need to improve climate model projections of hydrologic extremes, to reduce uncertainties in future projections. We also produced research that resolved why drought and aridity metrics applied in climate models show a drier future but direct simulations of future water-resource trends have been less pessimistic.

Our largest research program, the Climate Variability and Teleconnections program, has such breadth that it effectively functions through three distinct clusters. The Southern Annual Mode cluster explores extratropical atmospheric variability and its effects on surface climate variability and extremes, the Southern Ocean and Antarctic sea ice. The Tropical Variability cluster includes the Madden Julian Oscillation, monsoons, model errors, tropical cyclones, land, and so forth. Finally, an Oceans cluster focuses on the Modular Ocean Model developments, in close connection with the Consortium for Ocean-Sea Ice Modelling in Australia. Obviously these three clusters interact across CLEx, contributing to research on droughts, marine heatwaves, terrestrial heatwaves, cyclones and so on.

Beyond our research, we hosted our annual workshop in Wollongong. We have a long history of these workshops of course, but under the leadership of Michael Reeder, Andy Hogg and Amelie Meyer we changed the format in 2018 to encourage collaboration, engage everyone in whole-of-Centre themes, and to ensure everyone had a chance to present their work via posters. The refreshing of our workshop format proved very successful and, while in one sense that's very positive, it reinforced the fact our biggest problem is now one of scale: the workshop attracted over 150 participants, which is logistically hard to manage. We suspect we will continue to host these annual workshops, but we will continue to intersperse far smaller and research-focused workshops through the year.

Our Knowledge Brokerage team was established in 2018. This team has a broad agenda to engage beyond the Centre with stakeholders including government, partners, the media, schools and so on. One initiative is the development of briefing notes – an example is included later in this report. A great many more will be reported in the next annual report.

The researcher development program is now well established. We ran a successful winter school on Climate Extremes and High Impact Weather at the Australian National University. There is also weekly training on computational

Through 2018, the Centre of Excellence for Climate Extremes (CLEx) established its full capacity to engage in our research and outreach strategies.

modelling, virtual seminars on the publication process, tips for gaining jobs in data sciences, and guidance for preparing grant applications. Training in communication strategies, guidance on writing papers, CVs and responding to selection criteria for different sectors were all provided. We are very proud of our students. Our students were authors on 19 journal articles this year, 13 as first author. Over a dozen undergraduate students were introduced to climate science research via our summer scholarship initiative. Summer students were supervised by our early career researchers, which provides them with vital supervisory experience.

Finally, it is always nice to celebrate success and there are a lot of successes to celebrate. Major award winners include Lisa Alexander who received a highly prized Outstanding Service Award from the World Meteorological Organization Commission for Climatology. Jason Evans and Julie Arblaster were co-winners of the Australian Meteorological and Oceanographic Society (AMOS) Priestley Medal. Christian Jakob was made an AMOS fellow and won the 2018 AMOS Morton Medal. Andrew King garnered the Inaugural AMOS Science Outreach Award. Markus Donat won the 2017 World Climate Research Programme/Global Climate Observing System International Data Prize. Partner Investigator Sandrine Bony at the Institut Pierre Simon Laplace was awarded the Gérard Mégie Prize by the French Academy of Sciences. Another Partner Investigator, Harry Hendon, was named by *The Australian* newspaper's annual *Research magazine* as Australia's leader in atmospheric science. Associate Investigator Caroline Ummenhofer won the American Geophysical Union (AGU) James B. Macelwane Medal. We also congratulate Associate Investigator Graham Farquhar, who was named Senior Australian of the Year for 2018, and Trevor McDougall, who became a Companion of the Order (AC). Later in the year he was named an AGU fellow.

I hope you enjoy reading more about our achievements through this annual report. If you have any questions you are most welcome to contact me.

Professor Andy Pitman, AO

climate extremes
ARC centre of excellence

ARC Centre of Excellence for Climate Extremes Strategy 2017-2024

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.

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.

Centre Structure, Governance and Management

Governance and Management

Centre Advisory Board

The Australian Research Council (ARC) Centre of Excellence for Climate Extremes (CLEx) is overseen by an advisory board, which is chaired by distinguished scientific leader, Dr Tony Press. The 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 twice in 2018: once in person, in March, and via video conference in September. It is anticipated that this will continue to be the pattern of board meetings.

Advisory Board Members

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

Dr Tony Press is an adjunct professor at the Antarctic Climate and Ecosystems Cooperative Research Centre, where he served as its CEO from 2009 – 2014. He was formerly the head of the Australian Antarctic Division.

Dr Press has had a long career in science, natural resource management, public administration and international policy. He chaired the Antarctic Treaty's Committee for Environmental Protection from 2002 to 2006. He was Australia's representative to the CEP, 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. The Centre collaborates closely with national and international research partners to deliver knowledge and information products and services to a broad community of research and other end-users.

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

Ian Dunlop is a Cambridge-educated engineer, with a particular interest in the interaction of corporate governance, corporate responsibility and sustainability. Ian Dunlop was formerly a senior international oil, gas and coal industry executive. He was chairman of the Australian Coal Association from 1987-88, CEO of the Australian Institute of Company Directors from 1997-2001, and chair of the Australian Greenhouse Office Experts Group which developed the first emissions trading system for Australia from 1998-99. As a fellow of the Centre for Policy Development, Director of Australia21 and a member of the Club of Rome, he advises internationally on climate, energy and sustainability.

Dr Greg Holland, Willis Senior Scientist Emeritus at the Capacity Center for Climate and Weather Extremes (C3WE), NCAR, Boulder, USA

Dr Greg Holland is an emeritus Willis Senior Scientist in the Capacity Center for Climate and Weather Extremes (C3WE) at the National Center for Atmospheric Research (NCAR). He was previously Director of NCAR's Earth System Laboratory and Director of C3WE. His current research focuses on weather and climate extremes and their response to climate variability and change. His career in meteorology includes forecasting, teaching, research, and community service, including service on a number of committees and review boards for the National Oceanographic and Atmospheric Administration, the National Academies, NASA and Zurich Insurance, and chairing the Tropical Meteorological Program of the World Meteorological Organization. Dr Holland received his bachelor's degree with honours in mathematics from the University of New South Wales, Australia, and a Master of Science and PhD in Atmospheric Science from Colorado State University.

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 Commonwealth Department of the Environment and Energy. 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 Department of the Environment and Energy and the Department of Climate Change and Energy Efficiency, including 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 the 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. Dr May 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 Met Office Science Partnerships, UK

As Head of the UK Meteorological Office Science Partnerships Dr Jon Petch is responsible for the UK Met Office's national and international relationships with other science organisations. In addition, he currently leads a team that develops the regional weather and climate system models.

Dr Petch has worked on physical modelling and parameterizations since joining the UK Met Office in 1997, having previously worked on climate modelling at the National Center for Atmospheric Research, USA. 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 model evaluation and development and is currently a vice president of the Royal Meteorological Society in the UK.

Prof Ana Deletic, Pro Vice-Chancellor (Research) UNSW

Professor Ana Deletic is Pro Vice-Chancellor (Research) at the University of New South Wales. Until mid-2017 she was Associate Dean of Research Engineering Faculty and the founding director of the Monash Infrastructure research institute at Monash University.

Prof Deletic leads a large research group that is working on multi-disciplinary urban water issues focusing on stormwater management and socio-technical modelling. In 2012, the Victorian State Government awarded her the Victoria Prize for Science and Innovation (Physical Sciences) for her lifelong achievements in stormwater research.

Matt Riley, Director Climate and Atmospheric Science, Office of Environment and Heritage

Matthew Riley is Director Climate and Atmospheric Science at the Office of Environment and Heritage (OEH). He is the Project Director for the NSW and ACT Regional Climate Modelling Project and leads OEH's Climate Change Impacts research program. He is also responsible for the operation of the 80+ monitoring stations of the NSW Air Quality Monitoring Network and leads the NSW Government's Air Quality research program. Matt Riley 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 (Prof Andy Pitman), who carries overall responsibility for day-to-day leadership of the Centre and its research; the Deputy Director (A/Prof Todd Lane); the Director of Engagement Impact and Partnerships (Prof Christian Jakob); the Chief Operations Officer (Stephen Gray); the Graduate Director (A/Prof Melissa Hart); and the Manager of the Computational Modelling Support team (Dr Claire Carouge).

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 four 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, infrastructure and technology and the career development of our early career researchers.

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. The Centre is committed to implementing measures that enhance the diversity of our staff and student populations and proactively ensure an equitable culture. To this end, the Centre has established a Diversity and Culture Committee.

The committee will provide advice and recommendations to the Centre Director and Centre Executive on matters pertaining to equity, diversity and Centre culture. The committee will also have Centre-wide initiatives and draft policies and procedures within its sphere of influence. The committee's activities will be 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.

The initial meetings of the committee were concerned with developing terms of reference and determining priorities for the committee's first 12 months. Among the terms of reference are commitments to:

- develop, maintain and review an active strategy and policy on diversity, equity and culture
- identify opportunities to improve the Centre's diversity
- regularly report on initiatives, outcomes and ongoing concerns in respect of culture and diversity
- provide a safe and impartial forum for Centre personnel to discuss issues around professional inequity
- ensure diversity is reflected in invited visitors, speakers at conferences, workshops and so on
- recommend initiatives around Centre structure, internal communications and technology that enhance coalescence and cohesion within and across Centre nodes.

The committee is proud of its achievements in 2018. Highlights included:

- the drafting and dissemination of the Centre's Equity Plan
- successfully proposing to have sessions on kindness in science and managing productivity included on the program of the Centre's annual workshop
- instigating a weekly 'Hump Day Tip' email to the whole Centre which promotes tips on a range of topics including wellbeing, work-life balance, equity and diversity and more
- drafting the protocol for a career development award to be targeted at women and other under-represented groups within the Centre

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 Christian Jakob (Monash)

The Infrastructure Committee's primary role at the Centre of Excellence 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 the Centre. The committee is also tasked with helping the CMS team allocate, compute and storage resources to Centre 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 Centre 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:

- prioritisation of requests for in-depth CMS team engagement with new modelling capabilities
- prioritisation of new data set hosting and strategies for storage expansion
- diversification of CMS team member roles
- the management of resource allocation transfers from the ARC Centre of Excellence in Climate System Science 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), Julie Arblaster (Monash), Dietmar Dommenget (Monash), Jason Evans (UNSW), Amelie Meyer (UTAS), Alvin Stone (UNSW)

The Outreach Committee 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". An important step in this effort was made in 2018 with the first hire in the Knowledge Brokerage Team (KBT). Ian Macadam was appointed as the KBT lead. He has been working on assessing existing school outreach activities with a view to developing new tools in line with national and state curricula. He has also begun developing Centre of Excellence position papers and engaging with stakeholders. These stakeholders include the 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.

The Outreach Committee also ensures that the Centre maintains an effective outreach strategy by identifying opportunities and tools to engage with external groups, highlighting Centre activities and successes, and generally raising the Centre's profile. During 2018, the committee developed a social media policy and has tried to guide effective and sensible use of social media by Centre researchers. More broadly, the committee will develop a media plan across multiple platforms and also motivate researchers at all levels to contribute to outreach, including the annual report, newsletters, the website and social media.

Early Career Researcher Committee

The Early Career Researcher committee (ECRC) undertook several tasks in 2018. These included setting up this new committee after the transition from ARCCSS to CLEx, outlining a mission statement and preparing the Early Career Researchers Day for the annual Centre workshop in Wollongong. This activity took place on top of the regular support provided to the early career researchers (ECRs) at each Centre of Excellence node.

The committee defined its mission as follows: to facilitate, encourage, and contribute to the development of all Centre researchers undertaking postgraduate or honours study. To do so, we met regularly via video conference, discussing problems at hand and planning the Wollongong ECR Day. Every month, one of the two ECRC Chairs attended the Chief Investigator meetings to report information from the ECRs to the Chief Investigators and to provide feedback to the ECRs. At each node, small gatherings were organised at least once during the year for the ECRs – in the style of morning/afternoon tea. These gatherings were intended for people to get to know each other, share relevant information with the ECRs, and facilitate an open discussion on needs and feedback.

The ECR Day that took place at the end of the Centre's annual workshop in Wollongong in November was a great success, with about 70 ECRs attending. The theme was 'Future career pathways for our climate extremes ECRs, with Dr Tim Finnigan from CSIRO as a guest speaker. Most of the day was based on interactive sessions on 'Building a good CV', 'Selection criteria', 'How to get into government science jobs', as well as a session on 'How and why scientists can use social media'. This was achieved with contributions from Stephanie Downes (NSW Office of Environment and Heritage), Melissa Hart (UNSW), Angela Maharaj (UNSW), Alvin Stone (UNSW) and Steve Sherwood (UNSW).

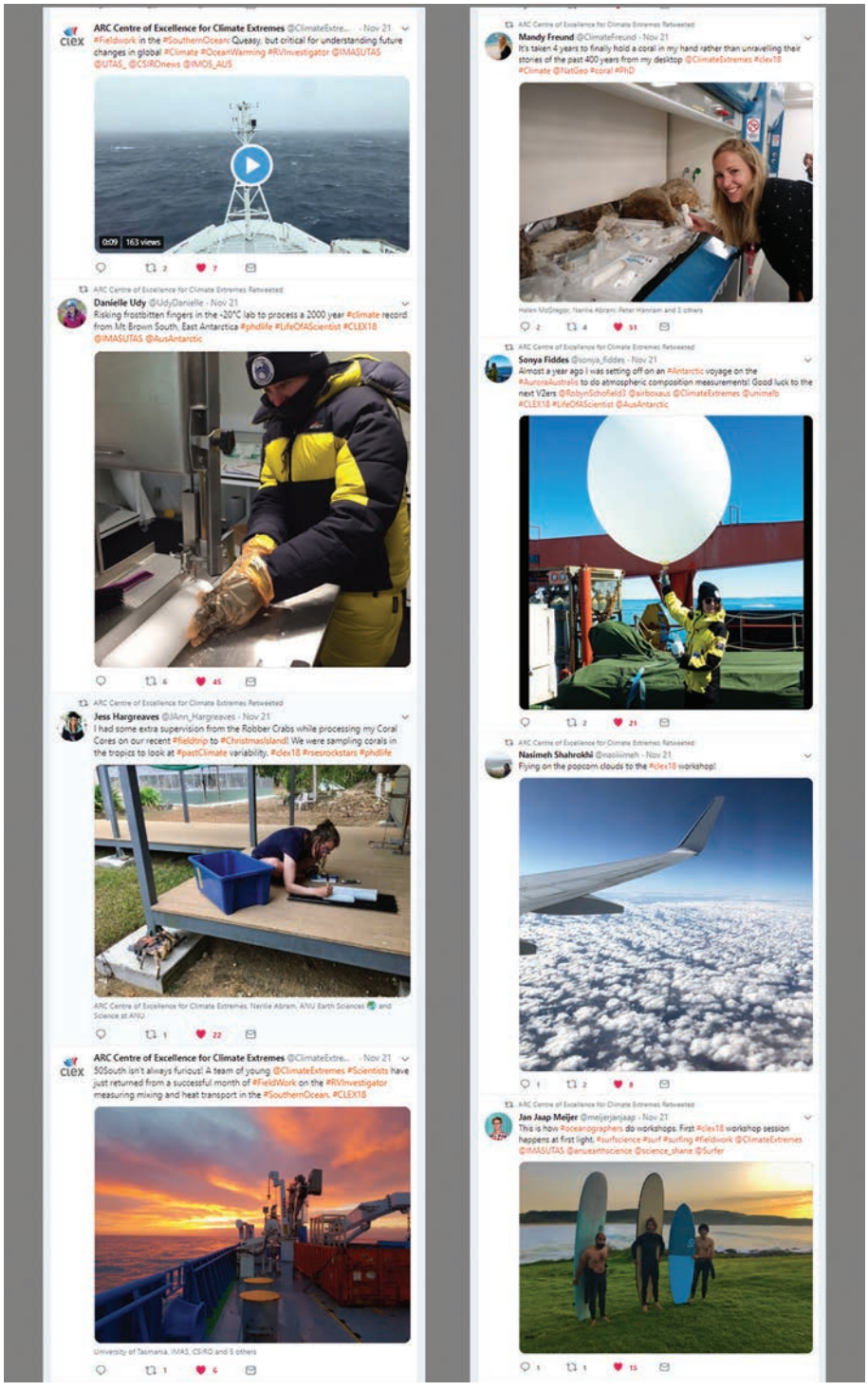
We thank all the ECRC members for their commitment and successful communication with ECRs in 2018 and look forward to continuing our work in 2019!

Amelie Meyer and Josue Martinez Moreno
(ECRC Co-chairs)

ECR Committee Composition

The committee is composed of one student and one postdoctoral representative from each of the five CLEx 'nodes' or Collaborating Institutions (UNSW, ANU, Monash, Uni Melbourne and UTAS). These 10 representatives have a standard tenure of 18 months but may vary. Additionally, the ECRC elects two committee Chairs on a six-monthly basis.

Josue Martinez Moreno: Chair and ANU PhD representative
Amelie Meyer: Chair and UTAS postdoctoral representative
Martin Bergemann: Uni Melbourne postdoctoral representative
Shreya Dhame: UNSW PhD representative
Zoe Gillett: Monash PhD representative
Ryan Holmes: UNSW postdoctoral representative
Sopia Lestari: Uni Melbourne PhD representative
Chen Li: Monash postdoctoral representative
Nicky Wright: ANU postdoctoral representative
Luwei Yang: UTAS PhD representative



Several highlights from CLEx early career researchers shared on Twitter in 2018.

Centre Business Team

The transformative research that the ARC Centre of Excellence for Climate Extremes 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, 0.2FTE), Alina Bryleva (ANU, 0.4 FTE) and Karla Fallon (Uni Melbourne 0.4FTE). 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.

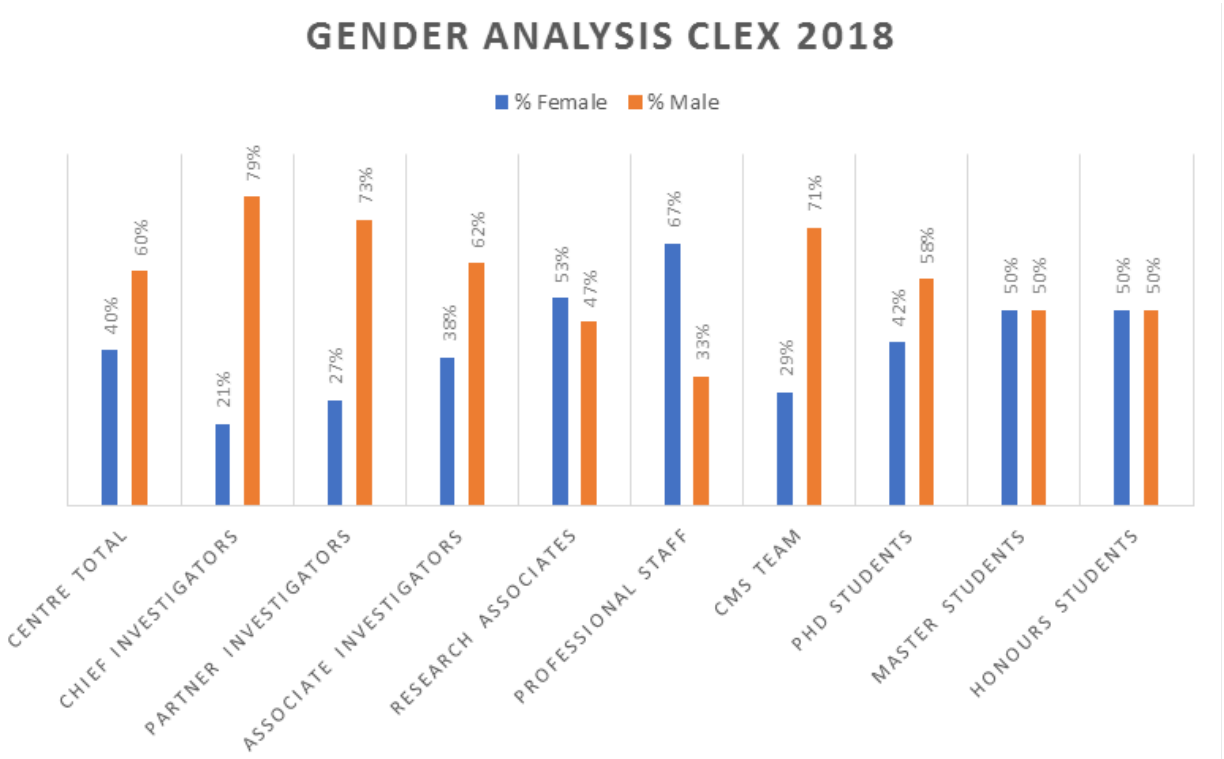
Leadership Development

As is evident from the Researcher Development Program chapter, we are strongly committed to providing leadership training, guidance and opportunities for all Centre researchers, including our students and early career researchers (ECRs and our professional and technical staff. Our students and ECRs are represented via our ECR Committee This committee 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.

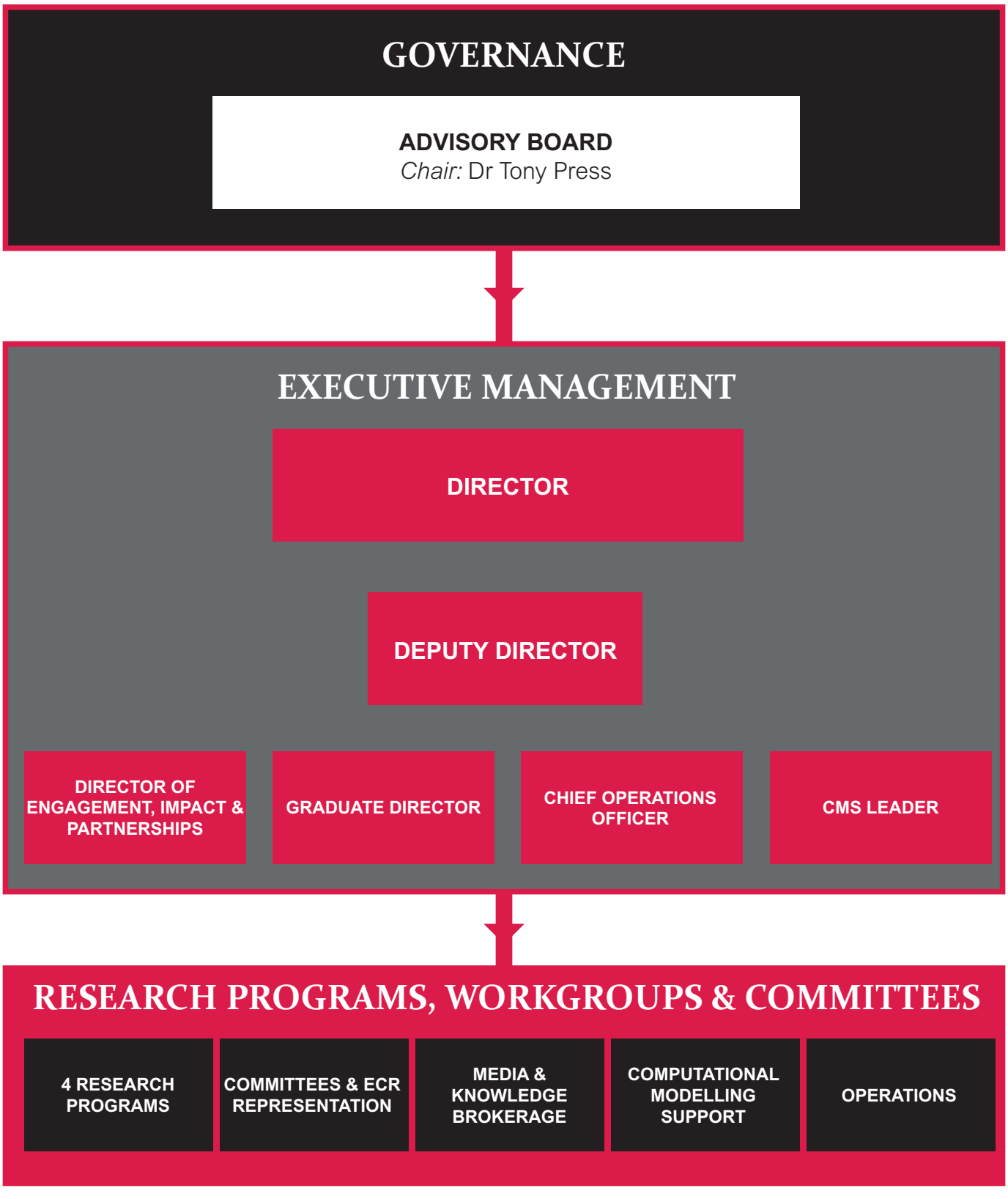
CLEx Personnel Gender Profile

The ARC Centre of Excellence for Climate Extremes is committed to providing an outstanding work and study environment that is inclusive, healthy and respectful. We strive to be an exemplar in tackling inequality and systemic challenges faced by women and other under-represented groups in science. To achieve this, we have formed a Diversity and Culture committee which works on a range of centre-wide initiatives. Our equity is available for download from our website.

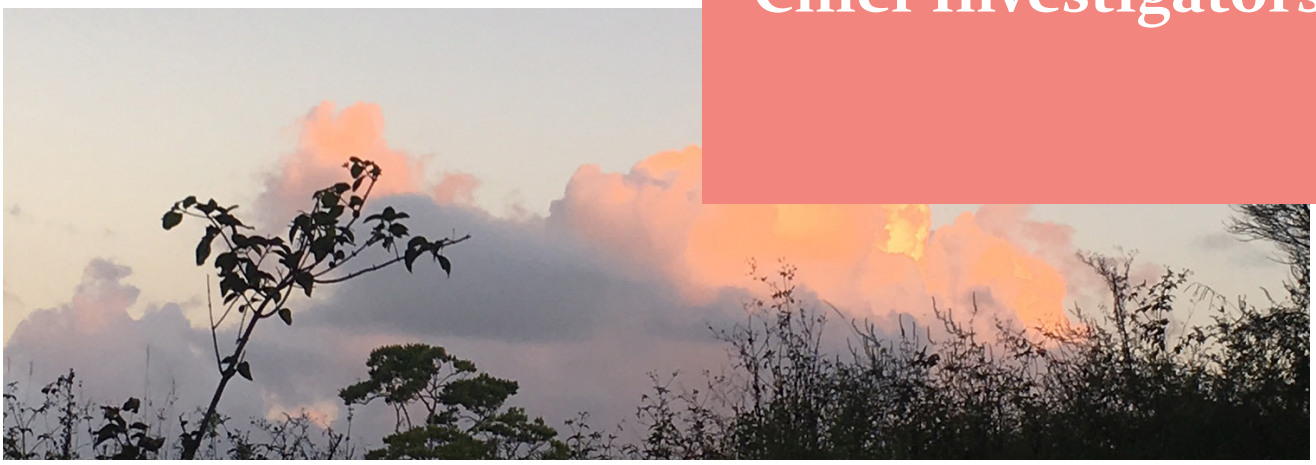
The table below shows the gender profile of various cohorts within the Centre. As is often the case in science disciplines there is more or less gender parity amongst our graduate students and ECRs, however women are underrepresented among more senior positions. We have set ambitious KPIs of 50:50 gender distribution at all levels of the Centre as a stretch target to ensure we continually work towards this goal.



Organisational Chart



Chief Investigators



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. Prof Pitman has been at the University of New South Wales since 2007. He was the director of the ARC (Australian Research Council) Centre of Excellence for Climate System Science (2011-2017) and is the 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. 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 Medal (2009), the Dean's Award for Science Leadership at Macquarie University (2005), the Priestly 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 the Australian Meteorological and Oceanographic Society 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.

A/ Prof Todd Lane

Deputy Director ARC Centre of Excellence for Climate Extremes

Associate 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 postdoctoral 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 Associate Professor and Reader in the School of Earth Sciences. Between 2010-2014 he was an Australian Research Council Future Fellow.

A/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 of Excellence is focused on extreme rainfall, and is using 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.

A/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 is currently a member of the World Meteorological Organization World Weather Research Programme's Expert Team on Severe Monsoon Weather. A/Prof Lane has received awards from the American Meteorological Society, the Australian Academy of Science, the Australian Meteorological and Oceanographic Society, and NASA.

A/ Prof Melissa Hart

Graduate Director ARC Centre of Excellence for Climate Extremes

Associate Professor Melissa Hart leads the Researcher Development Program for the Australian Research Council (ARC) Centre of Excellence for Climate Extremes (CLEx). In this capacity, and in her former role as graduate director with the ARC Centre of Excellence for Climate System Science, Associate Professor Melissa Hart has led and developed a national, cross-institutional program which has reimagined the traditional Australian PhD. In CLEx she continues to enhance the vital combination of breadth, depth, support and collaboration which has seen the program provide more than 120 graduate students and early career researchers 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.

A/Prof Nerilie Abram

Associate Professor Nerilie Abram uses paleoclimate 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.

A/Prof Abram's 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.

A/Prof Abram holds an Australian Research Council Future Fellowship. In 2015 she received the Dorothy Hill Award from the Australian Academy of Science for her research achievements. She is currently a Coordinating Lead Author of the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Dr Gab Abramowitz

Dr Gab 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. Dr Abramowitz asks such questions as: To 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 Global Land-Atmosphere System Study panel.

A/Prof Lisa Alexander

Associate 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 the Bureau of Meteorology.

A/ 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.

A/Prof Alexander 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

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) in the US, before that.

A/Prof 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.

Her 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 (WCRP) Stratosphere-troposphere Processes and their Role in Climate (SPARC) scientific steering group from 2011-2016 and served as a Lead Author of the IPCC's 5th Assessment Report and the latest World Meteorological Organization/United Nations Environment Programme Scientific Assessment of Ozone Depletion. She is a member of the National Climate Science Advisory Committee and the National Committee on Earth System Science.

Prof Nathaniel Bindoff

Professor Nathaniel 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.

He was the Coordinating Lead Author for the Oceans chapter in the Intergovernmental Panel on Climate Change (IPCC) 4th and 5th Assessment Reports (AR4 & AR5). Prof Bindoff 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.

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. 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.

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.

Prof Bindoff led the Climate Futures project for the study of impacts of climate change on Tasmania. He 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. Prof Bindoff has published more than 100 scientific papers, seven book chapters, eight conference papers and 43 reports. He has a H index of 39 and greater than 10000 citations (Google Scholar).

Prof Craig Bishop

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 United States. 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 won six outstanding contribution awards, three NRL Alan Berman Research 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 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.

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.

A/Prof Dietmar Dommenget

Associate Professor Dietmar Dommenget completed his Master of Science 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.

He 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 junior professor (lecturer) in the Meteorology Department at the GEOMAR - Helmholtz Centre for Ocean Research Kiel.

In 2010 A/Prof Dommenget joined Monash University as a senior lecturer in the atmospheric and climate science group of the School of Earth, Atmosphere and Environment, and was promoted to his current role in 2018. His research focuses on large-scale climate dynamics. A/Prof Dommenget 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.

Much of A/Prof Dommenget's research 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

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 (CNRS), 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. He has been with the University of New South Wales since 1995, where he held an Australian Research Council (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 Prof England 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's Drought Interest Group.

Prof England 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 over 180 peer-reviewed journal papers. He has been a Contributing Author for two Intergovernmental Panel on Climate Change (IPCC) assessment report and was the Convening Lead Author of the *2009 Copenhagen Diagnosis*. He has graduated over 20 PhD-holder 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

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, 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 and 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 Hydroclimate Panel and Australasia region coordinator of the Coordinated Regional Climate Downscaling Experiment, both elements of the World Climate Research Programme. He is also Lead Author on the Intergovernmental Panel on Climate Change Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. He has also 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 was bestowed the Australian Agricultural Industries Young Innovators and Scientists Award 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 invited to give 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

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 Australian Research Council 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 Australian Research Council 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, and won the Nicholas P. Fofonoff Award from the American Meteorological Society and the Australian Meteorological and Oceanographic Society Priestly Award in 2015.

Prof Neil Holbrook

Professor Neil 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. His research helps to reduce the uncertainties associated with human-induced (anthropogenic) climate change, the potential risks associated with abrupt climate change and the likely changes in climatic extreme events, by developing a strong understanding of natural climate variability on all time scales.

Prof Holbrook'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. Prof Holbrook 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, he 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 Commission on Climate of the International Association of Meteorological and Atmospheric Sciences/International Union of Geodesy and Geophysics, an associate editor of the *Australian Meteorological and Oceanographic Journal*, and a fellow of the Australian Meteorological and Oceanographic Society. Prof Holbrook is a University of the Sunshine Coast/UTAS/Griffith University Collaborative Research Network research leadership fellow (Sustainability; University of Tasmania), a visiting professor at Macquarie University; and an international participant in the South-west Pacific Ocean Circulation and Climate Experiment.

Prof Christian Jakob

Professor Christian Jakob was awarded his PhD in Meteorology from the Ludwig Maximilians University, Munich, in 2001. As a research, then 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 of the 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 scientific and collaborative 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

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, heatwaves, 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 fellow and past president of the Australian Meteorological and Oceanographic Society (AMOS). He is a winner of the Distinguished Research Award (AMOS) and the Loewe Prize (Royal Meteorological Society, Australian branch), and has given AMOS's Clarke Lecture.

Prof Michael L Roderick

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. He was a lecturer at the School of Spatial Sciences, Curtin University of Technology, from 1993-1996 and completed a PhD in satellite remote sensing and environmental modelling at Curtin University in 1994. He joined the Australian National University as a research fellow in 1996 and currently holds a joint appointment as Professor between the Research School of Earth Sciences and the Research School of Biology.

Professor 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. He led the Theoretical Developments in Carbon Cycle Science program of the Cooperative Research Centre for Greenhouse Accounting from 2001-2006.

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 he 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

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 Institute 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 Goddard Earth Sciences and Technology Centre 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 a professor at 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 Australian Research Council's (ARC) Centre of Excellence for Climate Extremes Prof Sherwood and his team contribute to the Extreme Rainfall research program and the Climate Variability and Teleconnections research program.

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 over 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 andthe 2005 American Meteorological Association's Clarence Leroy Meisinger Award. He was a Eureka Prize finalist in 2014, and in 2015 was granted 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

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, which he held until 2002. From 2002-2004 he was Assistant Professor with the State University of New York's Marine Sciences Research Center and from 2004-2010 he was Assistant, then Associate Professor at Oregon State University's College of Oceanic and Atmospheric Sciences. In 2010 he returned to Australia on an Australian Research Council (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 for Climate Extremes 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 research on Antarctica to the tropical Pacific and the Labrador Sea. A/Prof Strutton is a past editor for the journal *Geophysical Research Letters* and a leader of the Bluewater and Climate Node for Australia's Integrated Marine Observing System. He also serves on the Scientific Steering Committee and Biogeochemistry Task Team for the redesign of the Tropical Pacific Observing System (tpos2020.org).

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*Thesis submitted in 2018

CLEx Annual Workshop 2018

This year's Centre of Excellence for Climate Extremes (CLEx) workshop at Wollongong, structured by a committee comprised of Professor Michael Reeder, Professor Andy Hogg, Dr Amelie Meyer, Stephen Gray and Jenny Rislund thoroughly broke with tradition and introduced some intriguing innovations. The committee had three key goals: to make early career researchers (ECRs) feel part of the team, to forge cross-disciplinary research programs, and to introduce all staff to the science underpinning the Centre of Excellence. The key to this approach was the Primer sessions, which outlined the science at a level where everyone across the programs could understand the detail. These talks then extended into challenging areas of each of the Centre's research programs, enabling contributions across the Centre.

There was also a focus on a single, significant climate extreme – the current drought that has primarily affected New South Wales and Queensland for the past few years. What has made this drought a particular challenge is that it does not seem to have been instigated or prolonged by the usual climate contributors.

Two sessions on the first day were devoted to the causes of that drought, with contributions and presentations coming from all research programs. This was followed on the third day by an ad-hoc meeting of researchers who wanted to pursue the drought problem over the coming year. This final meeting focused the Centre's next research steps to enable our scientists to understand its causes and perhaps improve future forecasts of drought events in Australia.

Two other ad-hoc meetings were held at the same time. One was a school outreach stocktake, to find out who in the Centre had been involved in outreach and was developing school resources. The other meeting, led by the Climate Variability and Teleconnections research program, scoped out near-term plans for running Australian Community Climate and Earth System Simulator--Ocean Model version 2 (ACCESS-OM2) simulations.

This year also saw extended scientific poster sessions with each poster assigned two peers to to review the design and scientific content. This was a break from 'lightning lectures' used at past workshops, with the poster review system being used as a means to get more meaningful engagement with poster presenters. And it seemed to work, with many animated and engaged discussions in front of posters throughout the session. There was also a noticeable improvement in the design of the posters, with many of the presenters saying they had used the poster guide when putting them together.

Improvements continued with a State of the Centre presentation by CLEx Director, Professor Andy Pitman, painting a picture of a healthy Centre tackling some of the toughest problems in climate science. Highlights of the presentation included multiple examples of publications in high impact journals, the strength of the researcher development program, two new citizen science initiatives, and the development of the Knowledge Broker team that is now reaching out to stakeholders.

Another highlight was the plenary talk by the Chairman of the Centre's board, Dr Tony Press, who led us through the history of climate policy in Australia. He presented a detailed and, at times, depressing review of Australia's climate policy but finished on the very positive note that the PhD students and ECRs in the room were likely to help shape the future of Australia's response to climate change.

It wasn't all hard-core science and policy. A series of professional development workshops run in parallel, focused on the following: Science Communication, with Dr Simon Torok from Scientell; Kindness in Science, led by Associate Professor Nerilie Abram; and Productivity and Organisation, with Professor Christian Jakob.

Another non-science innovation that appeared to lift the energy level of the workshop was a two-and-a-half-hour break on Tuesday afternoon to take part in a range of sports and social activities. This had the added bonus of enhancing the relationships across the Centre.

The annual workshop dinner also focused on building new relationships. It had arranged seating that was designed to ensure that people from different nodes and research groups were seated together, breaking them out of their usual groups. Each table was headed by a Chief Investigator, whose role was to facilitate discussion and take on mentoring roles of students and ECRs during the course of the workshop.

These may seem minor additions amid our science work, but the relationships established here that extend across our nodes are vital to the work of the Centre of Excellence. In the past they have not only spawned a higher level of collegiality but have become the foundation of innovative research that has set CLEx apart from other ARC Centres of Excellence. It's why our annual workshops will continue to be one of the most important events on the Centre's calendar.

Research Partnerships & International 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
National Computational Infrastructure
NSW Office of Environment and Heritage
Risk Frontiers
Sydney Water

International Partner Organisations & Collaborators

ETH Zurich
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)
NASA-Jet Propulsion Laboratory (USA. MoU Pending)
National Center for Atmospheric Research (USA)
UK Meteorological Office (UK)
The University of Arizona (USA)

The ARC Centre of Excellence for Climate Extremes (CLEx) has 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 partners, CSIRO and the Bureau of Meteorology. Regular and ongoing discussions at both the researcher-to-researcher level and the organisational level, via representation on the Centre's Advisory Board, have informed our strategic and implementation plans at all levels. Similarly, 2018 saw deep engagement between CLEx and the NSW Office of Environment and Heritage.

We have also been working closely with the National Computational Infrastructure, both in terms of operational considerations and allocation of resources, and strategic considerations linked to ongoing investment in national high-performance computing.

Elsewhere in this report you will read of the establishment of our Knowledge Brokerage Team. The design, implementation and prioritisation of this capability has been informed through conversations with the National Environmental Science Program Earth Systems and Climate Change hub, Risk Frontiers and the Managing Climate Variability Program. We have also maintained an active dialog with staff within the Federal Department of Environment and Energy. While this department is not a Partner Organisation, we expect that maintaining strong and open discussions with it will prove invaluable in the longer term, and we are grateful for Department representation on our Advisory Board.

In the first half of 2018 we added Sydney Water as a new CLEx Partner Organisation. This partnership has enabled us to employ a research associate to work closely with Sydney Water to provide better high-resolution modelling of rainfall across NSW and the Sydney basin.

We have had strong engagement with our overseas partners. At the University of Arizona we farewelled Professor

Jonathan Overpeck, who has taken up a new position in Michigan. "Peck" as he's affectionately known, remains connected to the Centre as an Associate Investigator. We welcomed Dr Ali Behrangi as a new Partner Investigator at Arizona. Dr Behrangi's broad expertise and research track record will make him a valuable member of our Heatwaves research program.

We hosted visiting researchers from Partner Organisations ETH Zurich, National Center for Atmospheric Research (NCAR), , the UK Meteorological Office and the Max Planck Institute for Meteorology, as well as a number of other leading laboratories in Europe, Asia, North and South America. CLEx researchers made visits to the Geophysical Fluid Dynamics Laboratory, NCAR, the UK Met Office and numerous other research groups, thus demonstrating the interconnectedness of the Centre with global efforts to better understand climate extremes.

Significant Outbound and Inbound Research Visits and Travel

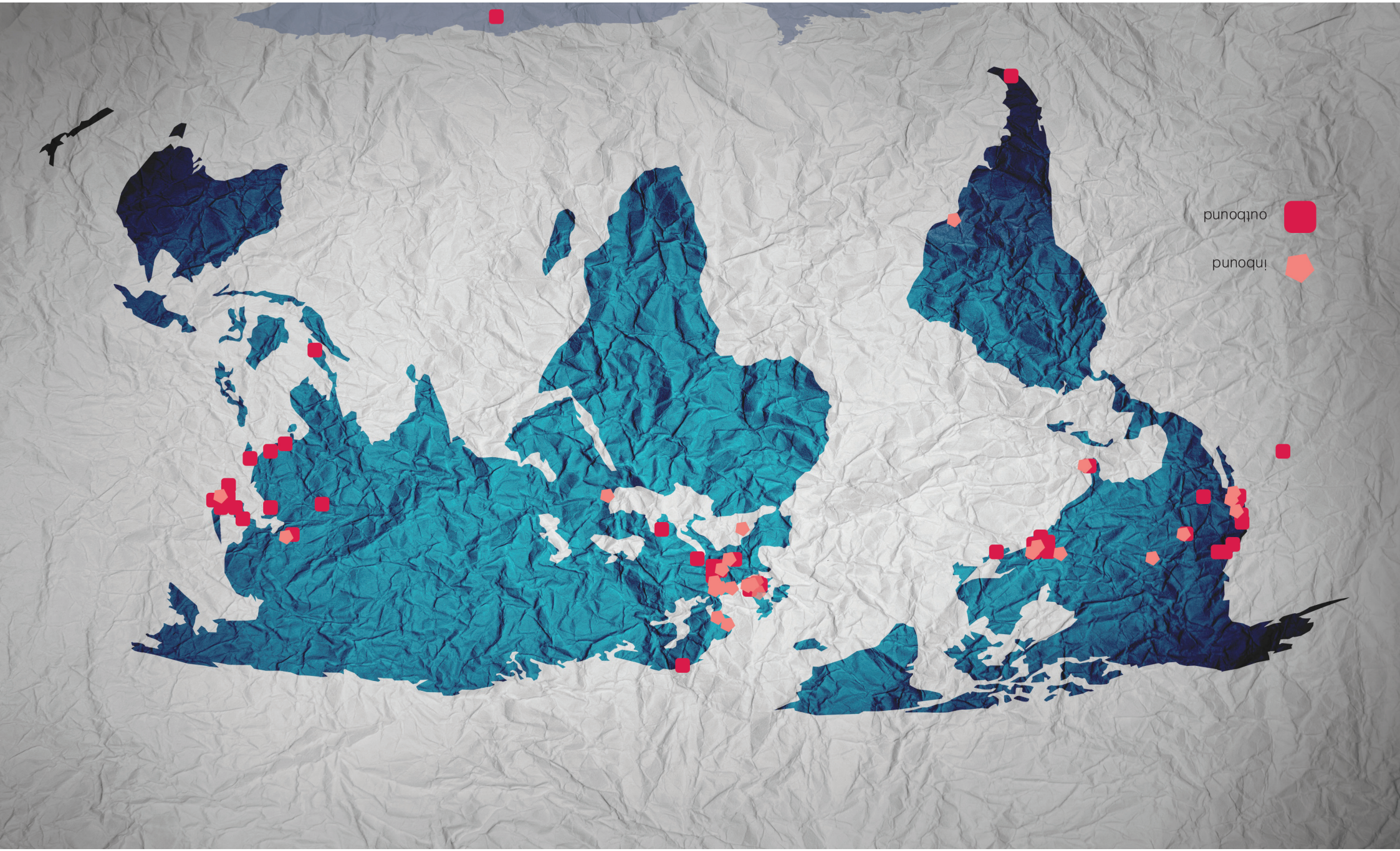
Inbound Visitors

Arguesso, D. University of Balearic Islands, Spain
Bachman, S. National Center for Atmospheric Research (NCAR), USA
Bain, C. UK Met Office
Bayr, T. GEOMAR, Kiel, Germany
Chenillat, F. LEMAR, France
Feliks, Y. Israel Institute of Biological Research
Furue, R. JAMSTEC, Japan
Ge, J. Nanjing University, China
Grabowski, W. NCAR (USA)
Griffies, S. Geophysical Fluid Dynamics Laboratory (GFDL), USA
Hanley, K. University of Reading/UK Met Office
Haustein, K. University of Oxford, UK
Huguenin-Virchaux, M. ETH Zurich
Jourdain, N. CNRS, France
Keenlyside, N. University of Bergen, Norway
Keysser, L. ETH Zurich
Knobloch, E. University of California, Berkeley, USA
Lacasce, J. University of Oslo, Norway
Lacour, L. CNRS, France
Maher, N. Max Planck Institute for Meteorology, Germany
Martin, P. University of Michigan, USA
Meehl, G. NCAR, (USA)
Meredith, M. British Antarctic Survey
Miller, M. European Centre for Medium-Range Weather Forecasts
Mullendore, G. University of North Dakota, USA
Munday, D. British Antarctic Survey
Nie, J. Peking University, China
Pincus, R. University of Colorado, USA
Rodrigues, R. University of Sao Paulo, Brazil
Ryan, J. Monterey Bay Aquarium Research Institute, USA
Schwendike, J. University of Leads, UK
Smith, R. University of Munich, Germany
Ummenhofer, C. Woods Hole Oceanographic Institution, USA
van Sebille, E. Utrecht Univeristy, Netherlands
Vreugdenhil, C. Cambridge University, UK
Waugh, D. Johns Hopkins University, USA
Wehner, M. Lawrence Berkeley National Laboratory, USA
Wing, A. Florida State University, USA
Wyss, A. University of Bern, Switzerland
Yano, J. CNRS, France
Young, W. SCRIPPS Institute for Oceanography, USA
Zhang, Y. Monterey Bay Aquarium Research Institute, USA

Outbound International Travel

(lab visits, significant international meetings)

Abram, N. Davos Switzerland, Polar 2018 and SCAR delegates meeting
Alexander, L. Kuala Lumpur, Malaysia, WMO Space-based weather and climate extremes monitoring project (SEMDP) meeting
Bindoff, N. Washington, CLIVAR Meeting
Bindoff, N. Lanzhou, China, IPCC SROCC meeting
Bishop, C. London, UK Met Office & University of Reading
Bishop, C. Tokyo Japan, WMO, Predictability Dynamics and Ensemble Forecasting Working Group
Constantinou, N. Princeton NJ, Washington DC, San Diego CA, Los Angeles CA, San Francisco CA, GFDL visit, AGU Fall Meeting, Scripps visit, UCLA Spinlab visit, Lawrence Livermore National Laboratory visit
Constantinou, N. London, Athens, Imperial College London, National and Kapodistrian University of Athens
Cougnon, E. Halifax, NS, Canada, Department of Oceanography, Dalhousie University
De Kauwe, M. Tucson Arizona, USA, University of Arizona
England, M. Qingdao, China , CSHOR, QNLM and China Ocean University
England, M. USA - LA, Visit to UCLA and Scripps
Evans, J. Washington D.C. USA, GEWEX Open Science Conference and SSG meeting at International Project Office
Gross, M. Canmore, Canada, GEWEX Open Science Conference 2018 and ECR Workshop
Hart, M. Antarctica, Homeward Bound Leadership Projects
Hogg, A. Cambridge, Southampton, Reading, UK & Davos, Switzerland, British Antarctic Survey, National Oceanography Centre Southampton, Reading University, Polar2018.
Holmes, R. Boulder, CO and Boston, MA USA, Visits to NCAR and MIT
Jakob, C. Beijing, Chinese Meteorological Administration
Jakob, C. Pasadena, CA and Washington DC, Visit to NASA JPL
Jakob, C. Exeter, UK and Hamburg, Germany, Visits to UKMO, University of Exeter and MPI
King, M. Boulder, CO, USA, Visit to NCAR Foothills Lab
Lane, T. Boulder Colorado, Visit to NCAR
Lewis, S. Gungzhou, China, IPCC Lead Author Meeting
Meyer, A. Tromso, Norway, Visit to Norwegian Polar Institute
Sabot, M. Oracle, AZ, USA, Biosphere 2, Oak Ridge National Laboratory
Sabot, M. London, UK, and Paris, FR, Imperial College London and Uni Reading lab visits, LSCE lab visit
Santoso, A. Jeju, South Korea, Inter-basin tropical interactions workshop II
Santoso, A. Taipei, Chinese Taipei, National Taiwan University
Sherwood, S. Bristol, UK; Toulouse, France; Paris, France, U. Bristol; Mateo-France; UPMC
Sherwood, S. Tokyo; Busan, U. Tokyo; ANEKKT
Sherwood, S. Boulder, CO, Visit to NCAR
Sohail, T. Antarctica and Punta Arenas, Chile, Antarctica Voyage and Punta Arenas, Chile
Strutton, P. Boston, USA, Woods Hole Oceanographic Institution


outbound
inbound

Research Program Overview

almost all published in elite international journals

The research carried out by the ARC Centre of Excellence for Climate Extremes (CLEx) revolves around its four key programs:

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

By mid-2018, the Centre of Excellence had appointed virtually all its research fellows and, bar one or two, all were on board and contributing. 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 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 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 (CMIP), 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 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 2018. We also highlight the statement of intent for 2019 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.

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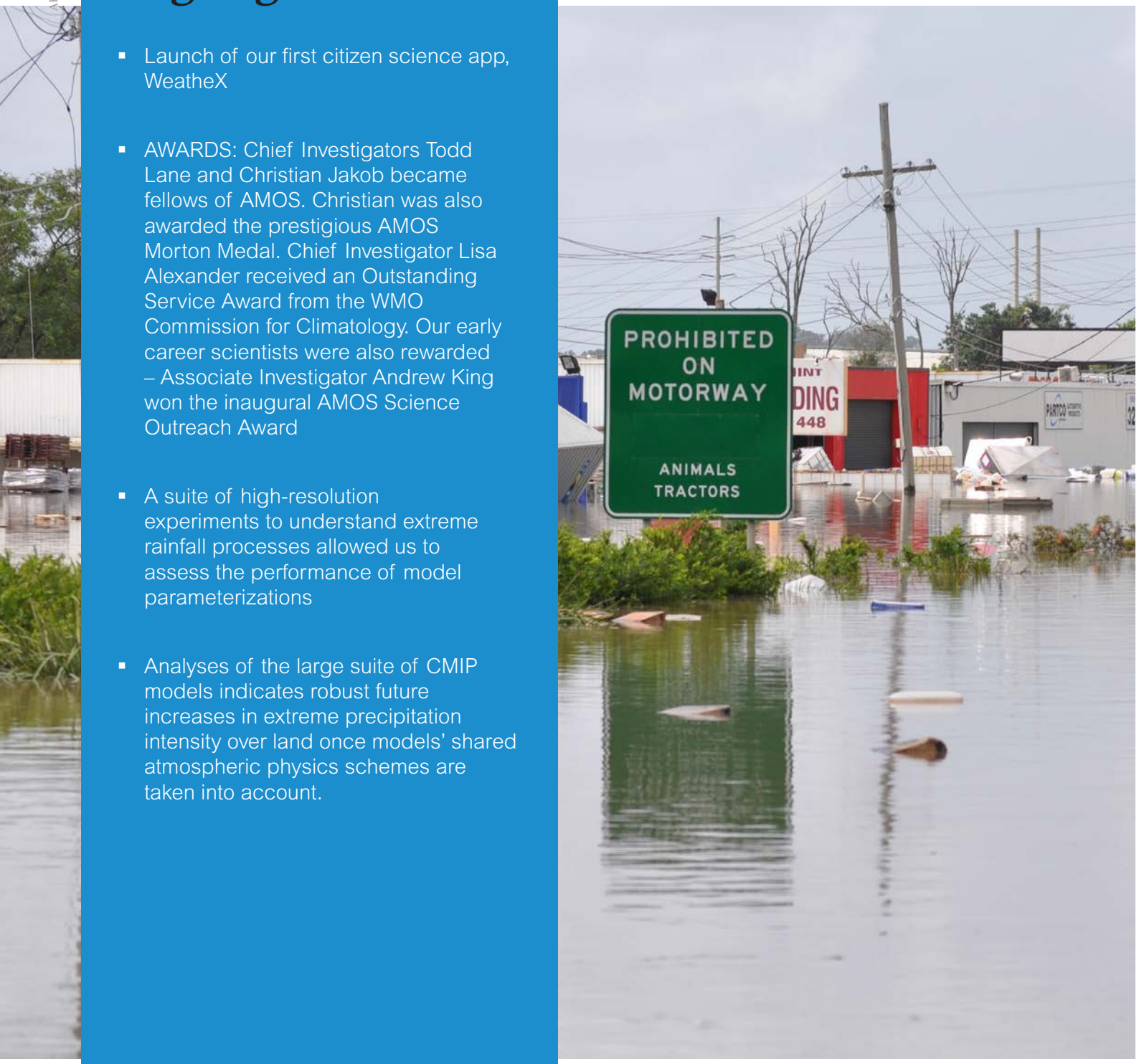
RP1: Extreme Rainfall

Highlights

- Launch of our first citizen science app, WeatheX
- AWARDS: Chief Investigators Todd Lane and Christian Jakob became fellows of AMOS. Christian was also awarded the prestigious AMOS Morton Medal. Chief Investigator Lisa Alexander received an Outstanding Service Award from the WMO Commission for Climatology. Our early career scientists were also rewarded – Associate Investigator Andrew King won the inaugural AMOS Science Outreach Award
- A suite of high-resolution experiments to understand extreme rainfall processes allowed us to assess the performance of model parameterizations
- Analyses of the large suite of CMIP models indicates robust future increases in extreme precipitation intensity over land once models' shared atmospheric physics schemes are taken into account.



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As the year commenced we finalised the recruitment of research staff, started major research programs and put in place a range of initiatives to bring the extreme rainfall research community together. The first of these initiatives occurred when Associate Investigator Dr Martin Singh organised the Understanding and Modelling Atmospheric Processes (UMAP) Pan-Global Atmospheric Systems Studies conference held at the end of February. The meeting was well attended by Centre of Excellence for Climate Extremes (CLEx) Extreme Rainfall research program members, and provided an opportunity to meet with many of our Partner Investigators and Partner Organisations. These meetings included a side meeting organised by the UK Meteorological Office on model physics developments.

There was a number of important research developments likely to impact all four areas of the research program. Early in the year, using new radar data, we commenced research to investigate the processes and large-scale conditions controlling extreme rainfall over Darwin.

We also celebrated news of our successful proposal for time on the RV Investigator to study convective processes during the Years of the Maritime Continent (YMC) international field experiment in late 2019.

It was a strong start to 2018 in a year that consistently picked up pace over the ensuing months.

Extreme Rainfall Research

As we noted in the previous annual report, because rainfall can be particularly localised, climate models struggle to represent it well and at times can produce contradictory results. This is especially true when looking at how precipitation may alter with climate change.

Observations and climate models say short, extreme rainfall events will increase in a warming climate. Australian observations also suggest these storms may become smaller in size, with increased rainfall concentrating even more around the centre of a storm cell. However, recent, contradictory climate model research suggests storm areas may become larger.

To understand this contradiction, members of the Extreme Rainfall research program compared two different model types to real-world observations of storm cell changes that occurred with rising temperatures. The researchers used a convective resolving model with two-kilometre grid spaces and a convective parameterization model with 10-km grid spaces. Both models successfully simulated peak precipitation and total precipitation when compared to observations. They also showed contraction in storms cell radius for one-hour events.

However, the convective resolving model underestimated peak precipitation for three-hour storm events. Other parameterizations, such as cloud microphysics and planetary boundary layers, appeared to influence this result. This was an unexpected outcome. It suggests that on some occasions a convective parameterization model can outperform a convective resolving model for regional studies. It offers another way to compare and evaluate the performance of regional climate models.

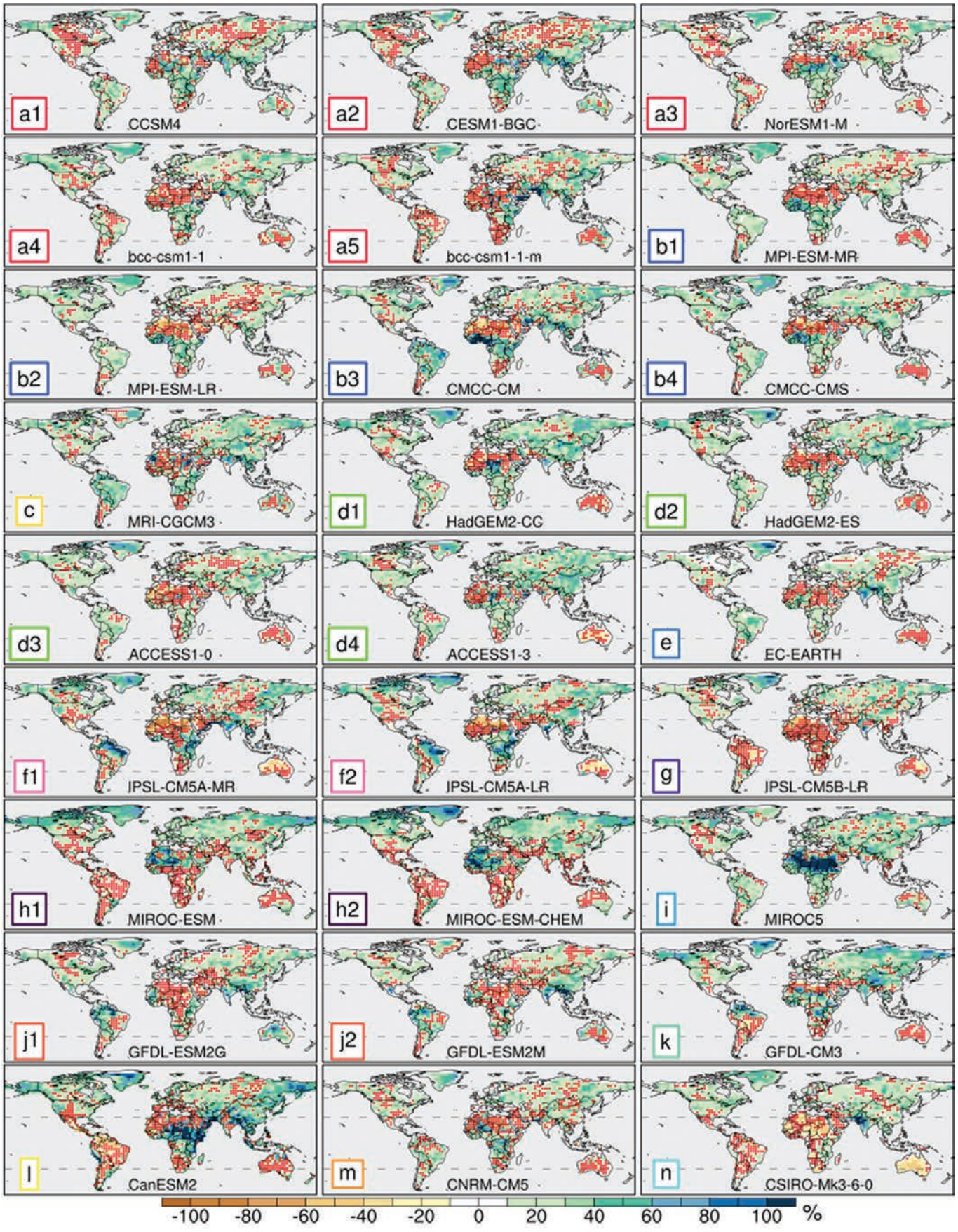


Figure 1: Changes in wet season maximum daily precipitation (relative to the historical period; %) between 2071–2100 (RCP8.5) and 1976–2005 (historical) for the 27 CMIP5 models (one per panel) grouped with regard to their shared atmospheric components (colours and letters). Red stippling indicates grid cells where the change is within the 90% interval of the changes in annual maximum daily precipitation driven by internal variability alone. Internal variability intervals are estimated in each model control simulation based on 5000 bootstrap realizations of changes between two 30-yr random periods.

The performance of parameterizations was also put under scrutiny in another paper from the past few months (http://climateextremes.org.au/heres-what-happens-when-you-turn-off-convective-parameterisations/). Convective parameterizations are widely believed to be essential for realistic simulations of the atmosphere, but are crude in today's weather and climate models.

Our researchers report on what happens when a number of models are run with these schemes simply turned off. Models were expected to perform very badly without these schemes, but we found that model climatologies over most regions are actually similar – and errors only slightly worse. However, extreme precipitation was strongly overestimated with the schemes turned off, and rain on land was too weak. The result suggests model biases in time-averaged climate are not as sensitive to how convection is treated, and to fix the biases probably requires improving other parts of the atmosphere model.

Some work has also been done on how robust future changes in extreme precipitation over land are across climate models (https://climateextremes.org.au/research-brief-increased-precipitation-under-climate-change-consistent-across-models/). Results show that models that share atmospheric physics schemes tend to produce similar results. When this is taken into consideration, future annual extreme precipitation intensity increases in the majority of models and over the majority of land areas.

Models show more similarities in dry compared to wet regions, in the dry season compared to the wet season and in the extratropics compared to the tropics. For each model, the future increase in the wettest day of a season or year exceeds the range of what can be explained by natural variability and this result is particularly robust in the extratropics.

Tropical convection as experienced in Northern Australia is perhaps the most difficult challenge of all. The processes governing the formation, maintenance and propagation of tropical thunderstorms are not fully understood. It has been hypothesised by many studies that cold pools are critical to the initiation and maintenance of thunderstorms in the tropics. CLEx researchers tested this idea, in collaboration with Colorado State University, by examining the maintenance of thunderstorms by cold pools in a suite of idealised numerical model experiments (http://climateextremes.org.au/tropical-thunderstorms-strengthen-without-cold-pools).

In these experiments, after the thunderstorms become organised, cold pools were artificially eliminated by suppressing evaporation. Surprisingly, the thunderstorms without cold pools propagated at approximately the same speed, lived for a similar amount of time, and actually intensified – demonstrating that cold pools can be detrimental to convection. Further investigations suggest that organised systems become maintained through atmospheric wave-convection interactions, which is a significantly different process to the established theory. These results confirm the importance of wave-convection interactions as a key contributor to convective organisation in the tropics, a process absent from all parameterizations.

In another piece of research aimed at improving climate models over the tropics, Extreme Rainfall program researchers performed fine-scale simulations of tropical thunderstorms over Sumatra (https://climateextremes.org.au/research-brief-climate-models-under-represent-tropical-heating-variations). The researchers aimed to better understand how heat is released from tropical thunderstorms. Heat release is influenced by a myriad of factors, including steep mountains, coastlines, time of day and mostly unseen atmospheric waves that move around the planet. Working at convection-permitting scales, they found significant variation in rainfall as planetary-scale waves passed through the region. Intriguingly, they also found that the interaction between cloud processes, geography and time of day also affected the way planetary waves themselves developed. These smaller processes are not well represented in climate models, so the next step is to compare the finer simulations with global climate models to find what may be missing and improve the performance of climate models overall.

In some interdisciplinary research, members of the Extreme Rainfall team looked at dimethyl sulfide (DMS), produced by phytoplankton, and how it contributes to atmospheric aerosols. Aerosols are important for cloud formation but natural aerosol emissions remain one of the largest sources of uncertainty in climate models. The study found important regional consequences for precipitation and cloud formation if large changes in DMS emissions were to occur (https://climateextremes.org.au/if-dimethyl-sulfide-emissions-ceased-earth-would-warm-0-5c-in-a-decade). As an example of the impact of these emissions, the researchers found that if all DMS emissions were to cease, global average temperatures would rise by 0.5°C over 10 years. This suggests that a better understanding of DMS and marine aerosols in general will be needed to improve climate models in some regions.

We continue to work closely with the Bureau of Meteorology (BoM) on the development and analysis of extreme rainfall from the C-band Polarimetric radar and gauge observations, which will continue with the development of a national radar archive early next year.

Engagement

Nationally and internationally, researchers in the Extreme Rainfall program have been building peer networks and reaching out to the public. Associate Investigators Dr Alejandro de Luca and Dr Sophie Lewis were named as Lead Authors on the next Intergovernmental Panel on Climate Change 6th Assessment Report, for Working Group 1.

As noted in the introduction to this section, our researchers have also organised important workshops, with Martin organising the UMAP Pan-GASS conference. The Extreme Rainfall program also held a foundational workshop with 30 key researchers and stakeholders from our partner universities, as well as local and international Partner Organisations, BoM, CSIRO, NSW Office of Environment & Heritage and the National Center for Atmospheric Research. The workshop focused on the Centre's four main projects in extreme rainfall, with 10-minute overview talks followed by deep discussion into plans for accomplishing our goals.

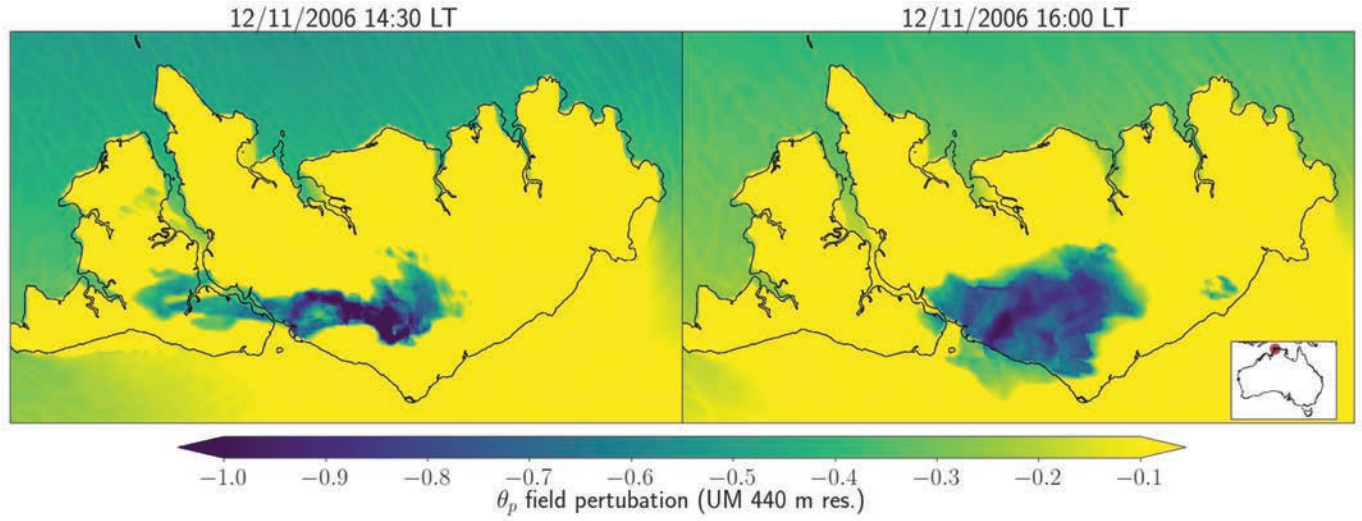


Figure 2: Cold-pool signature of two merging thunderstorm systems over the Tiwi Islands from a 440-m resolution convection-permitting simulation using the Unified Model. The image shows the density potential temperature (θ_p).

The UK Met Office, with support from its international Partner Organisations, held a convective-scale modelling workshop in Darwin in early November. The focus of the workshop was on the ongoing development and evaluation of very high-resolution regional versions of the Unified Model (the atmospheric component of ACCESS). A number of CLEx researchers attended the workshop, presenting work on modelling convection over the Darwin region at sub-kilometre resolution. The workshop sparked many interesting discussions and identified many opportunities for ongoing collaboration.

We also had a number of visitors assist with research program activities. Dr Gretchen Mullendore from the University of North Dakota collaborated primarily with University of Melbourne and (BoM) staff on rainfall classifications derived from radar observations. Gretchen was with us from January to late April, giving seminars at Uni. Melbourne, Monash and BoM.

Dr Wojciech Grabowski (NCAR,Partner Investigator) also visited University of Melbourne for a week in March, and UNSW and Uni. of Melbourne for two weeks in October. Dr Jun-Ichi Yano, Directeur de Recherche at Centre National de la Recherche Scientifique, Meteo, France, visited our University of Melbourne and Monash nodes in late October.

The program also launched its first citizen science app, WeatheX. One of the great challenges of studying extreme rainfall events and their constituent parts – like hail, wind, tornadoes and flooding – has been the spotty nature of these events. A flash flood from a large squall can occur 10 km away from an area that doesn't get a drop of rain. The distance between most meteorological instruments means that on-the-ground measurements are often incomplete. At the same time, while radar images are useful, they cannot tell the complete story of an extreme rainfall event.

The WeatheX app aims to get citizen scientists to record wind, hail, flooding and even tornadoes on mobile devices as or shortly after they occur. These on-the-ground observations can then be combined with radar images. With this additional information, it opens avenues for research that may help us better understand and forecast extreme rainfall events.

Awards

In terms of recognition of individual researchers it has been an impressive year for the Extreme Rainfall team.

Extreme Rainfall program Co-lead, Associate Professor Lisa Alexander, received a highly prized Outstanding Service Award from the World Meteorological Organization Commission for Climatology.

Chief Investigators Professor Jason Evans and Associate Professor Julie Arblaster were co-winners of the Australian Meteorological and Oceanographic Society (AMOS) Priestley Medal, while Associate Professor Todd Lane and Professor Christian Jakob were made AMOS fellows. Christian then added to this recognition by winning the 2018 AMOS Morton Medal for leadership in meteorology, oceanography, climate and related fields, particularly through education and the development of young scientists, and through the building of research environments in Australia.

Associate Investigator, Dr Andrew King, was awarded the Inaugural AMOS Science Outreach Award.

Partner Investigator Dr Sandrine Bony at the Institut Pierre Simon Laplace was awarded the Gérard Mégie Prize by the French Academy of Sciences. Another Partner Investigator, Dr Harry Hendon, was named by The Australian newspaper, in its annual Research magazine, as Australia's leader in atmospheric science.

Associate Investigator Dr Caroline Ummenhofer was in September named as a winner of the American Geophysical Union (AGU) James B. Macelwane Medal. This prestigious medal is awarded to an early career researcher within 10 years of their PhD, and includes becoming an AGU fellow in their own right.

Associate Investigator Dr Markus Donat was announced as the winner of the 2017 WCRP/GCOS International Data Prize. The prize committee said it "was greatly impressed by his strong profile and the outstanding quality of his contribution to the development of climate data sets".

Researchers Dr Mandy Freund and Dr Ben Henley were on a paper, Multi-century cool- and warm-season rainfall reconstructions for Australia's major climatic regions, which was highlighted in the Australian Energy and Water Exchange Initiative newsletter.

Student Zoe Gillettwas awarded the AMOS Regional Centre Award for Academic Achievement, for excellence in undergraduate study.

Statement of Intent

Project	Priority	Intent
1.1	1	Continue to investigate rainfall extremes in radar data and its links to the phase of the Australian Monsoon
	1	Continue to develop methods to analyse rainfall extremes using a combination of gauge and radar observations
	2	Use a single column version of the ACCESS model to examine the relationships between large-scale states and rainfall extremes (link to 1.4)
	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	Estimate precipitation efficiency for convective events using observations and link to existing model simulations (link to 1.1)
	2	Derive objective metrics of rainfall organization, structure, and other characteristics from satellite and radar data
	2	Identify key large scale characteristics associated with organized convection.
	3	Conduct a suite of idealized model experiments to determine the fundamental processes linking convective organization to extremes.
1.3	2	Investigate water vapour transport in a hierarchy of models
	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 heatwave RP)
1.4	1	Explore methods to upscale simulations and use these to evaluate rainfall extremes in models
	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 of RP	1	Identify and conduct high-resolution WRF and ACCESS model experiments of extreme rainfall events over Australia, including ECLs
	2	Across Centre model evaluation (links to all RPs)
	3	Across Centre model evaluation (links to all RPs)

Priority levels: 1 = to be achieved in 2019. 2 = substantial progress in 2019. 3 = progress towards in 2019.

Building Resilience against Catastrophic Climate Events

While the broad implications of climate change are well understood, the impacts of extreme events, some of which are expected to increase in number and/or intensity, are less clear. This raises a key question as to how can we manage risk around catastrophic weather events. It has been a particularly important conundrum for the business sector and policymakers. What makes it more difficult is that catastrophes caused by weather events are often the result of a combination of factors, rather than one single issue. Researchers call weather extremes associated with multiple causes 'compound events'.

There are multiple examples of compound events. One of these is the Russian summer of 2010 and Pakistan flooding in the same year, which appeared to be linked by dynamics of the atmosphere. Hurricane Sandy's sudden left turn, taking it into New York at the same time as a high spring tide came ashore, is likely another. In both cases, it was a combination of factors, not a single factor, which amplified the destructive nature of these events.

Currently, researchers use climate models to generate scenarios under different greenhouse gas forcings, and from these estimate the impacts of climate change. This scenario-based approach, and the subsequent analyses, tend to examine individual changes, or changes in isolation. For example, it is common to examine separately the effects on temperature, or rainfall, or runoff, etc. This approach has a range of shortcomings, however. A rainfall event in isolation, for example, may not have too extreme a consequence, but that same rainfall event occurring after weeks of heavy rain can cause flooding.

CLEx researchers, along with their international colleagues, have proposed an alternative method of determining future risk that is similar to the approach taken to stress-test businesses. Instead of starting with a climate scenario and estimating the impacts, they propose starting by examining what is viewed as vulnerable (say a city, or a particular ecosystem), and then give examples of the types of weather systems that could cause rainfall, temperature or other impacts that would exceed the resilience of the system. Researchers can then try to examine the probability of those weather systems, or how the probability might change in the future.

As an example, they suggest looking at the possible meteorological drivers that would lead to a citywide power outage. This would mean examining the climate-sensitive elements of the power system, such as renewable power resources, or physical assets like poles and wires that could be affected by heavy winds, lightning and flooding. With this knowledge as the starting point, it may become possible to understand what coincidence or combination of climate hazards could influence the system and then look at the

likelihood of these occurrences. It also gives business and infrastructure experts insights into where the most effective changes can be made to build climate resilience into a system.

In their summary, the researchers put forward six recommendations. They are:

- Put in place a systematic research program on climate-related catastrophes caused by compound factors to improve risk management of vulnerable communities
- Develop theoretical frameworks and supporting tools for risk assessment that explicitly include compound events
- Use the stress-test approach to identify which combinations of climate drivers and hazards are most likely to lead to catastrophic events. This will require climate stress testing of multiple systems to identify areas of vulnerability
- Introduce different analysis methods into climate projections that focus on impacts rather than drivers. This will require major improvements in global climate model resolution, improved downscaling techniques and innovations in computing and data management

they propose starting by examining what is viewed as vulnerable ... then give examples of the types of weather systems that could cause rainfall, temperature or other impacts that would exceed the resilience of the system

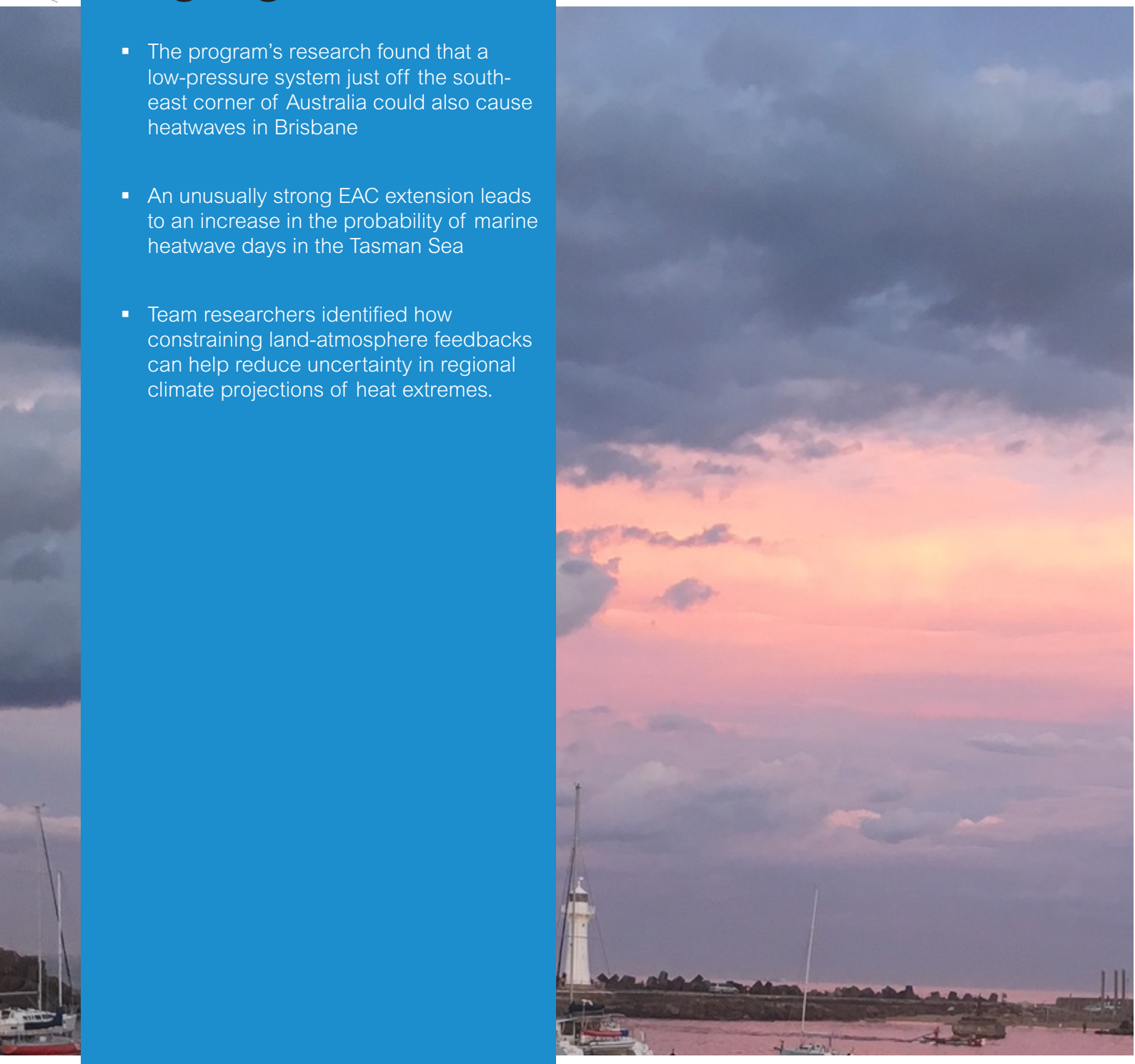
- Develop stronger collaborations across multiple fields of research to better understand how human activities will alter the impacts of compound events
- Adopt an impact-centric perspective to provide guidance to identify the most relevant hazards and climatic drivers.

These recommendations have the advantage of identifying system weaknesses before they occur and reveal paths to the most effective protective measures.

RP2: Heatwaves and Cold Air Outbreaks

Highlights

- The program's research found that a low-pressure system just off the south-east corner of Australia could also cause heatwaves in Brisbane
- An unusually strong EAC extension leads to an increase in the probability of marine heatwave days in the Tasman Sea
- Team researchers identified how constraining land-atmosphere feedbacks can help reduce uncertainty in regional climate projections of heat extremes.



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A focus on modelling improvements played a major role in the early part of the Heatwaves and Cold Air Outbreaks research program. We have made significant progress on understanding how well temperature extremes can be simulated with Community Atmosphere-Biosphere and Land Exchange (CABLE) coupled to the Australian Community Climate and Earth System Simulator (ACCESS). Coupling has been improved and the Heatwaves program team has identified possible causes for the tendency for the model temperature to overstate extremes. Early in the year the program also identified specific continental heatwaves for initial investigation.

Away from land, investigations commenced on what caused the intensification of the East Australia Current and its contribution to the 2015/16 Tasman Sea marine heatwave. We had some very important results on this front, which are likely to help improve forecasting of marine heatwaves in this area in the future.

Our research has also taken us into the policy domain, with papers touching on pollution, energy and comparing the impacts of different emission scenarios as a result of target outcomes negotiated during the 2016 Paris Agreement.

There have also been quite a few papers that required the combined expertise of multiple Centre research programs, which are described later in this report. Individually, a number of Heatwaves research program members celebrated awards for recognition of their outstanding work in the field.

Extreme Heatwaves and Cold Air Outbreaks Research

The first half of the year saw the publication of three papers with policy relevance for Australia and globally.

A paper led by Associate Investigator Dr Andrew King took its lead from the Paris Agreement, comparing the difference to our climate if the global warming target was limited to 1.5°C and 2°C levels above pre-industrial conditions. The aim of the paper was to look at regional temperatures when the global surface average temperature reached 1.5°C and see if there was a linear relationship when temperatures reached 2°C.

In general it found that there was a consistent linear relationship for most regions, with the exceptions of the North Pacific, north-west Atlantic, north-west Africa and China. Intriguingly, they found the difference in these areas was caused by other forcings, like aerosols, that are not related to changes in greenhouse gas conditions.

Heatwave program researchers looked at the atmospheric conditions that produce heatwaves over Brisbane (https://climateextremes.org.au/research-brief-summertime-heatwaves-in-brisbane). There is a general assumption that heatwaves are caused by the location of a high-pressure system over a region. However, the program's research found that a low-pressure system just off the south-east corner of Australia could also cause heatwaves in Brisbane. This research suggests that when we examine how heatwaves may change in the future, we not only have to look at how high-pressure systems may change but that the location, intensity and variability of midlatitude storm tracks will also play a role.

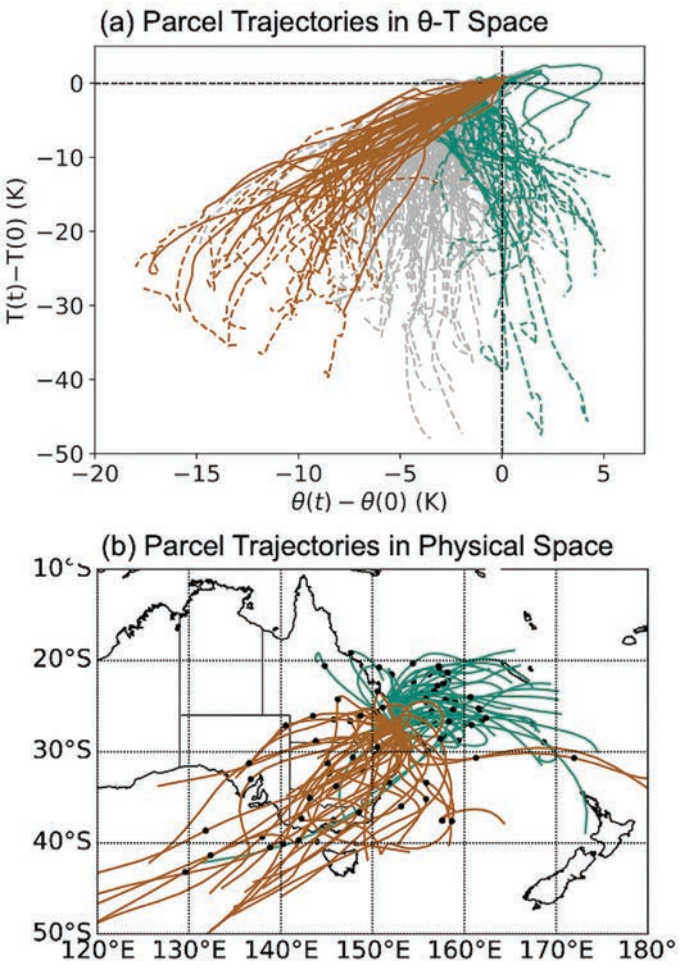


Figure 1 Change in temp RP2: (a) Change in temperature T (t) - T (o) (K) as a function of the change in potential temperature θ(t) – θ(o) (K) along the mean trajectories for each heat wave day. Strongly diabatic (brown), weakly diabatic (green), and remaining (grey) days. Dashed lines for -240 hr < t < -120 hr. Solid lines for -120 hr < t < o hr. (b) Geographical distribution of the mean trajectories for strongly diabatic and weakly diabatic heat wave days from -120 to o hr. Black dots mark the location at -60 hr.

A paper led by Heatwaves program Co-lead, Professor Jason Evans, looked at how climate change would affect wind-power generation. The research published in Environmental Research Letters looked at changing winds caused by climate change across Australia, advances in technology and investment-risk factors to explore how the economic viability of extracting energy from wind farms may change in the future. Those states south of the 20° latitude generally came out ahead, with Tasmania and Western Australia the biggest winners in terms of power generation and profitability. But it was not so positive for Queensland, which became less competitive with other states because of a slight drop in wind speeds and the increased investment risk that came with the ever-present threat of cyclones.

In another paper with policy significance Ji, Evans, Di Luca and others looked at how inversion layers may change with global warming along Australia's east and south-east regions, and what this would mean for pollution. Heatwave program researchers found inversion layers in east coast cities would be 40-80% stronger as a result of climate change – especially during winter. The overall frequency of low-level inversions did not change; however, there was a slight increase in the number of daytime temperature inversions. This suggested a likely increase in adverse air-quality metrics, as there is generally more pollution during daylight hours.

Meanwhile, the work on marine heatwaves has produced some very useful results. Researchers have long known the seas to the south and east of Tasmania are some of the fastest-warming ocean areas in the world. Marine heatwaves have become a familiar feature in this area but understanding their fluctuations has been elusive. Using observations over a 24-year period, Heatwave program researchers teased out the causes and characteristics of these heatwaves. They highlighted the role and interactions of the East Australian Current (EAC) and the Zeehan Current (an extension of Western Australia's Leeuwin Current) in determining the strength of marine heatwaves in this region (https://climateextremes.org.au/research-brief-how-strong-currents-influence-tasmanias-marine-heatwaves).

The researchers revealed that an unusually strong EAC extension leads to an increase in the probability of marine heatwave days. Conversely, a strong Zeehan Current during these seasons decreased the probability of marine heatwave days. This is work that will help improve our ability to forecast these events and understand their impact on marine ecosystems.

Heatwaves program researchers also examined the role of human-caused climate change in marine heatwaves globally, as part of the *Bulletin of the American Meteorological Society* Supplement, highlighting two case studies: the Great Barrier Reef heatwave of 2016 and an Alaskan marine heatwave in the same year. The researchers concluded these specific events were 50 times more likely as a result of climate change.

The Heatwaves program collaborated closely with other Centre research programs to produce important results. Working with some of our colleagues in the Drought program, our researchers tested a recently developed quantile-based bias correction scheme in combination with a new method to improve projections of extremes. Those climate models that were selected using this scheme effectively reduced biases in temperature/rainfall distribution shape. However, the scheme was less effective in reducing probability ratios that are used in the field of event attribution. This was fundamental research that could significantly improve projections of future extreme-temperature events.

Despite projected increases in future temperature, little is known about the response of large trees to extreme heatwaves. To address this gap in the knowledge, we again worked with the Drought program to monitor carbon and water fluxes during an experimentally imposed four-day heatwave of 43°C on *Eucalyptus parramattensis* trees. In response to the heatwave treatment, the plants maintained transpiration to cool their canopies, whilst reducing photosynthesis fluxes to near zero. This decoupling of water and carbon fluxes is a novel finding and, absent from any climate models, suggested that we may presently be underestimating

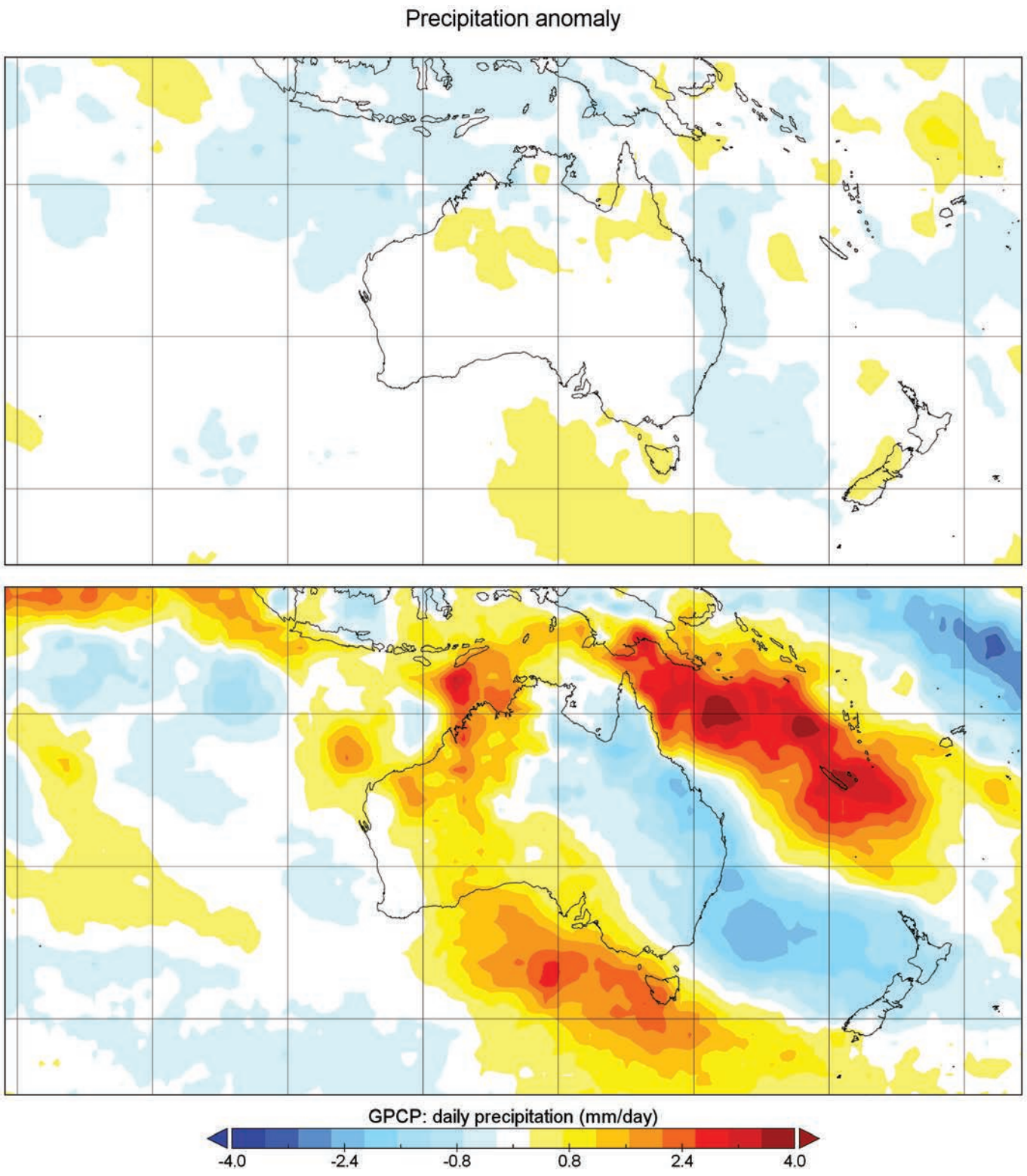


Figure 2 Composite precipitation anomalies for upper-troposphere anticyclones: Composite precipitation anomalies for upper-troposphere anticyclones not associated with south-east Australian heatwaves (top), and for those associated with south-east Australian heatwaves (bottom).

a feedback from the vegetation on heatwave intensity. This paper has already been cited 18 times and was one of the top 25 downloaded papers in *Global Change Biology* in 2018.

We worked again with the Drought program team to tackle a difficult modelling problem. Hot days are expected to become more frequent with climate change, and these heat extremes can be exacerbated by dry conditions due to a lack of evaporative cooling. Unfortunately, while climate model simulations of future changes in hot temperature extremes agree on the regions of strongest warming, they disagree on how much temperature will increase. We undertook two studies, both published in *Geophysical Research Letters*. The first paper showed that many models overestimate interactions between hot and dry conditions under current climate conditions. In a second study, we examined differences in the model-specific strength of land-atmosphere feedbacks and identified that a large part of current uncertainty is explained by inter-model differences in future precipitation changes. When we constrain the future climate model ensemble simulations by using only those models that simulate land-atmosphere feedbacks more similar to real-world observations over the past 60 years, the probability of the strongest increases in hot extremes is reduced. These two studies point to an area of necessary model improvement, but also show that if we did improve the models, we could likely increase confidence in future projections of heat extremes.

Engagement

Nationally and internationally, researchers in the Heatwaves program have been building peer networks and reaching out to the public.

Partner Investigator from ETH-Zurich, Professor Sonia Seneviratne, was named as the Coordinating Lead Author of Chapter 11, for the next Working Group 1Intergovernmental Panel on Climate Change 6th Assessment Report. Associate Investigator Dr Sophie Lewis has also been named as a Lead Author in the same chapter.

Associate investigator Dr Sarah Perkins-Kirkpatrick was made Editor of a special issue of the *International Journal of Environmental Research and Public Health* on changes in heatwaves – past, present and future. The brief is a wide one, with submissions covering the following: regional and local heatwaves, small and large-scale interactions, observed events, future projections, measuring heatwaves, addressing uncertainty in future projections, understanding impacts of heatwaves, physical mechanisms of heatwaves, risk and exposure, and attribution to natural and anthropogenic processes.

Following up on their marine heatwaves work, Eric Oliver, Neil Holbrook and three other co-authors wrote an article for the general public that appeared in *The Conversation*, explaining

that marine heatwaves are getting hotter, lasting longer and doing more damage to the environment.

The Heatwaves program organised and hosted a workshop that brought researchers from across Australia and around the world to examine and also to look at the effectiveness of detection and attribution of heatwaves and some extreme rainfall events. Michael Werner from Lawrence Berkeley National Lab (US), an expert in attribution studies of rain events, was a guest at this workshop and also spent some time with CLEx researchers, as a visitor. The third day of the workshop had a strong communications focus, bringing in four media professionals – Anja Taylor (*ABC Catalyst*), Wendy Frew (*BBC*, *The Sydney Morning Herald*, *ABC*), Tom Arup (*The Age*) and Michael Lucy (*Cosmos* magazine). Together with climate researchers they aimed to work through the best way to deliver information on extreme events to news organisations and the general public.

We also hosted Sophie van den Horst from Wageningen University in The Netherlands. Sophie worked on heatwaves and surface fluxes and has submitted a paper that, if published, will be reported on in the next CLEx annual report.

Awards

Individual team members in the Heatwaves program have had quite a successful year!

The program's Co-lead investigator, Professor Jason Evans, along with CLEx Chief Investigator, Associate Professor Julie Arblaster, opened the year as co-winners of the 2017 Australian Meteorological and Oceanographic Society (AMOS) Priestley Medal that honours the work of mid-career researchers.

Associate Investigator Andrew King was awarded the inaugural AMOS Science Outreach Award. Andrew has developed into one of our country's most prominent commentators on climate change and has been an active contributor to *The Conversation*. The AMOS judging panel described him as "one of the go-to experts on many aspects of weather and climate".

Associate Investigator Dr Markus Donat featured prominently in an article on early-career scientists by the International Association of Meteorology and Atmosphere Sciences. Markus has now relocated from UNSW to Barcelona but will continue to be a part of the program.

PhD student Mia Gross won Best Poster at the 8th Global Energy and Water Cycle Experiment conference for the sensitivity of daily temperature variability and extremes to data set choice. This is an impressive award for a student in a very competitive international field.

Statement of Intent

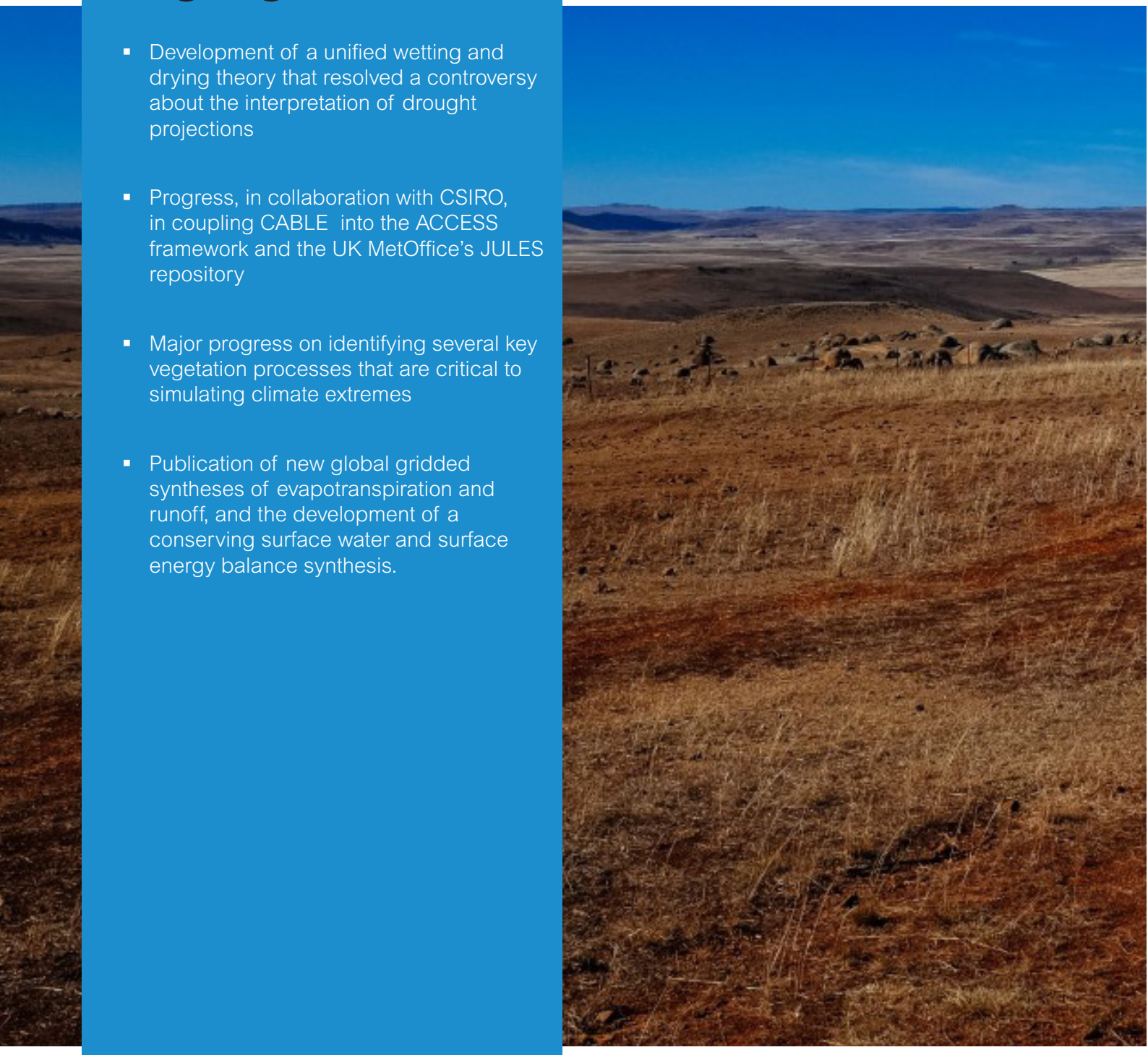
Project	Priority	Intent
2.1	1	Continue to investigate the relative importance of various physical processes in producing a heatwave, using the composite and trajectory analysis. These physical processes are: adiabatic compression, latent heating and surface sensible heating.
	1	Compare the difference between days with strong upper-level anticyclones but no heat wave against heat-wave days.
	1	Complete work on a new technique started in 2018. The technique has been developed to define the history of *heat wave events*, where an event is a heated region *contiguous in space and time*, parts of which satisfy the definition a heat waves (three consecutive days on which the maximum temperature exceeds the 90th percentile).
	2	Using the existing UNSW WRF ensemble runs the relative roles of adiabatic and diabatic processes in the dynamics of 3 (or 4) typical southern Australian heat waves will be determined.
	3	Extend the analysis to the ERA5 dataset
	3	Given the relative weakness of most climate models in producing realistic modes of tropical variability, 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) will be evaluated.
2.2	1	Use WRF experiments to quantify the impact on heatwave intensity and duration of changes in the land surface especially soil moisture.
	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 heatwaves intensity and duration of the local landscape (urban form and surrounds) compared to the regional/continental conditions
	3	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	1	Choose key heatwave events in Australia's recent climate record, categorize based on various readily-used heatwave definitions, isolate underpinning mechanisms specific to each event
	2	Investigate statistical methods to undertake attribution with co-incident inputs (e.g. physical drivers)
	3	Comparison of attribution assessments per heatwave across model ensembles, inclusive of definition used and underpinning observational/reanalysis products
2.4	1	Investigate the vertical scale of marine heatwaves in the Australian region and the mechanisms for deepening marine heatwaves
	2	Sensitivity analysis of the representation of marine heatwaves and cold spells to resolution in ACCESS-OM2 (e.g. ACCESS-OM2-01, ACCESS-OM2-025)
	3	Perform targeted model experiments to understand the key mechanisms causing marine heatwaves and cold spells in the Australian region

Priority levels: 1 = to be achieved in 2019. 2 = substantial progress in 2019. 3 = progress towards in 2019.

RP3: Drought

Highlights

- Development of a unified wetting and drying theory that resolved a controversy about the interpretation of drought projections
- Progress, in collaboration with CSIRO, in coupling CABLE into the ACCESS framework and the UK MetOffice's JULES repository
- Major progress on identifying several key vegetation processes that are critical to simulating climate extremes
- Publication of new global gridded syntheses of evapotranspiration and runoff, and the development of a conserving surface water and surface energy balance synthesis.



Team

Co-leads

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Prof Andy Pitman

Chief Investigators

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Dr Gab Abramowitz (UNSW)
Dr Dietmar Dommenget (Monash)
Prof Matthew England (UNSW)
Prof Jason Evans (UNSW)

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Dr Ali Behrangi (University of Arizona)
Prof Hoshin Gupta (University of Arizona)
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The ongoing drought across large areas of south-west Queensland and New South Wales brought a sharp focus to our research during 2018. Drought featured prominently in this year's Centre of Excellence for Climate Extremes (CLEx) annual workshop, with the opening sessions devoted to the causes of the drought, and with contributions and presentations coming from all research programs in the Centre. This was followed on the third day of the workshop by a meeting of Drought program researchers to pursue the drought problem over the coming year. This identified several scientific issues that will become a focus of the Centre's next research steps to enable our scientists to understand its causes and help improve future forecasts of drought events in Australia.

Beyond the immediate concerns of the current drought, much of the Drought research program's work has been on incorporating process-level understanding into models to help us better understand drought processes, with some impressive results that have already put the program on track to accomplish one of its major goals in its first full year.

This year has seen a focus on vegetation processes, with a body of work that demonstrates how small-scale processes in vegetation affect atmospheric processes that can influence heatwaves, drought and precipitation. As we bring more processes into our climate models, we are seeing improvements in projections and some surprising results that are setting directions for future research.

Drought Research

Drought program research continues to build capacity into the Australian Community Atmosphere-Biosphere Land Exchange (CABLE) model now running in the Australian Community Climate and Earth System Simulator (ACCESS) modelling system. The Centre of Excellence is working with CSIRO both on improving CABLE for ACCESS, but also building long-term capacity by building CABLE into a repository hosted by the UK Meteorological Office, from which future versions of ACCESS will be derived. New capacity in CABLE includes the science advances led by Mark Decker around hydrology and soil evaporation, and the science advances on stomatal responses to atmospheric CO2 and humidity, led by Dr Martin De Kauwe and Associate Investigator Dr Jatin Kala. It also includes major bug fixes identified by collaborators in the UK, and by colleagues in CSIRO.

As a result, for the first time we have a version of the CABLE model able to be coupled with an up-to-date version of the UK MetOffice's atmosphere model. This is being used in experimental versions of the ACCESS model. It allows us to examine how various processes affect the simulation of drought in ACCESS and achieves one of the major goals in the first year of CLEx.

One of the difficult problems we face is that individual climate models show bias (compared to observations) in many elements of drought. In studies of the changes in long-term averages, those biases generally cancel out when we take an ensemble across different models. However, this does not happen when trying to project extremes, and bias-corrections need to be made to the outputs of individual models. The best way to do this has yet to be established. With colleagues

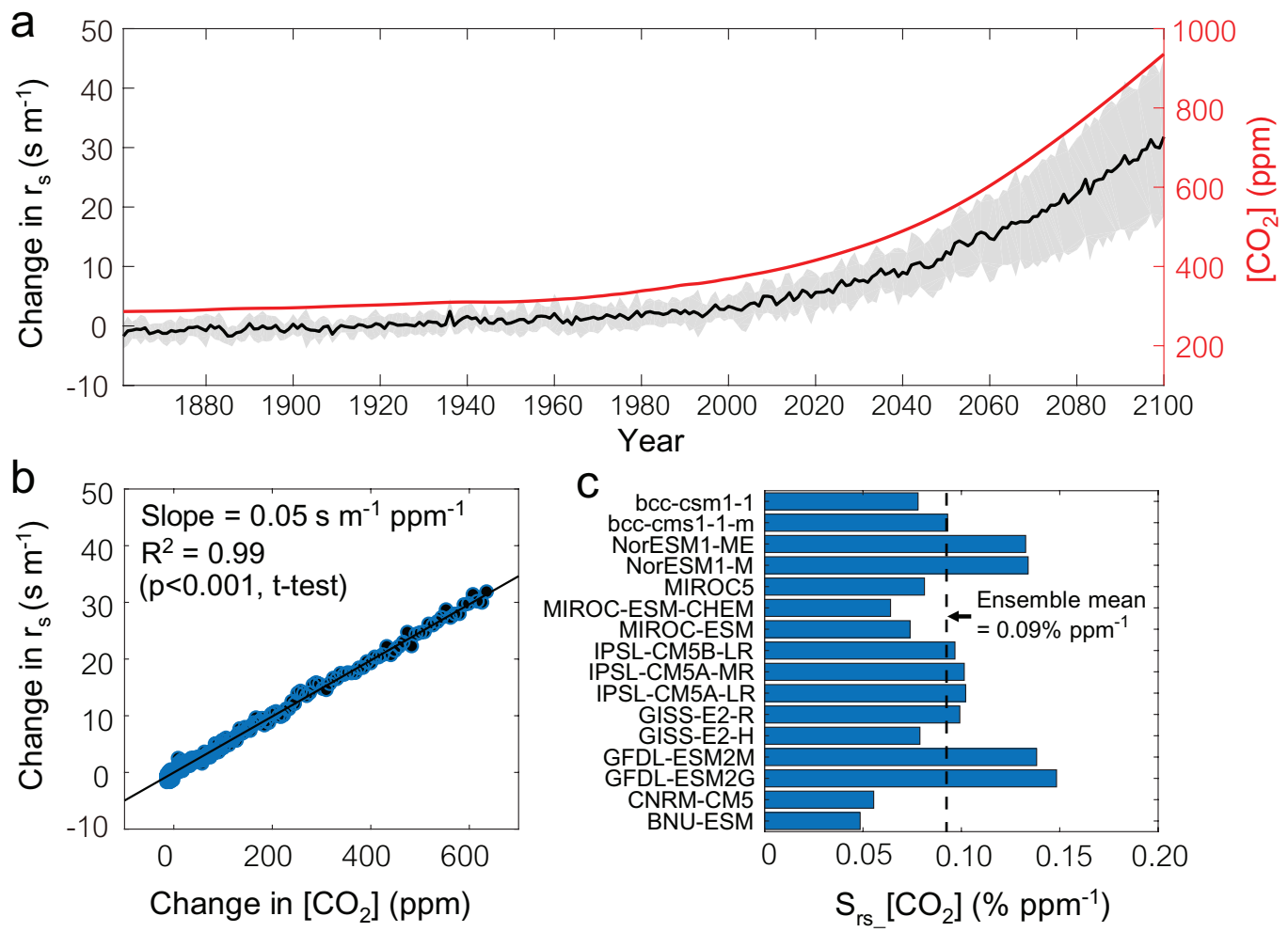


Figure 1: Changes in surface resistance over non-water-limited regions/months under elevated CO2 based on 16 CMIP5 models (Yang et al. 2019). Changes in surface resistance over non-water-limited regions/months under elevated [CO2]. a, Changes in annual mean surface resistance relative to the 1861-1960 baseline in 16 CMIP5 models. The solid curve indicates the ensemble mean of 16 CMIP5 models and the shaded area represents plus/minus one standard deviation among models. The red curve is the atmospheric CO2 concentration. b, Relationship between the ensemble mean of changes in rs and [CO2] (relative to the 1861-1960 baseline). c, Sensitivity of rs to [CO2] for 16 CMIP5 models (i.e., % change in rs per ppm increase in [CO2]). The vertical dashed black line indicates the ensemble mean of 16 CMIP5 models. (Adapted from Yang et al., 2019)

from Lawrence Berkeley National Laboratory, CLEx researchers aimed to test a new bias-correction scheme. The results showed the new method improved projections of extremes but it was also critical to account for changes in the long-term mean when making these projections.

Teasing out issues in climate models is vital to research across the Centre of Excellence, not just the Drought program. That is why members of the Drought program have been working with international colleagues to put forward an open-source, model-agnostic, modular framework called the Multi-Assumption Architecture and Test-bed (MAAT). MAAT is a generic framework designed to explore how different underlying model assumptions, hypotheses and parameters lead to differences in model behaviour. In the first applications, the MAAT has been successfully tested on a simple groundwater model and a widely used leaf-scale photosynthesis model. This is essentially intellectual infrastructure, and we expect an increase in applications of the new MAAT system in coming years.

In other research specifically focusing on how drought is represented in models, Dr Anna Ukkola led a team that evaluated global climate models for common drought metrics over the past 55 years. They found different climate models produced very different simulations of drought. The differences related to how the models represent the land-atmosphere interactions at the surface. The study demonstrated that existing models need to be improved to make useful drought projections.

Several recent model comparisons have shown large disagreements among models, compared to satellite-based estimates of the Leaf Area Index (LAI). LAI is a key structural attribute of vegetation and is central to understanding how vegetation interacts with the atmosphere. In particular, errors in simulated LAI significantly affects our capacity to simulate droughts. Bringing together observations and models, CLEx researchers collaborated with researchers at Western Sydney University to test a long-standing hypothesis (dating back to the 1980s), that LAI is dictated by the long-term water availability (http://climateextremes.org.au/ecohydrological-approach-improves-climate-models). The researchers

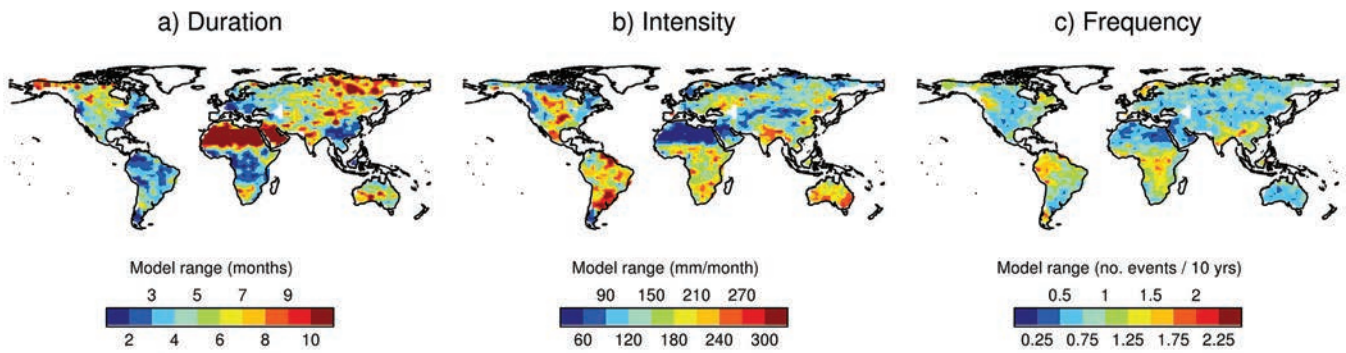


Figure 2: Differences in seasonal drought characteristics simulated by state-of-the-art climate models from the Coupled Model Intercomparison Project (CMIP5, adapted from Ukkola et al., 2018). For example, panel (a) shows the difference in the soil moisture drought duration in months such that values of 8 indicate variations across the models of 8 months in drought duration. Panel b shows drought intensity, here there are variations across the models of up to 300 mm per month in soil moisture content. Finally, panel c shows the frequency of drought. Here there are variations between the models of up to 2 events per 10 years.

used long-term climate data to test this hypothesis. Using this ecohydrological theory, they made predictions of "equilibrium" LAI across Australia, and compared the results with satellite-derived estimates. These results showed a high level of consistency between their model predictions and ground- and satellite-based measurements. They also made successful predictions about how LAI should have changed with recent (1980-2010) changes in atmospheric CO2. The results clearly demonstrated some of the fundamental principles of how vegetation interacts with the atmosphere.

Another cornerstone of current land surface models relates to the carbon balance of vegetation and how that might respond to ongoing increases in atmospheric CO2. Existing climate models account for these processes but the foundations of the climate models has proven difficult to evaluate, due to the lack of suitable field-scale observations. Working with colleagues at the Hawkesbury Institute for the Environment and Colgate University, we applied a novel data assimilation approach to accurately predict plant growth responses to environmental change. Current models couple growth with photosynthesis (http://climateextremes.org.au/new-insight-into-plant-growth-under-climate-change). However, if the carbon storage capacity of plants is limited, this relationship is expected to break down. The new analysis was able to infer that the imposed limitation not only led to a reduction in photosynthesis but also a reduction in the rate at which stored carbohydrates were used. Approaches like this one will facilitate improvements in the process-understanding embedded in models used to predict responses of vegetation -- and hence the terrestrial branch of the carbon cycle to climate change.

A characteristic of drought not represented in any of our land models is that vegetation can die. Some species die because of embolism-induced hydraulic failure, whilst others are able to avoid mortality and recover, following rehydration. Drought program researchers contributed to a paper outlining the processes that might allow some plants to recover from drought stress via embolism reversal. In the paper, they discussed how embolism repair may have evolved, explored trade-offs and proposed a potential framework to represent this process within vegetation models.

We should recall that Australia is not the only country to experience droughts and we can learn from experience elsewhere. For that reason, members of the Drought program looked at two droughts in the Amazon that had very different impacts – a once-in-a-century drought in 2005 and another even worse drought in 2010. The 2005 drought had a very high rate of tree mortality despite the fact that the 2010 drought was considered worse. We wanted to know what caused the different outcomes. The answer was found in the lead-up to the dry season, particularly in the transitional period from the wet-to-dry season (May-July). In 2005, this transition period was considerably drier than normal, whereas in 2010 the amount of rainfall during the transition was only slightly below average. This meant there was more water available in the soil during the drought period in 2010 than in 2005. Hence, even though the dry season drought of 2010 was worse, the tree mortality and reduction in carbon uptake was smaller than in 2005. This has obvious parallels with the wet-dry season pattern that occurs every year across northern Australia.

It turns out that drought and heatwaves share many processes in common. Hence it is no surprise that members of the Drought program have been working with colleagues in the Heatwaves and Cold Air Outbreaks research program, to test how well climate models simulate hot and dry conditions. In research led by Anna, Coupled Model Intercomparison Project -- Phase 5 (CMIP5) model simulations were compared with observations during heatwaves made at flux towers worldwide (known as FLUXNet). This work utilised the community tool built by Anna Ukkola and colleagues in late 2017. The results found that CMIP5 models do not replicate the surface-atmosphere coupling as recorded in the observations. One important consequence is that CMIP5 models tend to amplify the temperature during heat extremes and so our new results underline the need to improve model simulations under extreme conditions (https://climateextremes.org.au/research-brief-how-well-can-climate-models-simulate-interactions-between-cool-and-dry-conditions-under-the-current-climate).

In a second application using the FLUXNet database, research led by PhD student Ned Haughton aimed to

investigate how predictable the flow of heat, moisture and carbon is between the land surface and the atmosphere. The long-held assumption is that vegetation type (e.g. tropical forest, grassland, boreal forest, etc.) is the best predictor of land-atmosphere fluxes. The research did not find that: Instead, we found that predictability was in fact unpredictable. We are still working through the implications of this result.

At the heart of model evaluation are observational data. There are several products for evapotranspiration, or runoff that have been derived independently. Dr Dongqin Yin has been leading research to evaluate a new Hydrologic Reanalysis (HR) product called the Climate Data Record (CDR, developed by the HR group at Princeton University. This database represents the most comprehensive HR available to date. The data are available for the global land surface at 50 km-resolution for monthly periods from 1984 to 2010. Initial results have shown that the CDR fills an important gap in the available databases, and publications on the use of this database are currently being prepared. We expect to make use of the CDR for the duration of CLEx.

While the Princeton CDR is perhaps the first hydrologic reanalysis, there is a need for several such hydrologic products. In a major step forward, PhD student Sanaa Hobeichi has led projects to first derive a global gridded estimate of evapotranspiration, and separately, runoff, but then combine these into a product – the Conserving Land-Atmosphere Synthesis Suite (CLASS) – that conserves energy and water. The individual CLASS variable data sets are developed to combine a range of existing variable-product estimates to overcome the limitations of estimates from a single source. They are also constrained with observation. In addition, uncertainty estimates that are consistent with their agreement with in-situ observations are provided. Finally, by solving the water and energy budgets simultaneously the various components are consistent with each other.

The development of CLASS involves implementing a weighting method that accounts both for the ability of data sets to match in-situ measurements, and the error covariance between data sets. Then, the budget terms are adjusted by applying an objective variational data assimilation technique that enforces the simultaneous closure of the surface water and energy budgets linked through the equivalence of evapotranspiration and latent heat. Comparing component estimates before and after applying the data assimilation technique against in-situ measurements of energy fluxes and streamflow showed that modified estimates remain in good agreement with in-situ observations across various metrics, but also revealed some inconsistencies between water budget terms in June over the higher latitudes. We hope that CLASS will provide a new and consistent means to evaluate climate models' simulation of the surface water and energy balance, including drought.

In December 2018, the Drought program team produced research published in a Nature Climate Change article that tackled a long-standing contradiction in drought studies. Long-used drought and aridity metrics, for example the Palmer Drought Severity Index, are usually calculated by first taking meteorological outputs from a fully coupled climate model and using those outputs to independently calculate the relevant drought or aridity metric. The results usually show projections for increasing drought and aridity into the future, including a reduction in runoff. However, the fully coupled climate models actually project greening vegetation and a small, globally averaged increase in runoff. This has led to controversy for the last five years over future drought projections.

In a major new development, CLEx drought researchers were able to show that a key relationship between vegetation and CO2, specifically the increase in water-use efficiency with elevated CO2, was factored into fully coupled climate models, but this process was not included when calculating the existing drought and aridity metrics. With increased CO2 in the atmosphere, photosynthesis becomes more water-use efficient and we see increases in leaf area and greening of environments. This can happen even with declining rainfall. The researchers were able to show how the CO2-water use efficiency response that emerges in fully coupled climate models could be incorporated into standard drought and aridity metrics by modifying the calculation of potential evaporation. When they recalculated the projections, the drought and aridity metrics finally agreed with the fully coupled climate model output. The result is that the drought and aridity metrics now project a warmer future with more vegetation, in line with fully coupled climate model output. This has been a major puzzle for years and it is good to have finally tracked down, and then resolved, this particular problem. The outcome will be a more robust basis for using fully coupled climate model output to make drought projections.

An important part of the Centre's work involves looking at how our research can be applied in ways that can benefit the Australian and international community. CLEx researchers, together with an international team, suggested that a new approach is needed to interpret and manage risk around extreme events. The approach they put forward was similar to the concepts involved in "stress-testing a business", based on the idea that it is the confluence (or totality) of events that is critical. For example, in 2012, an unusual confluence of weather systems resulted in Hurricane Sandy taking a sharp left turn towards New York and New Jersey. As Sandy made landfall, it coincided with a high spring tide, leading to the highest storm surge for the region in 300 years. This sequence of events left 233 dead and US$50bn damage. The key point was that it was a combination of factors, and not a single factor, which amplified the destructive nature of this event.

The traditional approach to evaluating such risks is to begin with a base (climate) scenario and to then build other possible outcomes on top of this scenario. The new research advocated a shift towards examining the total system, with a focus on the outcome. For example, they suggest looking at the possible meteorological drivers that would lead to a city-wide power outage. This would mean examining the climate-sensitive elements of the power system, such as renewable power resources or physical assets like poles and wires that could be affected by heavy winds, lightning and flooding. With this knowledge as the starting point, it becomes possible to better understand the outcome from a confluence of climate hazards and then look at the likelihood of these occurrences. This approach gives business and infrastructure experts

insights into where the most effective changes can be made to build climate resilience into communities. The researchers describe the difference between the two approaches as a "shift from impact analysis to vulnerability analysis".

Engagement

Members of the Drought program have been very active building peer networks and reaching out to the public.

Research associate Dr Martin De Kauwe co-led an international workshop held at Biosphere 2 in Arizona that aimed to integrate evidence streams to describe the CO2 fertilisation effect on the global carbon sink. The chief outcome of the workshop will be a review paper, along with a number of spin-off manuscripts on topics including the following: global photosynthesis trends; scaling of leaf-to-canopy estimates of photosynthesis; reconciliation of water-use efficiency estimates, from Free-Air Carbon Dioxide Enrichment experiments and tree ring isotopes, evidence for satellite greening; and how vegetation communities are changing in response to elevated CO2.

We also hosted Partner Investigator Dr Martin Best from the UK Met Office for a week. Extensive discussions were had around collaborative approaches to land surface science, involving partners at CSIRO and the Bureau of Meteorology, and more broadly, discussions on drought, with other Centre researchers. Major progress was made on how to approach the integration of CABLE into the code repository of the UK Met Office, which would have long-term benefits for the national climate modelling initiative.

Partner Investigator Professor Sonia Seneviratne, from ETH-Zurich, was named as the Co-ordinating Lead Author of Chapter 11, for the next Working Group 1, Intergovernmental Panel on Climate Change Assessment Report 6. We hosted Dr Simone Fatichi, also from Partner Organisation ETH-rich, with whom we had discussions around modelling asymmetric responses to rainfall. As part of our global linkages, we also welcomed Lorenz Keysser, an undergraduate student from ETH-Zurich, who spent four months at the University of New South Wales hub working with Dr Annette Hirsch (UNSW), Sonia Seneviratne and Dr Benoit Guillod (ETH) to evaluate the land use scenarios derived by integrated assessment models.

Awards

The year started on a high note when Professor Graham Farquhar, an Associate Investigator, was named Senior Australian of the Year for 2018. We were also delighted when Partner Investigator, Professor Dani Or (ETH-Zurich), was awarded the 2018 Langebin Lecture by the American Geophysical Union.

Statement of Intent

Project	Priority	Intent
3.1	2	Investigate what controls the balances in the Australian hydrological cycle from the large atmospheric scale to the small regional land interaction
	2	Quantify how the atmospheric and oceanic teleconnections that modulate and amplify remote climate variability will change over Australia
	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
	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	Begin hypothesis-testing experiments to test the response of drought in models to different climate forcing scenarios.
3.3	1	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
	1	Examine how well CMIP-5 models capture the characteristics of observed droughts including the Millennium drought.
	1	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
	2	How does the land surface-atmosphere coupling evolve as we go into drought?
	2	Perform WRF and/or ACCESS simulations for earlier major droughts (e.g. WWII drought).
	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 the skill in simulating observed droughts
	3	Examine how land-atmosphere coupling varies between droughts, models and resolutions
	3	Test whether new approaches to hydrology and vegetation responses to drought change future projections of droughts
3.4	1	Systematic assessment using observations of continental scale vegetation response to rainfall/drought
	1	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 2019. 2 = substantial progress in 2019. 3 = progress towards in 2019.

Researcher Profile: Dr Martin De Kauwe

Dr Martin De Kauwe was awarded the 2018 Centre of Excellence for Climate Extremes Director's Prize after a year in which he has had quite an impact in terms of research and his engagement with the climate science community. He also was awarded an Australian Research Council Discovery Grant to examine how vulnerable eucalypts are to future droughts. This important research looks at the future for Australian eucalypts, which has flow-on effects as to how well climate models project the impacts of a changing climate in this country.

In the past year, Martin's work on the response of vegetation to global environmental change has led to some consequential insights into mechanistic processes that can affect droughts, heatwaves and the effects of global warming.

His work on transpiration has led to a new benchmarking metric that could be used to test existing hypotheses embedded in climate models, and also led to the development of a research pathway that may improve the way transpiration processes are simulated in climate models.

In another piece of research, with colleagues from Western Sydney University and international researchers, Martin analysed how plants responded to increased warming when they had limits on nutrients and water. The research gave insights into the lack of correlation between photosynthesis and growth under these limited conditions. It helped untangle a long-standing puzzle in plant ecophysiology that has compromised the capacity of models to project vegetation responses to global change.

Other research performed by Martin and colleagues included:

- How plants survive droughts and the mechanisms that allow this
- The resilience of trees to future heatwaves under global warming – which found Australian trees may be more resilient than expected
- The development of a new theory to estimate how the amount of leaves a tree grows is predictable from the total long-term precipitation received,
- How many models overestimate the interaction between hot and dry conditions in wet regions and consequently over-amplify heat extremes.

Aside from his research work, Martin has engaged with our stakeholders and built bridges to international colleagues.

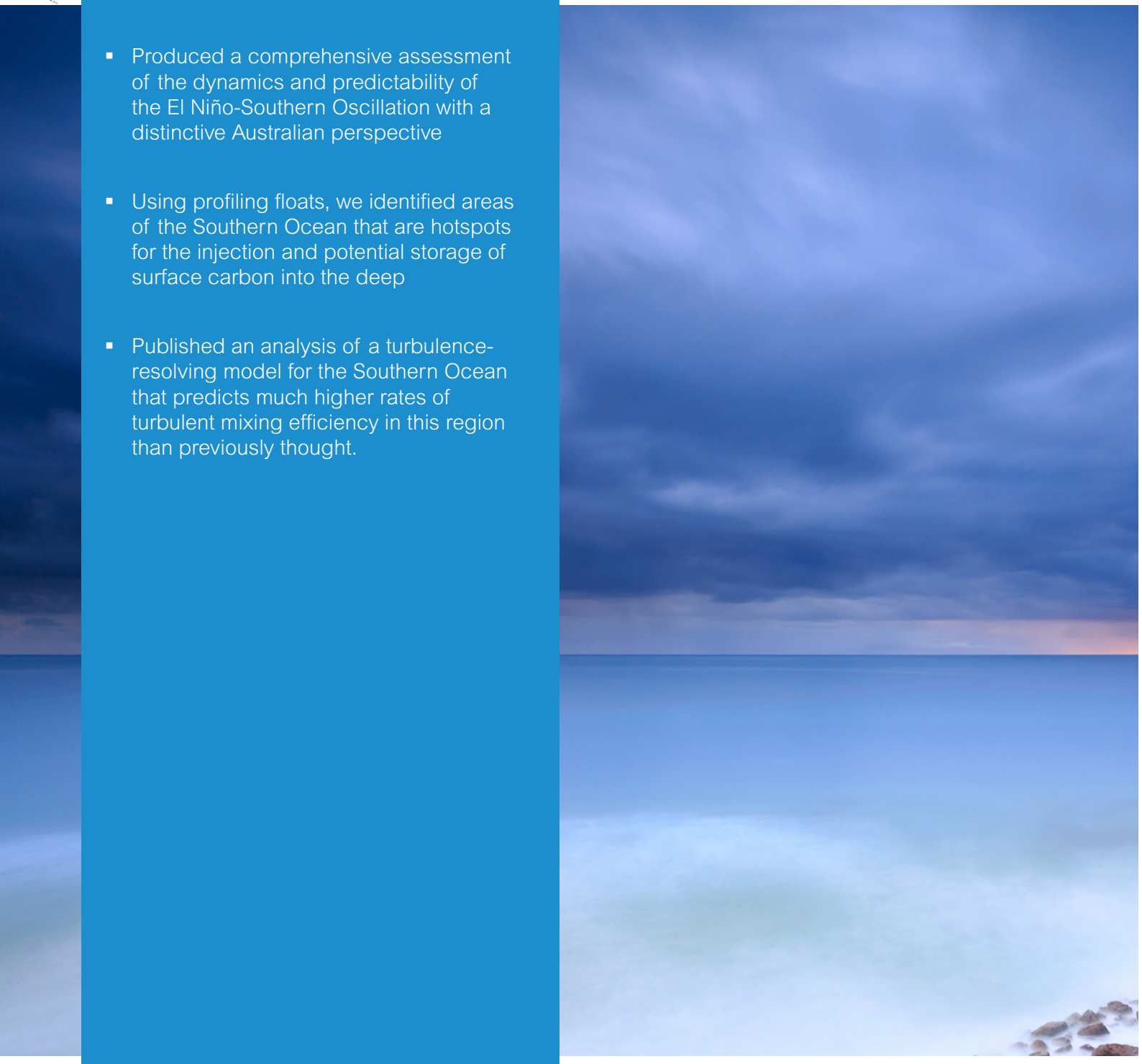
He co-led an international workshop held at Biosphere 2, Arizona, that aimed to integrate evidence streams to describe the CO_2 fertilisation effect on the global carbon sink. The chief outcome of the workshop will be a review paper, alongside a number of spin-off manuscripts on topics including the following: global photosynthesis trends; scaling of leaf-to-canopy estimates of photosynthesis; reconciliation of water-use efficiency estimates, from Free-Air Carbon Dioxide Enrichment experiments and tree-ring isotopes; evidence for satellite greening; and how vegetation communities are changing in response to elevated CO_2.

Without doubt, Martin has been a key contributor in the first 18 months of our Centre of Excellence.

RP4: Climate Variability and Teleconnections

Highlights

- Produced a comprehensive assessment of the dynamics and predictability of the El Niño-Southern Oscillation with a distinctive Australian perspective
- Using profiling floats, we identified areas of the Southern Ocean that are hotspots for the injection and potential storage of surface carbon into the deep
- Published an analysis of a turbulence-resolving model for the Southern Ocean that predicts much higher rates of turbulent mixing efficiency in this region than previously thought.



Team

Co-leads

Prof Matthew England (UNSW)
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Chief Investigators

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The Climate Variability and Teleconnections research program is the largest program in the Centre of Excellence for Climate Extremes (CLEx). The breadth of its work means that it has now separated into three distinct clusters – Southern Annular Mode (SAM), Tropical Variability and Oceans.

The SAM cluster, of around 20 researchers, has been meeting fortnightly since March 2018, exploring extratropical atmospheric variability and its effects on surface-climate variability and extremes, the Southern Ocean and Antarctic sea ice.

Meanwhile, the Tropical Variability cluster has sorted itself into five themes, with a leader for each theme. These themes and their leaders are: El Niño Southern Oscillation (ENSO) (Dr Andrea Taschetto), Decadal Variability (Dr Christine Chung), Climate Change (Dr Chen Li), Extratropics (students Kimberley Reid and Zoe Gillett) and Diverse (Dr Claire Vincent). The Diverse theme takes in the Madden Julian Oscillation (MJO), monsoons, model errors, tropical cyclones, land etc). The fortnightly meetings of the Tropical Variability cluster ran throughout 2018 with specific dates set aside for each of the themes.

The Oceans cluster holds weekly Modular Ocean Model (MOM) meeting-, and the modelling group is also maintaining close connections with COSIMA – the Consortium for Ocean-Sea Ice Modelling in Australia. COSIMA is funded independently of CLEx, but strong synergistic links exist, and several Centre of Excellence personnel attended the 3rd annual COSIMA workshop in Canberra in May.

The Variability program as a whole has also engaged in numerous outreach activities and has multiple authors working on the next Intergovernmental Panel on Climate Change (IPCC) reports. This, coupled with a range of awards, has led to a crowd of activity in the program's first full year.

Research

Fundamental modelling work took up much of the early part of 2018. The Oceans cluster has been evaluating model versions with COSIMA in an effort to produce a model evaluation paper and fully advertised publication release of the Australian Community Climate and Earth System Simulator -- Ocean Model 2 (ACCESS-OM2).

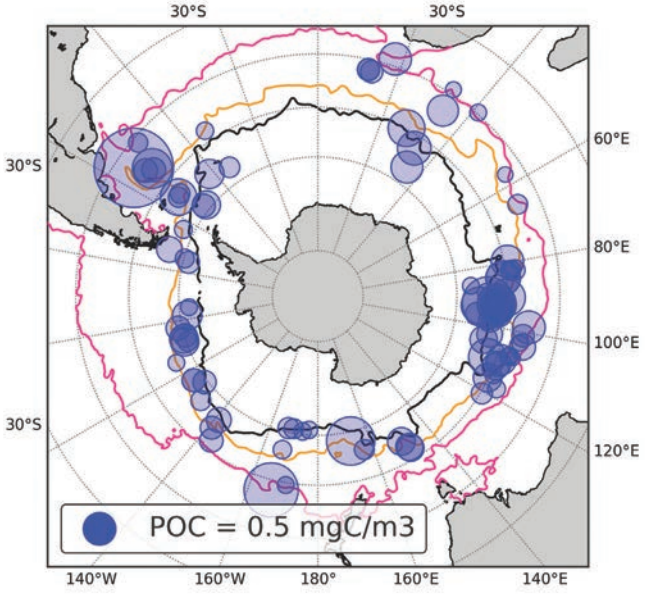


Figure 1: Injections of surface organic carbon across the Southern Ocean: Map of the Southern Ocean showing the locations where floats detected carbon-rich surface waters being injected between 200 and 600 meters depth. The size of circles represent the amount of organic carbon measured in the injected water parcel. Colour lines stand for the three main fronts: Sub-Tropical Front (pink), Sub-Antarctic Front (green) and Polar Front (black). (From Llort, et al 2018. doi:10.1002/2017JC012861)

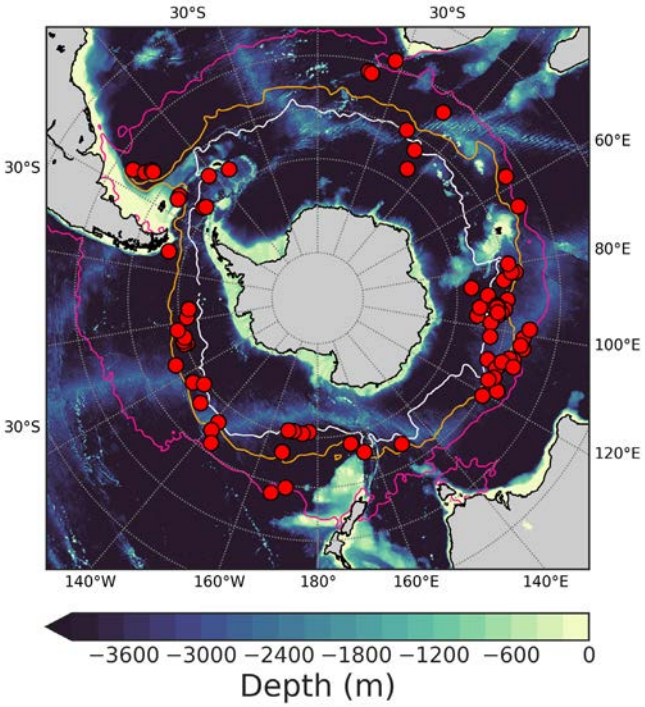


Figure 2: Southern Ocean bathymetry and injection events distribution: Red circles represent the locations where floats detected an injection of surface waters between 200 and 600 meters depth. Background colours represent Southern Ocean bathymetry and colour lines stand for three main fronts: Sub-Tropical Front (pink), Sub-Antarctic Front (orange) and Polar Front (white). (From Llort, et al 2018. doi:10.1002/2017JC012861)

The Tropical Variability cluster's Dr Chen Li is developing a perturbed physics ensemble with the low-resolution ACCESS-slab-ocean version for climate change simulation, with correcting for the mean-state surface temperatures by flux corrections. Meanwhile, the SAM cluster is continuing its efforts to produce a pacemaker version of the ACCESS-KPP (K-Profile Parameterization) model.

Even as this foundational work goes on, other modelling research has produced some impressive results. World-first modelling research by PhD student, Taimoor Sohail, using the National Computational Infrastructure (NCI) supercomputer, suggested the Southern Ocean's ability to absorb heat and carbon from the atmosphere varies significantly from previous estimates, due to the way the surface layers mixed with the deep ocean. This research was important for Australian fisheries as the nutrient-rich water rising from the bottom of the ocean boosts ecological activity that underpins much of the oceanic food chain in the Southern Hemisphere. Taimoor, along with colleagues Professor Andy Hogg and Associate Investigator Dr Bishakhdata Gayen, produced a narrated animation showing this work, which you can see on the CLEx website (https://climateextremes.org.au/new-research-rewrites-southern-ocean-mixing-calculations/).

Continuing on the theme of understanding nutrient development in the Southern Ocean, research investigating the behaviour of eddies in this region found they behaved opposite to expectations. After analysing thousands of Southern Ocean eddies, they found that in summer and autumn, clockwise-rotating eddies had lower plankton concentrations compared to neighbouring waters, and counterclockwise-rotating eddies had higher concentrations. This was the result of deeper mixing that brought nutrients to the surface, and of higher productivity. Eddy productivity plays a significant role in the exchange of carbon between the ocean and the atmosphere, which is thought to be changing in the Southern Ocean. This explains an important piece of that process.

Another study, this time based on 2016 observations from a voyage of the RV Investigator, which looked at ice-nucleating particles in clouds over the Southern Ocean, also produced some intriguing results. These were the first observations taken since 1972 and the 2016 results were 100 times lower than previously. Clouds made up of snow and ice are poorly understood, but we know they influence how many clouds there are, what type and how they are formed. Those particles that were found were primarily of organic origin, suggesting a link between these ice-nucleating particles and plankton blooms. The marked difference between the 1970s observations and these recent data have left a number of questions that will be explored in future research.

Observations of a piece of foreign kelp washed up on an Antarctic beach also led to some breakthroughs in our understanding of the Southern Ocean. Previously, it was assumed the winds and currents surrounding Antarctica prevented floating objects from the sub-Antarctic islands and further north from reaching these shores. But modelling and oceanographic analysis led by Dr Adele Morrison found that the

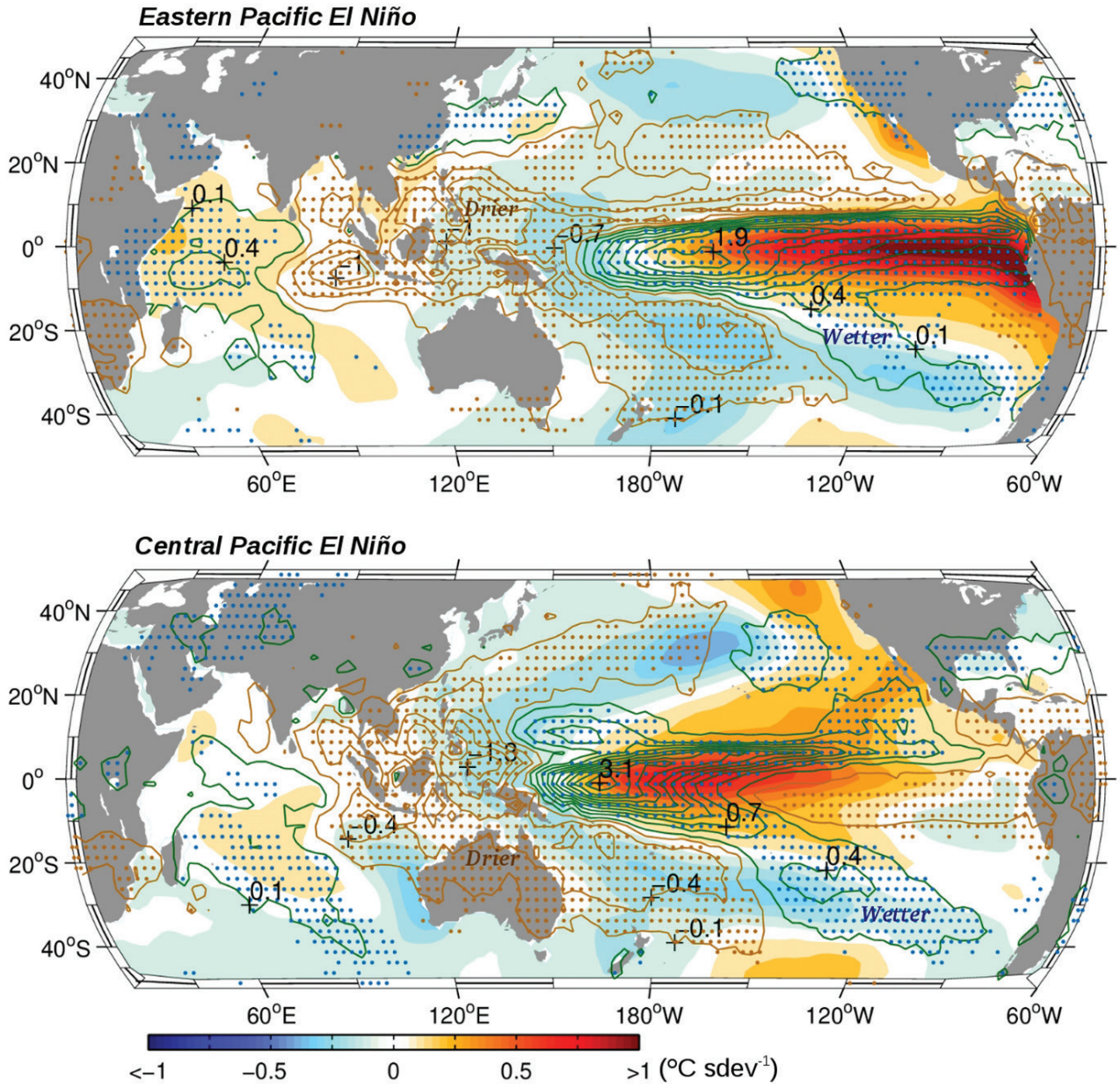


Figure 3: Rainfall (contours) and sea surface temperature (colour shading) anomaly patterns associated with Eastern Pacific El Nino (top) and Central Pacific El Nino (bottom). Units are in mm/day and degree Celsius per standard deviation of the Eastern Pacific and Central Pacific Nino indices. Drier condition is more extensive over Australia during Central Pacific El Nino events. This highlights the importance in predicting El Nino flavours, rather than just the strength of the event. For detail refer to Santoso et al. (2019) paper which also shows warmer condition over Australia during Central Pacific El Nino. Original figure courtesy Agus Santoso

addition of Stokes Drift – caused by storm generated waves – plays a major role in how drifting objects move through the Southern Ocean. It now suggests the Antarctic is much more vulnerable to biological colonisation and human pollution than previously expected.

The Variability group combined with our colleagues in the Heatwaves and Cold Air Outbreaks research program to gain an understanding of the disconnect between how sea ice volume around Antarctica is represented in CMIP5 models compared to observations. The teams looked at how 10 models simulated sea ice changes and the weighting they gave to dynamic processes – like sea ice movement – and thermodynamic processes of freezing and melting. The teams found it was likely that models gave too much weight to the dynamic processes.

While the Southern Ocean plays a major role in the climate of Australia and internationally, the tropical regions that produce drivers like ENSO and the MJO also wield a powerful influence. Even understanding these tropical processes at a distance from Australia reveals important influences on our own climate. Recent research looked at how the MJO affected midsummer droughts over South America, Costa Rica in particular. The researchers found two particular stages of the MJO led to the onset and then conclusion of droughts. This was caused by how the MJO interacted with wind anomalies on the Pacific coast. This work could be useful for seasonal forecasting and is likely to benefit agriculture in Central America.

Research within the Centre also included the development of a statistical seasonal forecast model of tropical cyclone

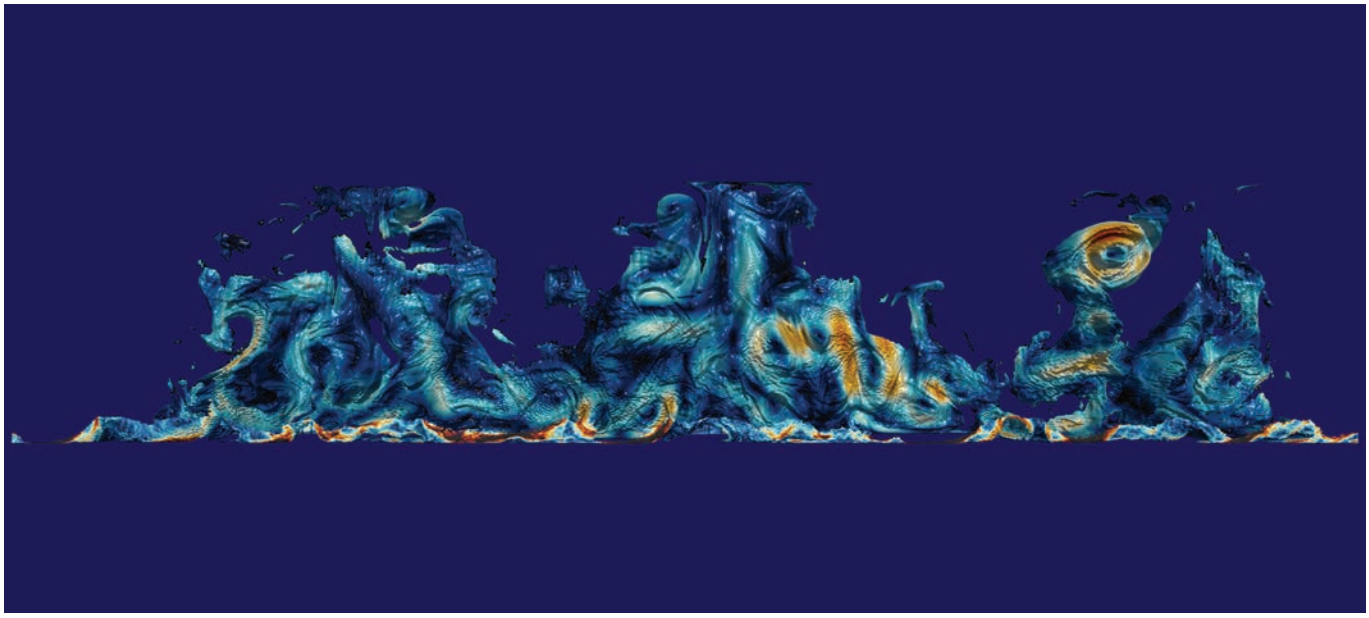


Figure 4: Flow field in the simulation. Visualised is a single temperature contour, with velocity colouring.

tracks and landfall probabilities into North Indian Ocean rim countries. This work uses the stratospheric quasi-biennial oscillation (QBO) as the three-month lead predictor variable. Overall, the model shows skill exceeding climatology by about 25%, and based on a suite of hindcast simulations, it suggests there is potential for useful forecasts several months in advance.

Workshops on ENSO in 2017 have produced two papers in 2018 that will help us better understand this annual phenomenon that has such an important influence on Australia's climate. The papers in Nature and the Bulletin of the American Meteorological Society looked at the reasons why prediction skill for El Niño and La Niña events had declined slightly in the 21st century, as well as the interactions that created different types of ENSO events, with varying impacts. Together, it is hoped these detailed summaries that propose a synthesis of two ENSO structures – namely their interaction with each other and how they respond to external forcing – will be the catalyst for future research and practical applications for forecasting and determining the impacts of present and future ENSO events.

Amidst this focus on the tropics and the Southern Ocean, the Variability program team has combined with other Centre research programs and stakeholders to produce groundbreaking work on marine heatwaves. It started with the basic research of defining the severity of these events. CLEx researchers and colleagues created a severity index for marine heatwaves. It is structured in a similar way to the category definitions for cyclones/hurricanes, with the severity of biological impacts being the key distinguishing factor. There are four categories – Category 1 (moderate), Category 2 (strong), Category 3 (severe) and Category 4 (Extreme). The aim of this research is to improve public communication of marine heatwaves, allow early detection of these events and to create a standard convention for naming and understanding heatwaves that can be used consistently by researchers around the world.

Another marine heatwave paper published in Nature Communications, co-authored by researchers from CLEx and the Institute of Marine and Antarctic Studies, revealed that globally marine heatwaves have increased over the past century in number, length and intensity as a direct result of warming oceans. From 1925-2016, the study found the frequency of marine heatwaves had increased on average by 34% and the length of each heatwave had increased by 17%. Together this led to a 54% increase in the number of marine heatwave days every year. This paper received considerable media attention.

A further piece of research looked at marine heatwaves much closer to home – off the east coast of Tasmania, a location recognised as a global warming hotspot. Average sea surface temperatures here have been rising at four times the global average rate in this area, and trends in marine heatwaves have showed significant increases in number. The East Australian Current (EAC) was found to be the dominant driver of heatwaves in this region, with warm air temperatures and northerly winds coming second. The researchers also identified 12 heatwave types, each with its own regional focus, seasonality, and associated large-scale oceanic and atmospheric circulation patterns. This is important research with direct application for the Tasmanian fishing industry.

Later research in 2018 revealed what influenced the severity of these marine heatwaves around Tasmania. The researchers found a significant increase in EAC Extension penetration into the region, with an associated increase in temperature and salinity throughout the water column, particularly in summer and autumn. The variability of the circulation on the shelf was dominated by the interplay of the EAC Extension and an extension of the Leeuwin current south of Tasmania, known as the Zeehan Current. This interplay could be captured in an

annual index developed by the researchers, which indicated the relative strength of these two currents over time. With this information, it may become possible to forecast the likely length and intensity of marine heatwave events in this region giving increased warming to aquaculture industries and fisheries.

As well as having a direct influence on industry, some of the research coming out of the Oceans cluster has paid close attention to policy outcomes.

Earlier this year, a paper led by Dr Andrew King focused on the Paris Agreement targets to see if the estimates of the difference between impacts at 1.5°C and 2°C levels above pre-industrial conditions was linear. Generally, the paper found that there was a consistent linear relationship for most regions, with the exceptions of North Pacific, north-west Atlantic, north-west Africa and China. Intriguingly, they found the difference in these areas was caused by other forcings not related to changes in greenhouse gas conditions, such as aerosols.

A second international paper that drew considerable media attention looked at past impacts on Earth when the planet was 2°C above pre-industrial conditions. It revealed significant changes in every part of the globe and, importantly, looked at the persistence of these changes due to the momentum of the climate system. The three past analogs of a 2°C warmer world suggest policymakers will need to prepare for changes in the climate and sea level that could continue for hundreds of years.

Engagement

The Variability and Teleconnections team has had a big year for engagement with our peers and the general public.

Three members of our team – Dr Catia Domingues, Dr Shayne McGregor and Dr Joelle Gergis – have been named as Lead Authors for the next IPCC Working Group 1 report for the 6th Assessment Report (AR6), due to be released in 2021. At the same time, Professor Nathan Bindoff and Associate Professor Nerilie Abram have been named Co-ordinating Lead Authors for the IPCC Special Report, Ocean and Cryosphere in a Changing Climate. It is one of three reports to be released in 2018 and 2019 that precede AR6. Associate Professor Julie Arblaster will be an author on the 2018 World Meteorological Organization/United Nations Environment Programme's Scientific Assessment of Ozone Depletion. These assessments are carried out every four years in accordance with the terms of the Montreal Protocol. Associate Professor Peter Strutton, as a member of the Tropical Pacific Observing System (TPOS) 2020 Scientific Steering Committee, and Co-chair of its Biogeochemistry Task Team, has been a key contributor to the TPOS implementation plan. Significant progress was made around infrastructure commitments from China and Japan, including the addition of biogeochemical sensors in the Western Pacific Region.

The Oceans cluster team has engaged strongly with the national and international climate science community. Nerilie presented at the Continuing Education series on Climate and Climate Change conference, speaking on Australia's changing climate from the perspective of the last millennium. Nerilie also presented at POLAR2018, along with Claire Krause and Andy Hogg.

Associate Investigator Joelle Gergis published her new book, Sunburnt Country: The History and Future of Climate Change in Australia, which secured her a guest spot at the Sydney Writers Festival and multiple television and media appearances. She was also named as a climate councillor with the Climate Council.

As well as travelling internationally, the Variability program has hosted multiple visitors as we seek to deepen our research collaborations. Professor Stephen Griffies visited from the Geophysical Fluid Dynamics Laboratory to attend the CO-SIMA meeting and collaborate with Andy Hogg. Dr David Munday from the British Antarctic Survey gave a seminar at ANU, and met with CLEx postdoctoral researcher. Other visitors included: Axel Timmerman; Ellen Corrick, an expert in rapid climate change; Joe Lacasce from the University of Oslo; Scott Bachman from the National Center for Atmospheric Research; and the Directeur de Recherche at Centre National de la Recherche Scientifique,, Meteo France, Dr Jun-Ichi Yano.

Awards

We can't finish this report without acknowledging some of the triumphs of individual researchers throughout the year.

An award of particular note was the announcement of Associate Investigator Trevor McDougall on Australia Day as a Companion of the Order (AC) for his work on ocean physics and ocean mixing, and his service to the profession. Later in the year he was named as a fellow of the American Geophysical Union.

Chief Investigator Julie Arblaster was recognised for her research when she was named as a co-winner of the Australian Meteorological and Oceanographic Society Priestley Medal for mid-career scientists.

All in all, this has been a jam-packed year for the Variability and Teleconnections research program, setting up what looks to be an even busier year in 2019.

Statement of Intent

Project	Priority	Intent
4.1	1	Characterise tropical climate variability (modes) and circulation, as potential drivers of climate extremes in Australia
	1	Assess the natural characteristics of Indian Ocean Dipole variability during the last millennium in reconstructions and simulations
	1	Diagnose mechanisms of heat transport into and out of the Pacific warm water volume using new water-mass transformation methods
	1	Analysis of tropical climate variability and change in mean state corrected coupled simulations
	2	Perturbed physics experiments with corrected mean states to study tropical climate variability and change
4.2	1	Advance a process-based understanding of the SAM via single forced experiments of a coupled climate model (ozone and GHGs)
	1	Examine the dynamics of recent and past SAM variability and trends, estimate how these have impacted climate extremes
	1	Understand the dynamics of and impacts of the subtropical jet
	2	Assessment of SAM response to solar forcing in last millennium simulations
	3	Analyse evidence that the SAM mean state affected southern hemisphere temperature extremes during the last millennium
4.3	1	Use CMIP5/CMIP6 simulations to estimate the way ENSO teleconnections to Australian climate extremes will be modified in the future
	1	Assess the performance of satellite ocean color products for the tropical Pacific
	2	Examine the large-scale tropical to mid-latitude forcing of marine heatwaves in the Tasman Sea
	2	Use existing model runs to investigate the biogeochemical processes associated with marine heatwaves. Regional focus TBD.
	2	Quantify tropical - extratropical interactions by studying pacemaker and partial coupled experiments forced separately in the tropics and mid- to high-latitudes. (Dongxia Yang is looking at IPO & storm tracks in CESM pacemaker runs; Ariaan Purich is examining ENSO teleconnections to high-latitude climate)
4.4	1	Begin work on framework for high-resolution ocean-sea ice model that includes biogeochemistry.
	1	Investigate how the structure of the Southern Ocean eddy field responds to changes in the SAM; and the effect of these changes on the mean ocean circulation.
	1	Delineate barotropic and baroclinic contributions to eddy saturation
	1	Conduct freshwater forcing perturbation experiments in ACCESS-OM2-01
	2	Use bio-Argo floats in the Southern Ocean to understand (1) seasonal drivers of phytoplankton blooms and (2) biogeochemical signatures of eddies.
	2	Develop method for forcing ocean-only perturbation experiments based on existing climate variability.
	2	Study how topography might promote the role of barotropic instability with respect to that of the baroclinic instability in the ocean.
	3	Use existing model runs to investigate biogeochemical processes in the Weddell Sea polynya
All RP	1	Development of ACCESS coupled model correction scheme for land and ocean.
	2	Begin new last millennium simulations using a suitable coupled climate model

Priority levels: 1 = to be achieved in 2019. 2 = substantial progress in 2019. 3 = progress towards in 2019.


TRIPLEX

A Voyage on the RV Investigator – Training Observers of the Deep Ocean

by Helen Phillips, Nathan Bindoff, Pete Strutton (University of Tasmania)]

Research Vessel Investigator returned to Hobart after a 32-day voyage to map a meander of the Antarctic Circumpolar Current (ACC) Polar Front. This meander is known to funnel large amounts of heat toward Antarctica and is one of four major hotspots for poleward heat transfer in the Southern Ocean.

In the science party were 11 Centre of Excellence for Climate Extremes (CLEx) students and postdoctoral researchers, three international students, a film-maker and visual artist, and collaborators from CSIRO, the Antarctic Climate and Ecosystems Cooperative Research Centre and the Woods Hole Oceanographic Institution.

Led by Professor Nathan Bindoff and Dr Helen Phillips from the University of Tasmania, with a biogeochemistry component led by Associate Professor Peter Strutton, also from UTAS, the voyage delivered a full-depth, full-width, 700-km-long survey of the meander. These new observations are a world first that will be used in conjunction with super-high resolution computer simulations to investigate the small-scale ocean processes that slow down the ACC and control poleward heat transfer.

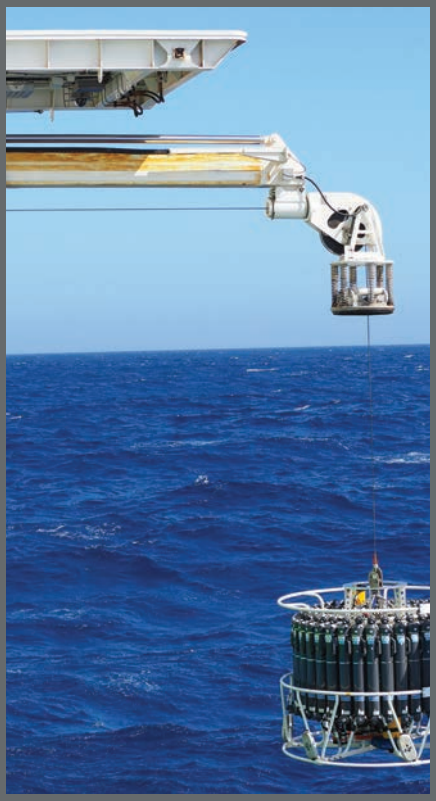
This voyage and the observations were funded by Australian Research Council Discovery Projects, and support for the participation of investigators and students was provided by CLEx and the Australian Government's National Environmental Science Programme.

We used a wide range of instruments to collect our observations. The early career researchers (ECRs) from the Centre of Excellence and overseas were trained in the use of all of these, as well as the very sensitive tasks of collecting water samples for the chemical and biological analyses that were conducted on board. The data totalled many terabytes-worth, and we kept a close eye on its quality through early data analysis.

All of the ECRs participated in a small research project that was focused on a particular data set or research question. In some cases, the projects aligned with the ECRs' existing research and has potential to be published. Other projects were an opportunity for ECRs to learn something completely new.

Because the ship at sea is a 24-hour, seven-day a week operation, we worked in two shifts: 2pm to 2am, 2am to 2pm. Lunch at 11:30 am is the main time for both shifts to overlap and catch up. We also had a daily update on voyage plans and early results from Nathan at 1:30 pm, followed by a science talk.

Nathan Bindoff



Early in the voyage, the science talks were often about the research background of each participant. On October 31 we had a Halloween party instead – with remarkably creative costumes, considering the lack of resources on board.

In the last week of the voyage, the talks switched over to presentations on the results of the research projects, and a very interesting discussion on the ethics of ocean observations. Some of the science talks weren't science at all; they were about communicating science through story-telling, visual art, and our own interactive map that is currently under development.

A collaboration with the Ocean Media Institute led to film-maker Sarah Lanier joining the voyage (http://www.oceanmediainstitute.org). Sarah was everywhere on the ship, capturing instrument deployment and retrievals, control room operations and funny moments, and she was obsessed with capturing the Aurora Australis on rare nights without clouds. Sarah will create a documentary that tells the story of our voyage, to be submitted to film festivals around the world.

Visual artist Annalise Rees from University of Tasmania was pivotal in developing and supervising communication activities from the voyage. In addition to working on her drawings of the ocean and voyage activities, Annalise coordinated the blogs that students prepared to explain what was happening on the voyage (http://www.imas.utas.edu.au/news/news-items/investigator-voyage-to-address-puzzle-of-southern-ocean-current). Annalise also captured the sounds, videos and interviews that we will use to populate an interactive map of the voyage. Digital artist Matt Daniels in Hobart will develop the map to help people who have never been to sea understand why we do it and what it's like to be out there.

Observing the ocean is difficult because of the extreme environment and isolation. However, the combined efforts of many oceanographers over many decades has delivered the data collections we use to understand the ocean.

It is easy to underestimate the power of making observations. Particularly for students and postdoctoral researchers, whose main connection to the ocean is classroom theory and computer models, there is no substitute for time on a ship watching the ocean structure unfold before their eyes. It creates a deeper understanding of ocean dynamics and a sense of gratitude for those who make the measurements that inform global syntheses and models.

Computational Modelling Support

Highlights

- Preparations for support of the latest ACCESS versions
- CMIP6 technical preparations. Development of CleF, a tool to simplify search for climate data at NCI
- Updates to CABLE coupled to WRF
- Work on implementing CABLE into the JULES framework to simplify scientific collaborations across both communities and ACCESS development
- Reorganisation of CMS training

Model Improvements

ACCESS

Centre of Excellence for Climate Extremes (CLEx) researchers are expected to use the next generation of the Australian Community Climate and Earth System Simulator (ACCESS) coupled models, the ACCESS Coupled Model version 2(ACCESS-CM2), and the ACCESS Earth System Model version 1.5 (ACCESS-ESM1.5). Centre researchers are already involved in an active research effort using the ACCESS Ocean-only Model version 2 (ACCESS-OM2) model suite. The Computational Modelling Support (CMS) team has been working in collaboration with CSIRO on a few specific projects:

- Harmonisation of the Modular Ocean Model (MOM) between the models ACCESS-OM2, ACCESS-CM2 and ACCESS-ESM1.5
- Simplified model setup for ACCESS-ESM1.5
- Some gains on speed and cost of running the models.

MOM5 code harmonisation. ACCESS-CM2 and ACCESS-ESM1.5 were developed using older versions of the MOM version 5(MOM5) than ACCESS-OM2. Updating the coupled models to the same MOM5 codebase means researchers can access new functionality in their coupled simulations, such as important heat budget diagnostics. They will also benefit from bug fixes in recent versions. From a scientific perspective this is crucial, as it allows the coupled model community to incorporate model improvements from the ocean modelling community. Aidan Heerdegen has led the harmonisation project in collaboration with several people at CSIRO, in particular Russ Fiedler and Peter Dobrohotoff. The harmonised code for ACCESS-CM2 has been delivered to CSIRO for testing and the effort is now ongoing for ACCESS-ESM1.5.

ACCESS-ESM1.5 model setup. ACCESS-ESM1.5 uses an older framework to set up a configuration and run the model. This framework is not user-friendly. In order to simplify the support of ACCESS-ESM1.5 in the future, Holger Wolff and Scott Wales from the CMS team are transitioning the set-up framework to payu, which is used for ACCESS-OM2. Supporting fewer model configuration and running frameworks means we can support more models and/or configurations. It will provide the users with a better experience using the ACCESS-ESM1.5 model, and they will benefit from improvements in payu.

Productivity gains. Finally, the CMS team identified a few possibilities for productivity gains in ACCESS-ESM1.5 or CM2. Scott Wales improved the speed of ACCESS-ESM1.5 by 17.5% by recoding a parallelization subroutine to limit waiting times on processors. We have also made some gains in productivity in ACCESS-CM2 with some changes on some input options (without changing the science used). These allowed for a slightly faster model using a lower count of processors. This means it is now slightly less costly to use the ACCESS-CM2 model.

CMIP

This year, National Computational Infrastructure (NCI) was leading a Data Enhanced Virtual Laboratory project funded by Australian Research Data Commons (ARDC) to prepare NCI and the climate and weather Australian communities for the release of the Coupled Model Intercomparison Project Phase 6 (CMIP6). The project aimed to prepare the technical infrastructure needed for CMIP6, in partnership with CSIRO, the Bureau of Meteorology (BoM) and CLeX. The CMS was involved in the project in several capacities:

- Technical advisory
- Product development
- Training development

Paola Petrelli has actively participated in designing the directory structure that will be used to host the CMIP6 data at NCI. This structure has been decided within limitations imposed by the CMIP project, and based on the extensive experience of Paola and other data managers (Claire Trenham and Tim Erwin at CSIRO) gained in supporting the CMIP5 users. Paola was also involved in discussions around the management of the data requests and user expectations.

Paola Petrelli and Scott Wales have significantly updated ARCCSSive, now named Climate Finder (CLeF), to help users request CMIP6 and CMIP5 data, find the data at NCI and use this data. This latest version of the software is based on the Metadata Attribute Search (MAS) database developed and provided by NCI. The development of CleF necessitated extensive collaboration with NCI staff for refining MAS abilities to suit the needs for CMIP6. Paola Petrelli also presented the tool to the climate and weather community at a training session and at CLeX's annual workshop in November.

CABLE

There have been two major projects involving the Community Atmosphere-Biosphere Land Exchange model (CABLE) this year at CMS:

- Integrating CABLE to the latest release of the NASA Unified Weather Research and Forecast model (NUWRF)
- Integrating CABLE to the Joint UK Land Environment Simulator (JULES) framework.

NUWRF

A new version of NUWRF was released in 2017. This version is significantly different to the previous version and extensive work was required to integrate CABLE to it. This work is now complete for the default options and features. Dr Claire Carouge at CMS will now implement additional features and options as well as updating the CABLE version.

JULES framework

The ACCESS model needs to couple the CABLE model and Unified Model (UM) together. This is a time-consuming effort, particularly as development of these two models happens separately. Usually, the UM is used with the JULES land surface model. This means JULES and UM model development is well linked together. As such, it was decided to try to incorporate the scientific part of CABLE within the JULES framework. Since the JULES framework follows the development of the UM model, this should simplify and accelerate the development of new versions of ACCESS. Additionally, it would facilitate greater collaboration between the CABLE and JULES communities in developing their respective models. Daniel Eisenberg has been working on this project during the year. He made some progress with several submissions to the UK Meteorological Office repository. Unfortunately, but not unexpectedly, the progress has slowed down in the last months of the year as Daniel needed to consult several people, Jhan Srbinovsky and Ian Harman at CSIRO in particular, to decide how to incorporate the CABLE code into the framework.

Software tools

CMS has developed or made available different software tools during the year, in addition to CleF. We continue supporting Python at NCI by maintaining and updating shared conda environments containing packages requested by CLEx users. We have added over 40 new packages in 2018.

Scott Wales, in collaboration with Aidan Heerdegen, has developed mppnccombine-fast, a new version of mppnccombine: a tool to combine tiled output from the MOM5 model. The new tool is orders of magnitude faster for higher spatial resolution models. For example, collating a 34GB file with the new tool was 6.5x faster, but more importantly, used a fraction of the memory (0.2%) compared to the original tool. As memory was becoming a bottleneck, this is a massive improvement.

The CMS team has also started the creation of a Python-based package of useful functions for CLEx researchers. It already contains a spatial interpolation function and we are implementing functions to: simplify the reading of centrally installed data sets, to concatenate and slice netcdf files in time, and to automate splitting variables by variable.

Aidan Heerdegen has written mdssdiff, a tool to aid researchers in archiving their data to the mass data store. This is the first of a suite of tools to aid researchers to effectively archive and retrieve their data, a crucial step in improving workflows by making better use of the largest and most cost-effective form of storage currently available.

Training

The CMS team has redesigned its training for CLEx, following experience gained from providing training for the ARC Centre of Excellence for Climate System Science (ARCCSS). During ARCCSS, the CMS training was centred on one or two in-person training events per year. These events were one-to-two days long and they had some advantages:

- Easy access for all participants to the trainer
- Focus days on training: no distractions
- Everything happens at once: participants just need to be free one or two days in the year.

But they also had some drawbacks:

- Need to travel to the event, which is not easy for participants with families and expensive for the Centre
- Very infrequent: if you miss it, you need to wait a year or find other training
- A lot of work to organise.

Since May 2018 we have been offering weekly one-hour training sessions via video conference. This new format allows us to cover more subjects and run more repeats, as needed. We also record the trainings and publish the recordings on YouTube, which provides future reference to users.

Additionally, we decided to enhance our offer for support with a weekly blog: https://climate-cms.org/ The entries in this blog are often based on questions received during the 'help desk' or are extensions of the hourly training sessions. This allows us to build a knowledge bank to which we can easily refer users as needed. We also hope the Centre's researchers will use this resource on their own, to learn new skills or improve their skills.

Data Sets

Although the main focus for 2018 was to get ready for managing CMIP6 in Australia, Paola Petrelli has managed more than 20 data sets during the year. These data sets are used by climate and weather researchers around Australia, and potentially outside Australia, by remote access to the data. Notably, the European Centre for Medium-range Weather Forecast (ECMWF) has released its new reanalysis ERA5. This data set will potentially be used by a large number of researchers at CLEx but also at the CSIRO and BoM. However, this is also a very large data set, so careful planning of what the Australian community needs and how it will be managed is needed. Paola Petrelli has worked in collaboration with CLEx Chief Investigators and others from the BoM and CSIRO to put forward both short and long-term strategies. These are to allow quick access to an ERA5 subset, while also ensuring sustainability of the data set at NCI over the longer term. Paola also guided and helped Centre researchers to publish 10 data sets hosted at NCI.

Statement of Intent

Priority	Intent
1	**Finish upgrade to NU-WRF (i.e. CABLE-LIS-WRF coupled model) to version 8. Steps are:** ▪ fully implement in LIS and LDT all forcing options for CABLE ▪ update CABLE to version used in ACCESSS-CM2 ▪ rewrite the Python scripts to launch simulations
2	**Model updates at NCI:** ▪ WRF ▪ MOM 6: start transition work to MOM6 ▪ ACCESS-CM2 and ACCESS-ESM1.5
1	**Transpose-AMIP with CABLE**
2	**CABLE in JULES framework: get CABLE to run offline**
3	**Automate and expand CABLE benchmarking suite** ▪ implement automated science tests on new repository commits ▪ include logic (energy, water, carbon conservation) and performance (e.g. ILAMB/PALS-based) tests
1	**Develop a benchmarking suite for NUWRF using the modelevaluation.org framework.**
2	**Develop tools to automatically save model experiments setup to enable better sharing and reproducibility of experiments**
3	**Improving quality and access of current and future CMIP collection:** ▪ improving and promoting CleF (Python tool for querying CMIP5/6 dataset) ▪ sharing information and solutions with the community to individuate and fix issues with data on raijin
1	**CMIP6** ▪ Maintain collaboration with NCI and the CMIP6 technical committee. ▪ post-processing of D&A ACCESS runs: updating the post-processing workflow. ▪ develop and delivering training around using CMIP6 at NCI.
1	**Complete publishing of new datasets and finalising Weather@Home re-organisation**
1	**Datasets reorganisation at NCI.** NCI needs to reorganised datasets for better compliance. Paola will link with NCI, BoM and CSIRO to ensure CLEx needs are considered and help communicate the changes to users.
2	**Making data procedures and access more automatic:** this includes datasets updates, adding more collections to clef and helping with software publishing and catalogues.
3	**Improve data workflows:** Help researchers manage their data stored at NCI more efficiently with using both disk and tape storage. ▪ Define efficient workflows ▪ Develop tools to help researchers follow such workflows
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 the Centre to enhance their future research
1	**Improving workflow to publish data at NCI** from DMPs to DOIs. This should include training/informing new and current researchers and students.
2	**More active participation in Research Programs.** Establishing relationships at relevant level, identifying possible improvements to workflows

Priority levels: 1 = to be achieved in 2019. 2 = substantial progress in 2019. 3 = progress towards in 2019.

CMS Team Profiles

Dr Claire Carouge

CMS Leader

Dr Claire Carouge is the leader of the Computational Modelling Systems (CMS) team at the Australian Research Council Centre of Excellence for Climate Extremes. She coordinates the efforts of the team members distributed over the five nodes of the Centre.

In parallel, Dr Carouge provides the Centre with the modelling support for the Weather Research and Forecasting (WRF) atmospheric regional model and CSIRO the Community Atmosphere-Biosphere and Land Exchange (CABLE) land surface model. As such, she has coupled CABLE to WRF via the integration of CABLE into the Land Information System (LIS). She has also developed new diagnostics in WRF required for simulations for the Coordinated Regional Downscaling Experiment. She now maintains, keeps up-to-date and documents a stand-alone modified WRF model and the CABLE-LIS-WRF coupled model.

Dr Carouge is also developing a proper suite of tests for CABLE in collaboration with the CABLE development team at CSIRO. She supports researchers using and developing the CABLE and WRF models at the Centre.

Dr Aidan Herdeegen

CMS

Aidan Heerdegen is a computational scientist with a background in physical chemistry, with experience supporting research in climate modelling, and statistical analysis of climate data. He is primarily responsible for supporting the use and development of ocean simulation codes within the Centre of Excellence.

A current major focus is development of a new high-resolution (1/10th degree) global ocean model configuration, in collaboration with the Consortium of Ocean-Sea Ice Modelling in Australia.

Aidan Herdeegen has a Bachelor of Science (Hons) in Physics and Chemistry from Massey University (NZ), and a PhD from ANU. He is based with the Climate Fluid Physics group, Research School of Earth Science, ANU, and joined the CMS team in 2014.

Dr Paola Petrelli

CMS and Data Manager

Paola Petrelli is the data manager for CLEx. Before joining the Centre of Excellence she managed oceanographic and climate data sets for the Tasmanian Partnership for Advanced Computing, acquiring extensive experience in web services and software used by the Earth sciences research community. She received a PhD from the University of Siena (Italy) in 2005.

Paola Petrelli sets the Centre's data strategy and provides advice on data-management practices. She leads the data collaborations with our Partner Organisation, including National Computational Infrastructure (NCI), to manage shared data resources. She represents CLEx in the Coupled Model Intercomparison Project Phase 6 technical and the Climate Data Set committees. An important part of her role is to publish CLEx data and metadata on public repositories such as the NCI data services, Earth System Grid Federation and the Australian National Data Service's Research Data Australia.

Scott Wales

CMS

Scott Wales supports the researchers at CLEx who work with the Unified Model, the atmospheric component of the Australian Community Climate and Earth System Simulator (ACCESS) model. He helps researchers to understand, run and modify the model, and works with our Partner Organisations to make their model configurations usable on the NCI supercomputers.

Scott Wales also works closely with leaders across the ACCESS community, providing technical advice and helping to develop and maintain the infrastructure needed to run the model at NCI, such as the Accessdev and Subversion servers. He also works with our partners at the UK Meteorological Office on collaborative development across the entire United Model (UM) partnership.

Scott has experience in a variety of different computational modelling techniques, including numerical atmospheric models, cosmological N-body simulations and stochastic partial differential solvers. He has a Bachelor of Science (Honours) in Physics from the University of Queensland.

Dr Holger Wolff

CMS

Holger Wolff has a background in physics. After graduating from the University of Hannover, he successfully completed a PhD in quantum-atom optics at Swinburne University in Melbourne, with a focus on micro-fabrication of atom chips for Bose-Einstein-Condensate Experiments. Following the PhD, he worked with CSIRO as a programmer for atmospheric modelling for three-and-a-half years.

Together with Scott Wales, Holger Wolff supports CLEx researchers with the UM, both stand-alone

and as the atmospheric component of ACCESS. Additionally, he enjoys training researchers in technical topics like UNIX, Fortran, and Version Control. Holger Wolff joined the one-time ARC Centre of Excellence for Climate System Science in November 2013, and has been a member of CLEx since its inception.

Daniel Eisenberg

CMS

Daniel Eisenberg is a computer scientist who joined the CMS team in August 2017, providing support for the CABLE land surface model at the Centre of Excellence

His past experience at the Centre is in web development, building the ModelEvaluation.org web application, which enables model evaluation and benchmarking.

A current focus involves integrating the code of two land surface models, Australia's CABLE model and the UK Met Office's JULES model, a project which promises to raise the level of international collaboration in land surface model development.

Researcher Development Program

Highlights

- A successful winter school on climate extremes and high-impact weather, held at ANU
- Weekly technical training delivered virtually by our CMS team
- Virtually delivered researcher development sessions on the publication process, tips for gaining jobs in data sciences, and guidance on preparing DECRA applications
- A full day of professional development training organised by and for our ECRs
- Two successful scientific paper writing workshops
- Our students were authors on 19 journal articles this year, 13 as first author
- 16 undergraduate students were introduced to climate science research via our summer scholarship initiative

The Researcher Development Program at the Centre of Excellence for Climate Extremes (CLEx) will further develop national capacity in climate science by training and mentoring the next generation of researchers. The Development program equips them with the intellectual and technical capacity required to take on the research challenges of the future. Its remit includes fundamental research and communication skills, professional development, mentoring and leadership opportunities, and it involves all Centre of Excellence researchers.

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

In 2018 we welcomed eight new honours students, five masters students and 26 PhD scholars to the Centre. All have been actively involved in our graduate activities. Including legacy students from ARCCSS, we celebrated 30 submissions in 2018. (23 PhD, four masters and three honours) and they have been moving on to positions in top institutions worldwide such as Ludwig Maximilian University, Munich; The University of French Polynesia, Tahiti; The University of Liverpool, UK; The Bureau of Meteorology as well as graduates going into research and data analysis positions with private sector firms.

In collaboration with our Computational Modelling Systems (CMS) team, technical training opportunities this year have included weekly technical training sessions delivered via our videoconferencing system, and Intro to National Computational Infrastructure (NCI) workshops delivered by our Partner Organisation NCI.

Our students and ECRs continue to be supported in their writing via our scientific paper writing workshops, the success of which can be seen through their success in publishing their research – with 19 papers published by Centre students this year (13 as first author). Included in this impressive publication list was a first-author paper in Geophysical Research Letters by Taimoor Sohail; two other papers with student authors in GRL; and a first-author paper by Luwei Yang in the Journal of Physical Oceanography are just a few highlights.

Professional development of our students continued via an Early Career Researcher Day developed by our ECRs, for our ECRs. This year we concentrated on what happens after thesis submission, with sessions on preparing a curriculum vitae and responding to selection criteria for a range of industries. This included incredibly useful guidance around applying for jobs in government, from CLEx Associate Investigator, Dr Stephanie Downes.

Researcher development included virtual and in-person training covering the knowledge, skills and resources our researchers will need to successfully move on to the next step in their career. In 2018 this included: sessions on the scientific publication process; how to get a job in the data sciences;

tips for writing a Discover Early Career Researcher Award (DECRA) application; how to write your career bio; how to deliver a successful 'elevator pitch'; and learning-by-doing three-day workshops, on how to write a scientific paper.

Winter School

Our winter schools are the cornerstone of our Development program and are open to all climate science honours and graduate students, regardless of CLEx affiliation. The theme and location of the winter school changes every year; in 2018 we were at ANU, investigating climate extremes and high-impact weather.

To ensure we build capacity in the climate sciences beyond our Centre of Excellence, we open up our winter schools to participants Australia- and New Zealand-wide. This year we had 60 participants from 10 universities. The winter school examined the key processes that affect long- and short-term weather and climate events, with an emphasis on how regional climate extremes are related to variability, climate teleconnections and climate sensitivity. Lectures were delivered by CLEx researchers alongside those by colleagues from our Partner Organisations, the Bureau of Meteorology (BoM) and CSIRO.

Undergraduate Scholarships

Climate science students come from a range of undergraduate degree course in the quantitative sciences. 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 Collaborating Institutions, or node universities, as well as national Partner Organisations, CSIRO, BoM and the federal Department of Environment. Undergraduate students are supervised by our ECRs, giving the latter vital supervisory experience. In 2018 we welcomed 16 undergraduate students from seven universities to the Centre, to work with us on research projects.

Travel

Many of our students had the opportunity during 2018 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, or talking to researchers and supervisors at other nodes via video conference.

Prizes

Our students were once again successful in winning both national and international prizes this year. The full list of prizes and awards can be found elsewhere in this report. In particular, we congratulate Jiawei Bao from UNSW for winning the 2018 CLEx prize for best paper by a student. Anna Ukkola, also from UNSW was the recipient of the CLEx prize for best paper by an ECR.

CLEX 2018 Winter School

This year's winter school was held at ANU, Canberra with a theme of Climate extremes and high impact weather. We accepted Australian and New Zealand graduate students regardless of their affiliation with the Centre and welcomed 60 participants from ten universities. All lectures were recorded and are available on our website. In addition to the lectures, participants worked on climate extremes mini-projects throughout the week.

The general structure of the Winter School involved lectures in the morning and a group activity in the afternoons. The groups were tasked with producing analysis investigating one of five complex questions.

Each group comprised of 6-7 students with various backgrounds and at various stages of their education. Graduate Director Melissa Hart, allocated students to various projects that highlighted their skills as well as giving them an opportunity to improve weak areas.

By the end of each project students understood how to design and conduct an experiment that involved analysing climate model simulations. This meant knowing what the different model output variables were, understanding the various run types (historical, future RCP projections, various forcings, various initial conditions etc.), how to use ensembles of models like those in the CMIP5 ensemble, the structure and location of variables on Raijin (Australia's supercomputer), and where to find information on these variables.

The Winter School concluded with a Researcher Communication workshop facilitated by Dr Merryn McKinnon from ANU's Centre for Public Awareness of Science. Merryn ran exercises on how to best communicate who you are and why you do what you do both written and orally.

Participants worked on an elevator pitch exercise and re-worked their bios. The key messages were to know who your audience is, know what you want to achieve and, importantly, make it interesting and relevant. Don't just list your CV. As a result of this final activity, many of the Winter School students went on to update their CV's.

The workshop continued a tradition started at the previous Centre of Excellence of focusing on career-relevant activities that improve the current skill set of participants and improve their future prospects as they move onto post doctorate positions.

Statement of Intent for 2019

Priority	Intent
1	Run a student focused winter school centred on climate modelling
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 postdocs that identify priority areas for development based on individual needs and career objectives
2	Provide a formal certification on completion of the Graduate Program
2	Develop a formal alumni network, including exit surveys, and opportunities for alumni to be involved in centre mentoring and events
3	Exploration of industry placements, or industry mentoring opportunities for students and ECRs

Priority levels: 1 = to be achieved in 2019. 2 = substantial progress in 2019. 3 = progress towards in 2019.

Selected Student Profiles

Jessica Hargreaves

Who in CLEx are you working with?

My primary supervisor is Associate Professor Nerilie Abram, in the Palaeoenvironments group at ANU. Dr Adele Morrision, from ANU, is also on my supervisor panel.

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

I started my bachelor's at ANU in 2014, where initially I just wanted to end up somewhere within the Earth Sciences school. I was interested in how the climate was being impacted by human influences. I completed a palaeoclimate special topic in my last year and absolutely loved the balance between lab work and the modelling that we can do. I completed my Bachelor of Science (Advanced) and my honours during 2017 at ANU, where I worked with Nerilie on a project looking at the Indian Ocean Dipole and climate interactions over the last Millennium. This year I started my PhD in paleoclimate, balancing hands-on lab work, field work to Christmas Island, and modelling work. The versatility that my PhD has is what I was looking for, and an aspect I hope to continue.

Tell us a little about your project.

Over the last 30 years there has been a southward shift between 1-3° of latitude for the edge of the tropical rainfall belt and the extent of the Hadley circulation. This shift has caused an associated southward shift in climate belts across Australia, and an intensification of the subtropical high. It is currently unclear as to whether these changes are part of natural variability or as a result of anthropogenic changes to the climate system and the associated warming of the tropical oceans. My project is exploring whether there is a natural component to these latitudinal changes in the climate bands, by reconstructing tropical climatic conditions over the last 200 years and identifying whether the changes over the instrumental period are reflected in the paleo record. Christmas Island is the perfect location for this sort of study, as currently it lies on the boundary between the tropical rainfall belt and the arid subtropics, and will fill in a current gap in records.

What opportunities has the Centre of Excellence offered you?

During my honours year I was privileged to be offered a scholarship through the Centre to complete my studies, and to participate in a number of activities. I have had the opportunity to travel to different institutions to complete different workshops, such as the winter school and writing workshops, and also to take part in research projects across the nodes.

What are your hopes/plans for after you graduate?

I would love to be able to continue research in palaeoclimate, and hopefully be able to investigate places across the world to develop a clearer picture of global palaeo changes.

A small portion of the corals collected on the recent field trip to Christmas Island, which will form the basis of Jess' PhD project. The longest coral in this image is over 2.7m, and will cover near 270 years of sea surface and rainfall data. Jess will be analysing this coral at monthly resolution, and will have a beautiful record. Watch this space!

Matthias Retsch

Who in CLEx are you working with?

I work within Christian Jakob's group and Martin Singh is my second supervisor.

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

I begun my studies in Hamburg, Germany, in 2012, after working as a waiter for a couple of years, and did my bachelor's and master's in meteorology. During my bachelor's I started working as a research assistant at the Max Planck Institute for Meteorology. I helped to rewrite and implement code for a convection parameterization. Through my supervisor I became aware of Monash University and Christian Jakob's group, as he went to Monash to work with Christian. So I spent a semester abroad at Monash in 2016. Getting along very well with Christian, both of us being interested in convection processes, and with the opportunity to live a few years in Australia, I decided to do my PhD here.

Tell us a little about your project.

I aim to find atmospheric processes leading to different forms of spatial convective organisation as seen in radar observation. Therefore, I firstly have to define the metric to measure the organisation state. That state will then be matched with the larger atmospheric state, which is given based on reanalysis data. To link both states I will make use of machine-learning techniques. Once important mechanisms are established, I might probe numerical models to represent them, or extend my analysis to other observational data.

What opportunities has the Centre of Excellence offered you?

I just began my PhD recently, but already met with researchers from all the other nodes, who also work on precipitation and convection subjects. Also, the Centre of Excellence provides me with additional financial resources for travelling -always needed in a place like Australia.

What are your hopes/plans for after you graduate?

Because it is not easily possible for my wife to work in her profession as an occupational therapist in Australia, we will most likely return to Germany/Europe after my PhD. What awaits us there remains open yet.

Photo credit https://www.nsf.gov/news/mmg/mmg_disp.jsp?med_id=73557

Maxime Marin

Who in CLEx are you working with?

I was introduced to CLEx by my two supervisors from UTAS, who are both members: Helen Philips and Nathan Bindoff. My PhD is part of the Heatwave program.

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

My journey to getting a PhD in oceanography in Australia started almost 10 years ago, as I entered an engineering school in France after completing high school. After my first year, I realised that I didn't like engineering and wanted to study something else. I had always been very passionate about natural phenomena, especially weather-related, but was also some kind of an ocean boy. After some quick research, I found out that oceanography (I had never heard of it before) was a field of study. Being able to make a living (eventually) out of the study of the oceans sounded like something I could not refuse.

I enrolled in a Bachelor of Oceanography in a school that offered dual-degree programs, where half of the four years were to be done in a partner university abroad. After my first two years, I decided to leave for Brisbane, for the University of Queensland. What could go wrong with being on the other side of the world? After three years in Brisbane and a Bachelor (Hons) in Marine Science, I fell in love with both oceanography and Australia, making it my priority to pursue postgraduate studies here to become an oceanographer.

Enrolling into a funded PhD I found quite challenging, so I decided to complete a Masters in Physical Oceanography in Paris, to boost my resume, and was finally able to be accepted at UTAS. What a journey, and it's not even close to being finished!

Tell us a little about your project.

My PhD focuses on Marine Heatwaves (MHWs) on a global scale. Research on MHWs only started to emerge after a few strong events causing damage to biological communities and fishery industries. The mechanisms of those particular events are well understood, but there is still little knowledge on the overall distribution and drivers of MHWs that vary from event to event. It is important to enhance our understanding of MHWs as they are poorly represented in GCMs, especially in the context of climate change, where extremes are expected to increase in frequency and intensity over the coming decades.

The first step of my research consists of understanding the global distribution and characteristics of MHWs throughout coastal areas, and to identify the influence of climate change on these during the last 35 years. Secondly, my project will focus on the drivers of MHWs globally, to better identify the variability of events locally. The final part of my project will include a projection of MHWs in the next century, to quantify the increased threat related to biological communities and/or a specific case study of MHWs in an area that hasn't been studied before.

What opportunities has the Centre of Excellence offered you?

I am grateful for the Centre of Excellence because it has provided me with a number of different opportunities since I joined.

Networking is the most obvious one. The Centre of Excellence regroups a number of experts in designated fields, especially in climate science, but also postgraduate students and ECRs. Although being able to collaborate with senior researchers is essential, students and ECRs will be our colleagues in the near future. Networking within the Centre is encouraged by the different events organised but also by the research groups created, which meet on a monthly basis and aim at directing new areas of research within our specialty.

The Centre also provided me with funds to attend a variety of workshops organised internally, such as a writing workshop, or general conference-style workshops to improve my knowledge in climate extremes. Although I have not yet participated in conferences, the Centre of Excellence provides funds for that purpose and I am certain that it will grandly benefit me during my PhD.

What are your hopes/plans for after you graduate?

I started a PhD in Quantitative Marine Science to become a scientific researcher. After I graduate, I plan to apply for postdoc positions in Australia or elsewhere in the field of physical oceanography. Although I would love to continue living in Australia, I am not scared to start my career in another country where my skills are valued too. As strange as it can sound, I do not, however, plan to go back to France…Don't ask me why.

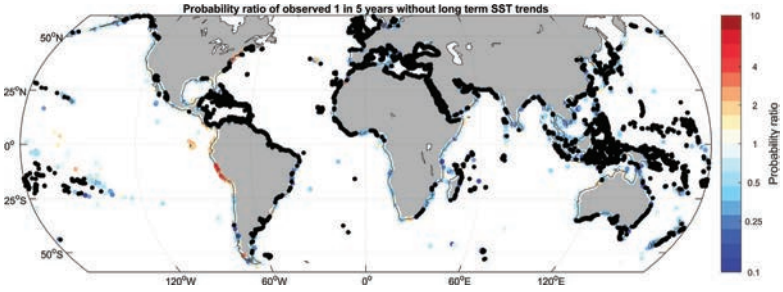


Figure: Probability change of 1 in 5 year events after removing long term SST trends. Probability ratio less than 1 indicates that observed 1 in 5 year events are less likely to occur. Probability ratios of 0 (impossible) are plotted in black

Mengyuan Mu

Who in CLEx are you working with?

Dr Martin De Kauwe and Professor Andy Pitman.

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

Being thrilled by the sagacious heroine in the film Super Typhoon, who professionally predicted the typhoon would retrace and successfully avoided casualties, I aspired to study atmospheric science at university since high school. After graduating as the first batch of Hydrometeorology bachelors, I continuously gained my master degree in Meteorology with a thesis, Sensitivity Tests and Improvements of Canopy Interception Simulation Based on CLM4.5, at Nanjing University of Information Science and Technology (NUIST), China.

After that the idea of pursuing a PhD degree naturally came up since I realised my enjoyment in scientific exploration from my undergraduate and master's research projects. With helps from my two amazing supervisors, I luckily become a member of CLEx.

Tell us a little about your project.

I will try to explore how important groundwater is to the resilience of Australian vegetation during drought. Specifically, I will identify where and on what temporal scale groundwater access is critical to maintaining vegetation function during drought. And by understanding the key hydrological and plant physiological processes necessary in accurately simulating plant resilience to water deficits, I aim to ameliorate the parameterization of CABLE. Finally, I will attempt to shed light on how and where projected increases in human groundwater extraction will intensify the vulnerability of ecosystems to drought.

What opportunities has the Centre of Excellence offered you?

I attended this year's annual workshop, which provided me an excellent opportunity to freely talk with these great scientists and to extend my research interests beyond my field. The CMS courses regularly organised in CLEx also benefit me a lot in model familiarity and programming learning.

What are your hopes/plans for after you graduate?

As for the future, I will seek a postdoc position after my graduation and continue my research on climate model improvement.

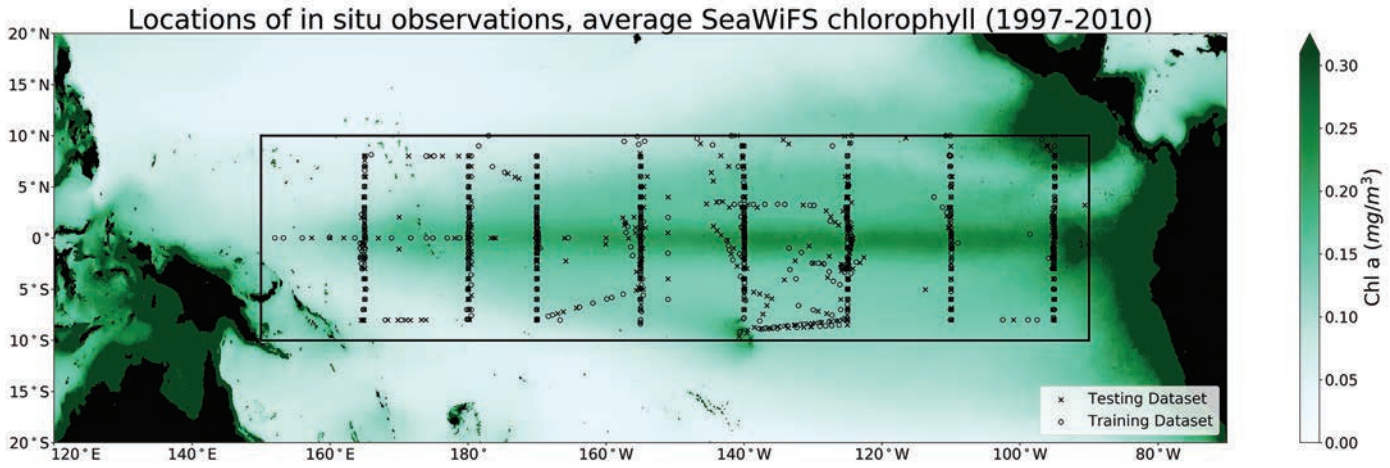
Nic Pitman in His Own Words

I am a PhD student studying at the University of Tasmania's (UTAS) Institute of Marine and Antarctic Studies in association with CLEx and CSIRO. I started my PhD in June 2018, titled "Climate-driven variability in tropical Pacific productivity", with Dr. Pete Strutton (UTAS) who is a Chief investigator in the CLEX's Climate variability and teleconnections program, as well as Dr. Richard Matear (CSIRO) and Dr. Rob Johnson (BOM).

I have had a round-about academic adventure so far, graduating from Macquarie University (Sydney) in 2015, with a bachelor's degree in geology. I moved to UTAS for my honours project on sea-level rise estimates during 2016, where I fell in love with physical oceanography (and Tasmania). I then took a year off and became a tour guide on Tasmania's Overland Track, which was amazing, but reminded me that I am passionate about and want to continue researching climate and ocean science.

I am currently less than 6 months into my PhD, where I am currently creating a regional satellite ocean colour (chlorophyll and phytoplankton) algorithm for the tropical Pacific Ocean. The tropical Pacific is the largest oceanic source of CO2 flux into the atmosphere, and is also the most variable region of primary productivity and the ocean carbon cycle due to inter-annual modes of climate variability. Once this current study is complete and submitted to the Journal of Geophysical Research, I will begin assessing ENSO driven variability on chlorophyll, primary production and the carbon cycle in the equatorial Pacific.

CLEx has provided an incredible support and networking experience throughout my honours and PhD work so far. I have been provided many travel, conference and skill-building activities through the Centre, including my PhD scholarship; the 2016 winter school (with the old Centre of Excellence, ARCCSS), an NCI computing workshop at the University of Melbourne; the 2018 CLEx conference in Wollongong; and funding to attend the 2019 Advanced Scientific Programming in Python workshop, in Canberra. The Computational Modelling and Support team has also been invaluable in my progress so far, and I am very happy and privileged to be a student with CLEx.

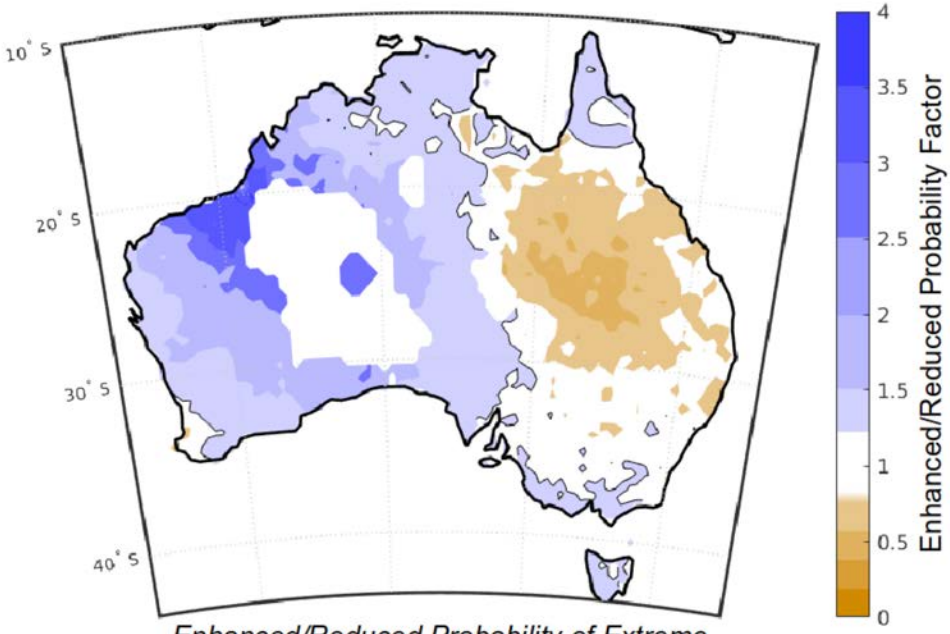


Kimberley Reid in Her Own Words

For the past two years, I've been working on my master's project researching the Australian North-west Cloudband (NWCB). With guidance from my supervisors, Ian Simmonds and Claire Vincent from CLEx, I've created a novel algorithm to automatically identify NWCBs from 32 years of satellite images. This allowed us to extend the record of NWCBs, and to understand their annual to decadal variability. I also proposed a new conceptual model for the physical mechanisms that drive NWCBs, and showed that NWCBs can enhance the probability of extreme rainfall over central and north-west Australia, but reduce the probability over eastern Australia.

I finished my Bachelor of Science in 2016, at the University of Melbourne, majoring in climate and weather. Initially I did not want to do research as I feared a life in academia would be like being in school forever. However, during my undergrad studies, I completed an internship at the Bureau of Meteorology with Beth Ebert and found I enjoyed research. I submitted my master's thesis in October, 2018, and am hoping to start my PhD in 2019, at the University of Melbourne, with Andrew King and Todd Lane.

Throughout my master's I've attended multiple workshops, including the annual CLEx workshop in Canberra, 2017. I've also attended a winter school on climate extremes, and short-term courses on using the Australia supercomputer, data visualisation, making posters, and coding skills. These opportunities have helped me make valuable connections with scientists around Australia, and facilitated insightful discussions about my own work, which greatly improved my thesis. The regular opportunities to present my own work have boosted my science communication skills and general confidence.



Enhanced/Reduced Probability of Extreme (>95th Percentile) Daily Rainfall Amount During a Northwest Cloudband Day

The Returned

Developing world-class climate researchers at the previous Centre of Excellence for Climate System Science (ARCCSS) has paid early dividends for the current Centre of Excellence for Climate Extremes (CLEx). Over the course of this year we have welcomed back former ARCCSS PhD students as research associates and Associate Investigators to the new Centre.

They bring with them added experience, a deep understanding of the tools we use, and their own national and international networks.

One of them, Dr Ian Macadam, was recently appointed Knowledge Brokerage Team Leader at CLEx. He returns after working with the NSW Office of Environment and Heritage, the UK Meteorological Office and CSIRO. The networks he has established here and overseas have already yielded advantages in this key position.

Dr Annette Hirsch is another. After completing her PhD she joined the Land-Climate Dynamics group at ETH-Zurich, Switzerland. Her experience at ETH Zurich has allowed her to quickly shift her focus and use our high-resolution climate models with little or no familiarisation period to explore urban processes. This is important work that will have implications for infrastructure resilience and energy use in Australia as our major cities continue to grow in size while experiencing more extreme weather events.

Dr Acacia Pepler, who developed her expertise in east coast lows completing a PhD with ARCCSS, and works with the Bureau of Meteorology, has now joined the Centre of Excellence for Climate Extremes (CLEx) as an Associate Investigator, working in the Extreme Rainfall research program.

These are just a few of the young researchers trained by ARCCSS who are now key personnel in CLEx. But they are not alone. Around a dozen former ARCCSS early career researchers have become associate investigators for the new Centre, working out of multiple national and international climate research groups.

We have also seen three summer scholars with ARCCSS take up master's and honours degrees with the new Centre of Excellence. Six honours students from the previous Centre have also started PhDs with CLEx, and we expect this number to increase in the coming years.

The advantage of two back-to-back Centres of Excellence producing world-leading climate research oughtn't be underestimated. It has already helped our research agenda get rapidly up to speed and set in place a long-term legacy that will put Australian climate research at the forefront of the world for a generation to come.

Around a dozen former ARCCSS early career researchers have become associate investigators for the new Centre, working out of multiple national and international climate research groups.

Media and Communications

Highlights

- A highly successful combined Centres of Excellence media workshop
- Improvement in academic posters as result of design training
- Launch of the WeatheX app
- Launch of research briefs
- New website launched with 277 pages of content
- The creation of the Knowledge Brokerage Team

Introduction

This has been a year of challenges, innovations and some remarkable successes as we strive to build on our key foundations of communications: the development of media/communications resources, and improving our public profile.

Of particular note is the creation of a Knowledge Brokerage Team (KBT). Led by Dr Ian Macadam, the KBT is specifically focused on building relationships with external stakeholders and ensuring the research at the Centre of Excellence for Climate Extremes (CLEx) has increased impact. You can see more detail on this in Dr Macadam's report on page 89.

Over the past year, the single largest challenge has been in the development of our website. This was primarily caused by teething problems with behind-the-scenes structural development and slow server speeds due to unexpectedly high traffic. This last issue was likely the result of a rapid increase in content – particularly research briefs. Most of these issues have now been overcome with the migration to a new server and hosting support.

Another challenge was the result of further changes to the Facebook algorithm that came into force in early 2018. This change aimed to have friends' posts appear in Facebook feeds, and diminished or removed unpaid posts from organisations like ourself. This has impacted all social media managers across the communications industry, with reports of a substantial reduction of around 80% in post shares and consequent web traffic for many organisations. We have been very fortunate that our Facebook page has primarily been used for internal communication. As a result, the drop-off has been minimal, as our followers, which include scientific organisations as well as individuals, continue to share our posts directly with their friends.

That said, Twitter has now superseded Facebook as the means of sharing our work externally and driving web traffic. We have seen good growth in our Twitter feed during 2018, which we expect to accelerate in 2019.

Despite the headwinds mentioned above, we have had some remarkable triumphs in 2018. Namely:

- The new research briefs are being shared widely though peer networks
- The launch of the WeatheX app has seen our first serious move into citizen science with another citizen science project already planned for 2019
- We have had an incredibly successful combined Centres of Excellence media workshop. This was not only the first of its kind but it is now being expanded in early 2019 to include a third ARC Centre of Excellence
- Our academic poster-design workshops are now making their influence felt, as we saw an impressive array of well-designed posters at our recent annual workshop.

We have also continued to find strength in our newsletters

and the CLEx Weekly Update with growth in both mailing lists and further sharing of these updates beyond our immediate networks.

Finally, the employment of a KBT team leader, Dr Ian Macadam, in late 2018 and the creation of a CLEx Outreach Committee is likely to present opportunities for coordinated activities between the Centre's Media Manager, Alvin Stone, and these new points of contact.

CLEx Website

The official CLEx website went live on April 22, 2018. Prior to this we had managed a placeholder website and transferred the content across. Since the migration, our site has seen:

- 11,469 unique users
- 21,744 sessions
- 49,655 page views
- Top 5 countries – Australia (57%), US (15%), India (3.78%), UK (3%), China (1.7%)
- Most popular pages: Landing page (17%), WeatheX (7%).

Extrapolating the current numbers to a full year, we are on track for annual figures of around 15,000 unique users, 29,000 sessions and 50,000 page views.

Since its launch, the website has grown rapidly and now includes 277 pages in total, with 42 of these being research briefs. These research briefs add to the richness of our content. They are designed to be 'plain English' summaries of our research, which means that any visitor to the website, instead of being confronted with a list of papers, can find easily understandable explanations and a link to the work itself. These allow us to make sure every paper can be part of our social media feed in an easily accessible way for the general public, media and our peers.

The website also hosts a page for the new WeatheX app. It has links to download the app, and when there are storm events of significance we post interactive graphics that combine reports from the app with Bureau of Meteorology radar of the events. The app has already captured three storm events that can be found on the website. A recent Sydney storm event that included large hailstones, flooding and damaging winds is also likely to be the subject of research using this data.

Social Media

Our Twitter and Facebook feeds continue to grow steadily. On Twitter we have 772 followers and an above-average engagement rate. More than 450,000 people saw our tweets, with the most popular tweet being about hurricane research, by Associate Investigator, Professor Kevin Walsh. Our audience is evenly balanced between male and female. Facebook has 1159 followers, with the majority aged 25-54. Men make up 53% of our Facebook followers but women interact more.

Towards the end of 2018, we put in place social media administrators at each of our nodes. The aim is to encourage multiple users to engage with our social networks to spread the load, and to ensure that successes in each node can be posted promptly, as they happen. We particularly want to celebrate PhD graduations and individual successes of staff at local levels.

An early career researcher (ECR) social media workshop coordinated by Associate Investigator, Dr Amelie Meyer, at our annual ECR workshop saw a lot of engagement. As a result of this workshop, we may look at expanding our social media presence into Instagram in the coming year.

Media Engagement and Training

In 2018, we saw 253 stories published highlighting the Centre's work. These stories appeared in most major Australian outlets but also saw the Centre and its researchers feature in international media, including Deutsche Welle, New York Post, The New York Times, The Sun (UK), USA Today, International Business Times, The Atlantic, The Washington Post, Toronto Star, Radio Canada, Malay Mail, The Irish Times, The Guardian, Hindustan Times, CBC Canada, BBC and many more.

This is at a time when the media continues to change and relationships have to be re-established with major outlets on a regular basis. Even with all these changes, major media outlets still play a leading role in disseminating our research and triumphs. For this reason we have continued to train our young researchers in interview technique, writing opinion pieces and generally engaging actively with mainstream media outlets.

As part of this process, Alvin initiated a combined Centres of Excellence workshop between CLEx and the ARC Centre of Excellence in Convergent Bio-Nano Science & Technology (CBNC), with his counterpart at CBNS, Ann Meyer. The aim of the workshop was to bring together researchers from vastly different fields. The coordinators took the researchers through practical methods of explaining their research and the preparation process for interviews, writing and media releases. In the afternoon they did practice interviews in front of a camera.

The key to the success of the workshop was the level of engagement. The researchers were genuinely interested in each other's work, and because the cutting-edge science of each Centre was so different, they were full of questions. This meant the participants were forced to simplify their explanations but never considered the process to be 'dumbing it down' for their audience. They also learned, in a very supportive environment, tips and tricks for simplifying and for delivering strong messages to an audience. The post-workshop responses included statements such as this was the best workshop they had ever attended, and many of them used the skills they learned here in real media interviews, with considerable success. In addition, it revealed a number of researchers who are likely to become very useful media performers.

In 2019 we will run another such workshop in Melbourne, this time with three Centres of Excellence, as the Centre of Excellence for Mathematical and Statistical Frontiers has also asked to be involved.

CLEx also continued its academic poster-design workshop for students and ECRs. These workshops aimed to improve poster design and are based around design principles rather than scientific content. There has been considerable interest in these poster workshops, and the website resources derived from them are being used regularly. The change in design approach could be seen at this year's annual workshop and many participants commented on the improved quality of the posters.

In other outreach activity, our Media Manager was a special guest panelist at the Australian Science Communicators Annual Conference, talking about communicating contested science. Alvin also organised and hosted a media panel at the 2018 joint Australian Meteorological and Oceanographic Society (AMOS) and International Conference on Southern Hemisphere Meteorology and Oceanography (ICSHMO), featuring Peter Hannam (The Sydney Morning Herald), Anja Taylor (Catalyst, ABC), Chris Hall (advisor to six NSW ministers) and Jenni Beattie (social media founder of Digital Democracy). In addition, Alvin ran a media workshop for AMOS-ICSHMO participants.

Looking Ahead

In 2019, we move from the solid establishment of our communications foundation to expanding our external reach and internal communications networks.

The research-brief template established in 2018 will be disseminated across the Centre, allowing any researcher to compose a research brief with relative ease. The initial tests with this in 2018 have proved to be very successful, with minimal editing required to place each piece of research on the website.

In terms of outreach, we will aim to increase the use of the WeatheX app and highlight any research that is derived from its reports. We plan to develop relationships with weather-focused Facebook groups to help us spread the word further, because of their high engagement across a wide area.

We will also be looking at strong support for a new outreach activity, Schools Weather and Air Quality, that will engage with schools to measure air quality and meteorological conditions across the Sydney basin.

It is expected the increase in social media administrators at each of our nodes will improve our online activity with little additional effort. If this is the case, we intend to take the opportunity to explore Instagram and the use of this image-based medium to reach a younger audience interested in science.

We are also hopeful that we will see more stability in media outlets that will allow us to increase and deepen existing relationships with mainstream media.

Finally, it is our intention to engage more closely with the KBT Manager to assist in our engagement with key stakeholders, and to explore opportunities generated by the work of the Outreach Committee.

Citizen Science App: WeatheX

Citizen scientists play a role of growing importance in many scientific endeavours. With so many keen weather watchers and storm-chasers in Australia, it was only a matter of time before Australian researchers would engage with this community.

On October 17, 2018, a partnership consisting of the Bureau of Meteorology (BoM), Monash University and the ARC Centre of Excellence for Climate Extremes (CLEx) launched the mobile app, WeatheX. The release of WeatheX allows citizens fascinated by storms to help climate researchers and operational forecasters gain a better understanding of extreme events.

Monash University researchers Dr Joshua Soderholm and Professor Christian Jakob coordinated the app development. Its aim, according to Prof Jakob, is simply to fill in the observational space between our current networks.

“Extreme rainfall events often happen in very localised areas – you can have a downpour in one area and five minutes’ drive away it is still bone dry – so it’s very hard to get useful observations when recording stations are so far apart,” said Prof Jakob.

“If citizen scientists can help us fill these gaps, then we can get more detail of these extreme events and potentially improve our understanding of how they develop, which could improve our prediction of severe weather events and their likely impacts.”

WeatheX takes crowd-sourced observations that are focused on wind, hail, flooding and tornadoes. The information gathered from these citizen scientists then goes through a manual quality-control process and is stored in a database. This database of observations will then be made available to researchers from BoM and other research institutions.

The app is disarmingly simple in its approach. Once it has been downloaded to a mobile device, it takes users of the app through a series of short multiple-choice options to quantify the severity of the weather. The process concludes by allowing users to make a comment and add a photo. It follows the time-honoured principle of making something as easy as possible to encourage timely engagement.

The observational data collected is defined by location down to street but not specific-address level. The app does not access identifying data of the person making the observations, so all submissions are completely anonymous. Identifying features such as number plates and faces are also removed from photos.

Already, the first crowd-sourced observations of storm events have come in. You can find animations combining BoM radar with crowd-sourced reports for the Brisbane storms on Sunday, October 21, (https://climateextremes.org.au/weathex-reports-brisbane-storms-sunday-october-21/) and the Melbourne hail storm on Wednesday, November 7, (https://climateextremes.org.au/weathex-captures-cold-snap-hail-reports-across-melbourne/) on the CLEx website.

According to Dr Soderholm, this simple app could be a genuine boon for researchers of extreme rainfall.

“If enough people download the app and start sending in their observations, then this project could provide a quantum leap forward in documenting and understanding extreme events in Australia,” Dr Soderholm said.

You can view the most recent reports from the WeatheX app and download it from the CLEx website at https://climateextremes.org.au/weathex/.

Knowledge Brokerage Team

A Knowledge Brokerage Team (KBT) was initiated in late 2018 with the appointment of Dr Ian Macadam as team leader. The team will work closely with the Outreach Committee and the Media and Communications Manager at the Centre of Excellence for Climate Extremes (CLEx). The KBT is a key component of delivering the Centre's Strategic Objective 5, Research that engages and has impact. Dr Macadam will be based at the University of New South Wales and an additional team member will be appointed to a joint position with the Monash Climate Change Communication Research Hub in 2019.

The KBT ensures government, the private sector, schools and other stakeholders can use the work of the Centre. It facilitates collaboration between these stakeholders and CLEx researchers and ensures that Centre research is communicated to these stakeholders. Examples of key deliverables are topical briefing notes, data sets that contribute to decision making, and curriculum-aligned resources to support the teaching of climate science in high schools.

In 2018, the KBT began to build and manage partnerships between CLEx and public and private sector stakeholders. The projected formation of the team has been informed by conversations with the National Environmental Science Program Earth Systems and Climate Change hub, the NSW Office of Environment and Heritage, Risk Frontiers and the Managing Climate Variability Program.

Conversations continue with these stakeholders to develop an understanding of their needs for information about climate extremes. The aim of this dialogue is to identify problems where the expertise of the Centre of Excellence can be brought to bear. The KBT is already planning workshops to promote collaboration between CLEx and the NSW Office of Environment and Heritage, and to consult potential stakeholders on the further development of the Centre's WeatheX mobile phone app.

In 2019, the KBT will start mapping existing high school teaching resources related to climate science to the requirements of high school science curriculums, with the aim of identifying opportunities for the Centre to build on existing resources to better meet the needs of teachers. It is anticipated this will involve working closely with teachers and education authorities.

Publications

Open Access

The ARC Centre of Excellence for Climate Extremes is committed to taking all practicable steps to ensure our published research is made available through online open access channels within 12 months of publication, or as soon as publishers' copyright allows thereafter. The default position of a number of the top journals in our field is to make publications open access from the date of publication or at the 12-month mark. Additionally each of our five institutions maintains an open access repository and our researchers are routinely reminded to comply with institutional processes to ensure suitable versions of their work are deposited in a timely manner

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Prizes, Outreach and Engagement

Prizes, Awards, Nominations

Alexander, L. World Meteorological Organisation Commission for Climatology Outstanding Service Award

Arblaster, J. Clarivate Analytics highly cited list

Bao, J. 2018 CLEx prize for best paper by a student

Bony, S. 2018 CNRS Silver Medal for research

Cooper, N. Clean Air Society of Australia and New Zealand Student Air and Environment award

De Kauwe, M. 2018 CLEx Director's Prize for outstanding contributions to the Centre

England, M. Tinker-Muse Prize for Science and Policy in Antarctica

Farquhar, G. Senior Australian of the Year, 2018

Fiddes, S. Runner up, earth sciences section of The Royal Society of Victoria's Young Scientist Research Prize

Gillett, Z. Australian Meteorological and Oceanographic Regional Centre Award for excellence in undergraduate study

Goyal, R. Indian Institute of Technology Bhubaneswar's (IITBBS) Gold Medal for outstanding results. The medal was presented by the President of India

Gross, M. Best poster at the 8th international GEWEX conference

Hendon, H. Named by *The Australian* as the Australian leader in atmospheric science

Hobeichi, S. CCRC Prize for best PGR talk

Jakob, C. 2018 AMOS Morton Medal

King, A. 2018 AMOS Science Outreach Award

Lane, T. Elected as a Fellow of AMOS

McDougall, T. Companion of the order of Australia.

McDougall, T. Fellow, American Geophysical Union

Morrison, A. 2018 AMOS Meyers Medal

Pitman, A. Eureka prize finalist in the category 'Leadership in Innovation and Science'

Raavi, P. John and Allan Gilmour Research Award 2018, School of Earth Sciences, University of Melbourne

Stephens, G. Nominated Fellow of the Royal Society

Stephens, G. The Royal Meteorological Society's Mason Gold Medal

Ukkola, A. 2018 CLEx prize for best paper by an ECR

Vreugdenhil, C. AMOS Uwe Radok Award for best PhD thesis

Engagement with Government, Industry, NGOs and Professional Bodies

Alexander, L. Overview of CLEX extreme rainfall RP activities presented to the Office of Naval Research (ONR) Commander Joe Martin

Evans, J. Briefing to Central Coast Council on "Climate Science and the Central Coast Context"

Henley, B. Advice and presentation to a large Australian Agribusiness, Kilter Rural. The company manages large agricultural assets in Victoria. They are interested in better understanding climate variability and change on inter-annual to decadal timescales.

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Lane, T. Attended NSW OEH NSW Extreme Climate Events Scoping Workshop as a Subject Matter Expert

Lane, T. Visit Australian Department of Environment and Energy for workshop on summary for policy makers.

Macadam, I. Attended "Climate Science in Industry: Governance, Standards and Accessibility" event at USyd

Macadam, I. Visit to Risk Frontiers

Macadam, I. Attended "Climate Science in Industry: Governance, Standards and Accessibility" event at USyd

Perkins, S. Understanding extremes briefing to parliamentary secretaries

Pitman, A. Evidence to the Federal Senate inquiry into research funding

Pitman, A. Authored primer paper on climate extremes to be distributed within Department of Environment

Pitman, A. Gave evidence in the Murray Darling Basin Royal Commission, Adelaide SA, 21 Sept 2018

Pitman, A. Antarctic Science Foundation Reception November 27th

Pitman, A. Briefing to APRA on climate risk and financial resilience

Pitman, A. Visit to Partner Org Sydney Water to brief them on climate risk associated with climate change

Pitman, A. Visit to Partner Org Sydney Water to brief them on climate risk associated with climate change

Schofield, R. Invited speaker at PLANET 2018 - Emerging issues in Urban Planning hosted by Planning Institute Australia

Schofield, R. Invited speaker at PLANET 2018 - Emerging issues in Urban Planning hosted by Planning Institute Australia

Sherwood, S. Invited keynote talk to the NSW Environmental and Planning Law Association annual meeting

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Public Talks and Community Engagement

Abram, N. Scientific expert in the play: *The Poets Guide to Science*. Run at Smiths Alternative Bookshop, Canberra during National Science Week

Abram, N. Profile piece in Cosmos magazine, *Cold green life: the climate scientist balancing Antarctic research and sustainable living*

Abram, N. Lecture to adult students at ANU Climate Change Institute "Australia's changing climate from the perspective of the last millennium"

Abram, N. Public talk at the Australian National Botanical Gardens, "Australia's changing climate from the perspective of the last millennium"

Alexander, L. AMOS presentation on international engagement

Dommenget, D. High school students project week with the Monash Simple Climate Model

Dommenget, D. GTAV Conference field equipment & teacher: Professional development for teachers using the Monash Simple Climate Model

Dommenget, D. Interview with the "Schüler-Klimagipfels" (High school students climate conference) in Germany.

England, M. Science Exchange, Adelaide. Coasts and conflicts: threats of climate change to the marine environment

Gergis, J. Book launch of *Sunburnt Country*

Gergis, J. State Library NSW author talk

Gergis, J. ANU event - Climate Change Institute Public Symposium

Gergis, J. National Library of Australia author talk

Gergis, J. QGCI/AMOS event including book talk and audience questions

Gergis, J. Chermside Library author talk presented as part of Lord Mayor's Writers in Residence series

Gergis, J. Panel discussion. "Cracking Climate by Cracking Consumption". Blue Mountains Cultural Centre

Gergis, J. Sydney Writers Festival panel: "Climate Change: A Hastening to Catastrophe"

Gergis, J. Euroa Environment Series for Strathbogie Voices

Gergis, J. Byron Bay Writers Festival, panel discussion, "The Anthropocene: Human Survival in the New Epoch"

Henley, B. Interviewed by a journalism student about climate variability and drought.

Jakob, C. Talk on climate change to the University of the 3rd Age (U3A) Surfcoast Shire group

Lane, T. Interview with 2 high school students (MacRobertson's Girls High School) about clouds

Macadam, I. Presentation "The IPCC Report on Global Warming of 1.5°C" at UNSW Climate Change Network Launch

Martinez Moreno, J. National Science Week talk "What are we forgetting about Climate Change?"

Meyer, A. Collaborating with Mary Finsterer (Australian Music composer and adjunct professor at UTAS) on an opera she is writing to be released and performed in Australia and overseas in 2019. She is incorporating science in to the music with the help of a handful of scientists.

Perkins, S. AMOS 1.5C report public event

Pitman, A. Probus Club of Wahroonga "Climate science, climate change, climate impacts"

Pitman, A. Politics in the Pub. "Impacts of climate change on government, business and the public"

Pitman, A. Presentation at the Climate Science and Industry Discussion and round table at Sydney University

Schofield, R. Springer *Nature Sustainability* launch panel speaker

Schofield, R. Spoke to group of year 9 students from Footscray City College on Air Quality and environmental sustainability

Strutton, P. Presented careers-focussed talks to high school students interested in Antarctica.

Intergovernmental Panel on Climate Change, AR6 Working Group 1

Abram, N. Coordinating Lead Author IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, Ch1

Bindoff, N. Coordinating Lead Author of IPCC Special Report on the Ocean and Cryosphere in a Changing Climate , Ch5

Di Luca, A. Lead Author, Chapter 11

Domingues, C. Lead Author, Chapter 2

Gergis, J. Lead Author, Chapter 8

Henley, B. Contributing author to the IPCC's Working Group 1 AR6 chapter 3

Karoly, D. Review Editor for IPCC Working Group 1 AR6 report

Lewis, S. Lead Author, Chapter 11

Marsland, S. Lead Author, Chapter 9

McGregor, S. Lead Author, Chapter 3

Seneviratne, S. Coordinating Lead Author, Chapter 11

Scientific and Advisory Committee Memberships

Abram, N. Member, National Committee for Earth System Science

Abram, N. Member, National Committee for Antarctic Research

Abram, N. ANU Climate Change Institute advisory board member

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

Abram, N. Member, CLIVAR water isotopes working group

Abram, N. PAGES (Past Global Changes) 2k network: member of scientific co-ordination team

Abram, N. Co-lead, PAGES (Past Global Changes) Coral Hydro2k working group

Arblaster, J. Member, National Climate Science Advisory Committee

Arblaster, J. Member, National Committee for Earth System Science

Arblaster, J. Author, Chapter 5, 2018 WMO/UNEP Scientific Assessment on Ozone Depletion

Bishop, C. Organiser and co-chair of the World Meteorological Organization's Working Group on Predictability, Dynamics and Ensemble Forecasting.

Fiddes, S. Secretary, Australian Meteorological and Oceanographic Society

Gergis, J. Member, Australian Climate Council

Goldie, J. Member, AMOS ACT Committee

Green, D. Member, expert advisory panel for the Climate and Health Alliance

Jakob, C. Member, Technical Committee of the Managing Climate Variability Program

Jakob, C. Scientific Steering Committee of the Numerical Weather Prediction Centre of the Chinese Meteorological Administration

Jakob, C. Member, GEWEX Scientific Steering Group

Karoly, D. Member, Scientific Steering Committee, WMO/UNEP Scientific Assessment of Ozone Depletion 2018

Karoly, D. Member, External Advisory Board, European Prototype demonstrator for the Harmonisation and Evaluation of Methodologies for attribution of extreme weather Events (EUPHEME) project.

Lane, T. Advisory Board, Journal of Southern Hemisphere Earth Systems Science

Lane, T. National Councilor and Immediate Past President of the Australian Meteorological and Oceanographic Society

Lane, T. Council of the International Forum of Meteorological Societies

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

Meissner, K. Member, PAGES Board

Perkins-Kirkpatrick, S. Co leader of expert team 4.4 of the WMO commission for climatology.

Phillips, H. Chair, Tasmanian Regional Centre of the Australian Meteorological and Oceanographic Society (AMOS)

Pitman, A. Member, National Committee for Earth System Science

Pitman, A. Member, Monash Foundation Scholarships committee

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

Santoso, A. CSHOR steering committee, member

Schofield, R. Chair, AMOS expert group on atmospheric and oceanic composition

Schofield, R. Lead of the Environment and Energy Resources program of the Melbourne Energy Institute, and member of the Melbourne Energy Institute executive committee

Schofield, R. Member, IGAC Southern Hemisphere working group

Schofield, R. Member, International Ozone Commission

Sen Gupta, A. Member, National Committee for Earth System Science

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

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

Editorships

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

Bishop, C. Editor, *Quarterly Journal of the Royal Meteorological Society*

Dommenget, D. Associate Editor, *Journal of Climate*

Evans, J. Editor, *Journal of Climate*

Hogg, A. Editor, *Geophysical Research Letters*

Jakob, C. Associate Editor, *Journal of Climate*

Lane, T. Editor, *Monthly Weather Review*

Meehl, G. Associate Editor, *Journal of Climate*

Meissner, K. Editorial board member, *Environmental Research Letters*

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

Perkins, S. Editor, *Scientific Reports*

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

Schofield, R. *Atmosphere* special issue: *Air Quality in New South Wales, Australia*, guest editor

Schofield, R. Associate editor, *Journal of Southern Hemisphere Earth System Science*

2018 Key Performance Indicators

Performance Measure	Reporting interval	Target 2018	Achieved 2018
Number of research outputs	Annually		
Journal articles		20	65
Book chapters		3	0
Software modules published		2	1
Data sets published,		2	9
Facebook posts		52	154
Centre website updates		25	>100
Science explainer videos		2	0 (1)
Quality of research outputs	Annually		
Percentage of publications in journals with impact factors greater than 2.0		80	93.9%
Percentage of publications in journals with impact factors greater than 4.0		60	60.0%
Number of papers in journals with impact factors greater than 10		4	13.8%
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	Weekly
Science fundamentals workshops		1	4
Leadership and professional development workshops		1	3
Communications/writing workshops		1	3
Number of centre-wide virtual lectures/seminars		5	11
Percentage of students/ECRs attending researcher development activities		90%	87%
Number of workshops/conferences held/offered by the Centre	Annually		
National workshop		1	1
International conference/workshop		1	1
Topical/Research Program workshops		3	3
Number of additional researchers working on Centre research	Annually		
Postdoctoral researchers		14	13
Honours students		10	8
HDR students		20	31
Associate Investigators		26	29
Graduate Student Training	Annually		
Number of PhD completions		0	0
Number of Masters by Research completions		0	1
Number of Honours student completions		10	18
Percentage completing PhD students submitting within 4 years (FTE)		-	
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 apersonalised 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

Performance Measure	Reporting interval	Target 2018	Achieved 2018
Number of presentations/briefings	Annually		
To the public		10	26
To government		10	7
To industry/business/end-users		5	6
To non-government organisations		5	1
To professional organisations and bodies		5	4
Number of new organisations collaborating with, or involved in, the Centre	Annually	1	1

Additional CLEx-specific Performance Measures	Reporting Frequency	Target 2018	Achieved 2018
Equity and Diversity Initiatives	Annually		
Percentage of female graduate students		50%	46%
Percentage of female research fellows		50%	53%
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%	57%
Computational Modelling Support	Annually		
New/refined/enhanced software modules for the climate models developed and served to the community.		2	2
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	20
Monthly bulletin to all researchers on CMS-related updates		12	6
Explainer videos on key CMS issues		4	7
Percentage of students with cross node and/or partner organisation supervision	Annually	60 %	33%
Percentage of students/ECRs making a research visit to other nodes and/or Australian partner organisations	Annually	55%	26%
Student / ECR internships in industry/government		1	1
Percentage of students/ECRs making a research visit to international partner organisations or organisation with a collaborative relationship	Annually	30%	8%
Number of undergraduate summer scholarships offered	Annually	15	17
Regular Research Program videoconference meetings p/a	Annually	10	62

Additional CLEx-specific Performance Measures	Reporting Frequency	Target 2018	Achieved 2018
Media KPIs	Annually		
Media Releases		10	10
Website – Unique Hits		20,000	~15,000 (3)
Website – Page Views		30000	49,655
Stories in media		200	254
Social Media – Twitter (followers)		100	843
Social Media – Facebook (followers)		100	1,168
Knowledge Brokerage Team	Annually and at mid-term review		
Establishment of significant partnerships		1	Ongoing (4)
Data sets provided to stakeholders		1	0
Strategic advice provided to stakeholder		1	1
Demonstrated examples of model improvements available for use in national modelling systems	Annually and at mid-term review	2	2 (5)

Footnotes

1: We didn't produce any 'explainer' videos in 2018, however 20 accessible lectures were added to our on our youtube channel in 2018

2: Total number includes 2017 enrolled students submitting in 2018

3: Due to a change in web hosting during 2018 precise metrics are unavailable. This is a conservative estimate based on available data

4: Our Knowledge Brokerage Team Leader was appointed in the second half of 2018. He has been building relationships with select groups. Similarly the Director and senior CIs maintain dialogue with local, state and federal government and industry groups

5: Enhancements made to CABLE to improve groundwater modelling. Harmonization of code versions between ACCESS-CM2 and ACCESS-OM2.

Financial Statement

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 2018, CLEx received $6,143,064 (101%) income compared to the full-year budget of $6,102,502. In terms of the Centre's expenditure, $3,287,093 (68%) was spent compared to the full-year budget of $4,860,918. This was due to the late commencement start date and delays in personnel appointments.

In 2018, personnel accounted for the highest proportion of expenditure of $2,445,818 (74%), followed by travel expenditure of $416,183 (13%). Overall, the Centre's cash balance in 2018 is $2,855,971.

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 Board meetings.

The Centre meets its reporting requirements to the ARC by submitting the annual Centre Outputs and Detailed Income and Expenditure report. The Centre also meets all other reporting obligations set by Partner Organisations that provide financial support.

2018 Income

Cash income totalled $6,143,064 from all sources. The Centre derived its income from the ARC, participating universities, the Bureau of Meteorology (BoM), the NSW Office of Environment and Heritage (OEH), the NSW Department of Industry Research Attraction and Acceleration Program (RAAP) and the Sydney Water Corporation. Income is summarised by source in detail in the tables that follow.

1: Australian Research Council Funding

The Centre received indexed income from the ARC of $4,378,456. This was distributed to the institutions in accordance with 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 $20,000 in year two of the Centre's operations. This cash contribution was targeted at PhD top-up scholarships for students working collaboratively with BoM.

2.2 NSW Office of Environment and Heritage

The cash investment from OEH 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 2018.

2.3 NSW Department of Industry RAAP

RAAP funding is invested in appointing a Research Fellow to focus on high resolution modelling of processes relating to climate extremes (e.g. hail, drought processes, vegetation-climate extremes etc.). The Centre received $143,000 in 2018.

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 will be $200,000. This year the Centre received $200,000.

3: Collaborating Organisation Funding

Cash contributions to the Centre of Excellence from the Administering Organisation and the Collaborating Organisations amounted to $1,285,737, as follows:

$522,895	UNSW
$212,502	ANU
$158,947	University of Melbourne
$144,586	University of Tasmania
$246,807	Monash University

4: In-kind Contributions

In-kind support totalled $6,752,168 in 2018. The Centre is grateful for $4,538,839 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 $2,213,329. Again, this was mainly personnel time. The actual in-kind was lower than budgeted, due to the Centre's late employment appointments.

Organisation	In Kind Budget $	In Kind Actual $
ANU	813,599	769,778
BOM	137,102	137,102
CSIRO	317,000	324,983
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	842,317	857,218
NASA Goddard Space Flight Centre	39,436	39,436
NCAR	105,927	105,927
NCI	858,700	858,700
NOAA	30,000	30,000
OEH	312,785	312,785
Risk Frontiers Grp	42,000	42,000
Swiss Federal Inst of Tech	80,580	80,580
UMEL	804,496	646,825
University of Arizona, USA	49,089	73,416
UNSW	1,789,280	1,682,322
UTAS	507,252	582,696
TOTAL	6,937,962	6,752,168

2018 Leverage

The Centre's 2018 cash income of $6,143,064 and in-kind support of $6,752,168 total $12,895,232, with ARC funding accounting for $4,378,456 of the total income. The Centre's leverage of $8,516,776 equates to $1.95 of external funding and in-kind contributions for each $1.00 received from the ARC.

2018 Expenditure

In 2018 the Centre expended $3,287,093, analysed below:

Personnel (including on-costs)	$2,445,818	74%
Scholarships	$161,815	5%
Equipment and Maintenance	$54,077	2%
Consumables and Events	$209,200	6%
Travel	$416,183	13%

2018 Income Vs Expenditure

Income and Expenditure is based on cash and is derived from the institutions' general ledgers. The Collaborating Organisations certify income and expenditure by formally acquitting all grants as at 31 December, 2018.

The Centre's cash expenditure of $3,287,093 was below income of $6,143,064 by $2,855,971.

The Centre will carry over a balance of $2,855,971 to 2019. The carry-over by institution is as follows:

University of New South Wales	$1,524,585	surplus
Australian National University	$128,517	surplus
University of Melbourne	$355,020	surplus
University of Tasmania	$352,192	surplus
Monash University	$495,655	surplus

In summary, as at 31 December, 2018, the financial position for the life of CLEx after its second year of operation is as follows:

Total Cash Income	$6,143,064
Total Expenditure	$3,287,093
Surplus carried forward to 2019	**$2,855,971**

COECX Cash Income & Expenditure

	Actual		Budget/ Forecast						
1. Cash Income	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**TOTAL**
Australian Research Council- Centre of Excellence	4,350,000	4,250,000	4,250,000	4,300,000	4,300,000	4,300,000	4,300,000	0	30,049,999
Australian Research Council- Centres of Excellence Indexation	65,250	128,456	0	0	0	0	0	0	93,706
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	1,243,798	1,236,879	1,227,652	1,227,635	1,227,635	0	8,552,478
Other (Interest Distribution)	0	15,871	0	0	0	0	0	0	15,871
Sydney Water Corporation	0	200,000	0	0	0	0	0	0	
Total	5,771,392	6,143,064	5,766,655	5,809,736	5,800,509	5,790,492	5,790,492	0	40,872,340
2. ARC Expenditure	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**TOTAL**
Personnel	114,662	1,941,921	3,312,905	3,474,549	3,570,326	3,630,729	3,747,004	3,997,345	23,789,442
Scholarship	6,358	90,723	252,783	252,783	252,783	252,783	252,783	234,599	1,595,594
Equipment and Maintenance	0	5,105	152,000	40,000	15,000	15,000	15,000	15,000	257,105
Consumables and Events	16,369	165,632	223,686	175,954	182,965	181,372	180,048	175,799	1,301,826
Travel - Conference, workshops and meetings (Staff, AI)	12,634	133,395	326,459	325,959	325,929	325,529	326,459	316,279	2,092,641
Travel - Conference, workshops and meetings (Postdocs and Students)	0	40,497	131,777	131,777	131,777	131,777	131,777	147,433	846,814
Travel - Visitor travel to the Centre and other	1,336	38,236	25,894	25,894	25,894	25,894	25,894	20,000	189,044
Travel - New staff relocation expenses	0	0	0	0	0	0	0	0	-
Travel - Research Visits (Staff, AI)	0	9,585	10,715	10,715	10,715	10,715	10,715	10,000	73,159
Travel - Research Visits (Postdocs and Students)	1,341	380	16,072	16,072	16,072	16,072	16,072	16,000	98,082
Total	152,701	2,425,476	4,452,290	4,453,703	4,531,460	4,589,870	4,705,751	4,932,454	30,243,706
3. Nodes Expenditure	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**TOTAL**
Personnel	65	311,556	611,935	543,273	481,670	487,829	567,645	620,500	3,624,473
Scholarship	10,706	61,092	363,970	347,264	416,116	420,771	420,771	415,586	2,456,275
Equipment and Maintenance	6,182	48,972	21,343	35,853	27,353	27,353	20,853	11,298	199,210
Consumables and Events	4,575	43,568	14,685	18,121	18,068	23,469	23,345	4,555	150,384
Travel - Conference, workshops and meetings (Staff, AI)	12,901	49,055	162,226	162,226	177,871	177,871	177,871	138,584	1,058,607
Travel - Conference, workshops and meetings (Postdocs and Students)	2,969	60,341	96,576	90,576	101,074	106,074	95,074	48,276	600,960
Travel - Visitor travel to the Centre and other	0	9,570	19,377	20,106	24,467	24,467	20,106	10,000	128,093
Travel - New staff relocation expenses	7,354	55,163	0	20,000	16,000	6,000	0	10,000	114,517
Travel - Research Visits (Staff, AI)	5,132	8,979	29,000	29,000	29,000	29,000	29,000	0	159,111
Travel - Research Visits (Postdocs and Students)	0	10,981	9,000	9,000	9,000	9,000	9,000	4,868	60,849
Total	49,885	659,276	1,328,113	1,275,418	1,300,619	1,311,835	1,363,666	1,263,667	8,552,478
4. Others	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**TOTAL**
Personnel	61,192	192,341	376,671	242,857	242,857	242,857	242,857	324,524	1,926,156
Scholarship	0	10,000	30,000	30,000	30,000	20,000	20,000	10,000	150,000
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	0	0	0	0	0	0	-
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	406,671	272,857	272,857	262,857	262,857	334,524	2,076,156
5. Summary Income Vs. Expenditure / Carry Over	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**TOTAL**
ARC									
Total Income	4,415,250	4,378,456	4,250,000	4,300,000	4,300,000	4,300,000	4,300,000	0	30,243,705
Total Expenditure	152,701	2,425,476	4,452,290	4,453,703	4,531,460	4,589,870	4,705,751	4,932,454	30,243,706
Income less Expenditure	4,262,549	1,952,980	-202,290	-153,703	-231,460	-289,870	-405,751	-4,932,454	0
Nodes									
Total Income	1,103,142	1,285,737	1,243,798	1,236,879	1,227,652	1,227,635	1,227,635	0	8,552,478
Total Expenditure	49,885	659,276	1,328,113	1,275,418	1,300,619	1,311,835	1,363,666	1,263,667	8,552,478
Income less Expenditure	1,053,257	626,461	-84,315	-38,539	-72,967	-84,200	-136,030	-1,263,667	0
Other									
Total Income	253,000	478,871	272,857	272,857	272,857	262,857	262,857	0	2,076,156
Total Expenditure	61,192	202,341	406,671	272,857	272,857	262,857	262,857	334,524	2,076,156
Income less Expenditure	191,808	276,530	-133,814	0	0	0	0	-334,524	0
Carry over surplus / deficit	**5,507,614**	**2,855,971**	**-420,420**	**-192,242**	**-304,427**	**-374,070**	**-541,782**	**-6,530,646**	**-1**

2018 Cash Income & Expenditure

1. Cash Income	UNSW	ANU	U.Mel	U.Tas	Monash Uni	Total $	FY Budget
Australian Research Council- Centre of Excellence	1,705,379	544,916	548,321	538,105	913,276	4,250,000	4,250,000
Australian Research Council- Centres of Excellence Indexation	128,456	0		0	0	128,456	128,456
Bureau of Meteorology	20,000	0		0	0	20,000	20,000
NSW Office of Environment and Heritage	100,000	0		0	0	100,000	100,000
NSW Department of Industry/ RAAP	143,000	0		0	0	143,000	143,000
University Node Cash Contributions	522,895	212,502	158,947	144,586	246,807	1,285,737	1,245,175
Other (Interest Distribution)	15,871	0	0	0	0	15,871	15,871
Sydney Water Corporation	200,000	0	0	0	0	200,000	200,000
Total	2,835,601	757,418	707,268	682,691	1,160,083	6,143,064	6,102,502
2. ARC Expenditure	**UNSW**	**ANU**	**U.Mel**	**U.Tas**	**Monash Uni**	**Total $**	**FY Budget**
Personnel	613,630	413,844	205,510	194,646	514,291	1,941,921	2,396,576
Scholarship	1,000	36,903	16,053	15,667	21,100	90,723	248,713
Equipment and Maintenance	5,105	0	0	0	0	5,105	108,000
Consumables and Events	96,276	14,048	20,817	15,029	19,463	165,632	263,350
Travel - Conference, workshops and meetings (Staff, AI)	42,608	36,689	29,039	6,590	18,470	133,395	286,888
Travel - Conference, workshops and meetings (Postdocs and Students)	15,918	0	239	458	23,882	40,497	74,777
Travel - Visitor travel to the Centre and other	15,204	10,660	8,989	3,081	302	38,236	101,888
Travel - New staff relocation expenses	0	0	0	0	0	0	0
Travel - Research Visits (Staff, AI)	1,285	5,051	3,250	0	0	9,585	46,844
Travel - Research Visits (Postdocs and Students)	380	0	0	0	0	380	32,144
Total	791,405	517,194	283,898	235,471	597,507	2,425,476	3,559,179
3. Nodes Expenditure	**UNSW**	**ANU**	**U.Mel**	**U.Tas**	**Monash Uni**	**Total $**	**FY Budget**
Personnel	178,637	37,376	39,153	479	55,910	311,556	314,971
Scholarship	18,994	22,213	0	19,885	0	61,092	285,140
Equipment and Maintenance	6,245	12,659	12,691	15,103	2,274	48,972	46,853
Consumables and Events	31,355	1,915	1,426	7,241	1,631	43,568	33,723
Travel - Conference, workshops and meetings (Staff, AI)	37,235	138	1,888	5,291	4,504	49,055	162,657
Travel - Conference, workshops and meetings (Postdocs and Students)	16,932	17,110	9,033	15,474	1,793	60,341	149,576
Travel - Visitor travel to the Centre and other	7,702	526	533	0	809	9,570	24,769
Travel - New staff relocation expenses	10,806	9,710	3,627	31,019	0	55,163	46,007
Travel - Research Visits (Staff, AI)	8,443	0	0	536	0	8,979	15,000
Travel - Research Visits (Postdocs and Students)	921	10,060	0	0	0	10,981	20,700
Total	317,270	111,707	68,350	95,028	66,921	659,276	1,099,397
4. Partner Organisations	**UNSW**	**ANU**	**U.Mel**	**U.Tas**	**Monash Uni**	**Total $**	**FY Budget**
Personnel	192,341	0	0	0	0	192,341	192,341
Scholarship	10,000	0	0	0	0	10,000	10,000
Equipment and Maintenance	0	0	0	0	0	0	0
Consumables and Events	0	0	0	0	0	0	0
Travel - Conference, workshops and meetings (Staff, AI)	0	0	0	0	0	0	0
Travel - Conference, workshops and meetings (Postdocs and Students)	0	0	0	0	0	0	0
Travel - Visitor travel to the Centre and other	0	0	0	0	0	0	0
Travel - New staff relocation expenses	0	0	0	0	0	0	0
Travel - Research Visits (Staff, AI)	0	0	0	0	0	0	0
Travel - Research Visits (Postdocs and Students)	0	0	0	0	0	0	0
Total	202,341	0	0	0	0	202,341	202,341
5. Summary Income Vs. Expenditure / Carry Over	**UNSW**	**ANU**	**U.Mel**	**U.Tas**	**Monash Uni**	**Total $**	**FY Budget**
ARC							
Total Income	1,833,835	544,916	548,321	538,105	913,276	4,378,456	4,378,456
Total Expenditure	791,405	517,194	283,898	235,471	597,507	2,425,476	3,559,179
Income less Expenditure	1,042,430	27,722	264,423	302,634	315,770	1,952,980	819,277
Nodes							
Total Income	522,895	212,502	158,947	144,586	246,807	1,285,737	1,245,175
Total Expenditure	317,270	111,707	68,350	95,028	66,921	659,276	1,099,397
Income less Expenditure	205,625	100,795	90,597	49,558	179,886	626,461	145,778
Partner Organisations							
Total Income	478,871	0	0	0	0	478,871	478,871
Total Expenditure	202,341	0	0	0	0	202,341	202,341
Income less Expenditure	276,530	0	0	0	0	276,530	276,530
Carry over surplus / deficit	**1,524,585**	**128,517**	**355,020**	**352,192**	**495,655**	**2,855,971**	**1,241,584**

Australian Government
Australian Research Council

UNSW SYDNEY

Australian National University

UNIVERSITY of TASMANIA

MONASH University

THE UNIVERSITY OF MELBOURNE