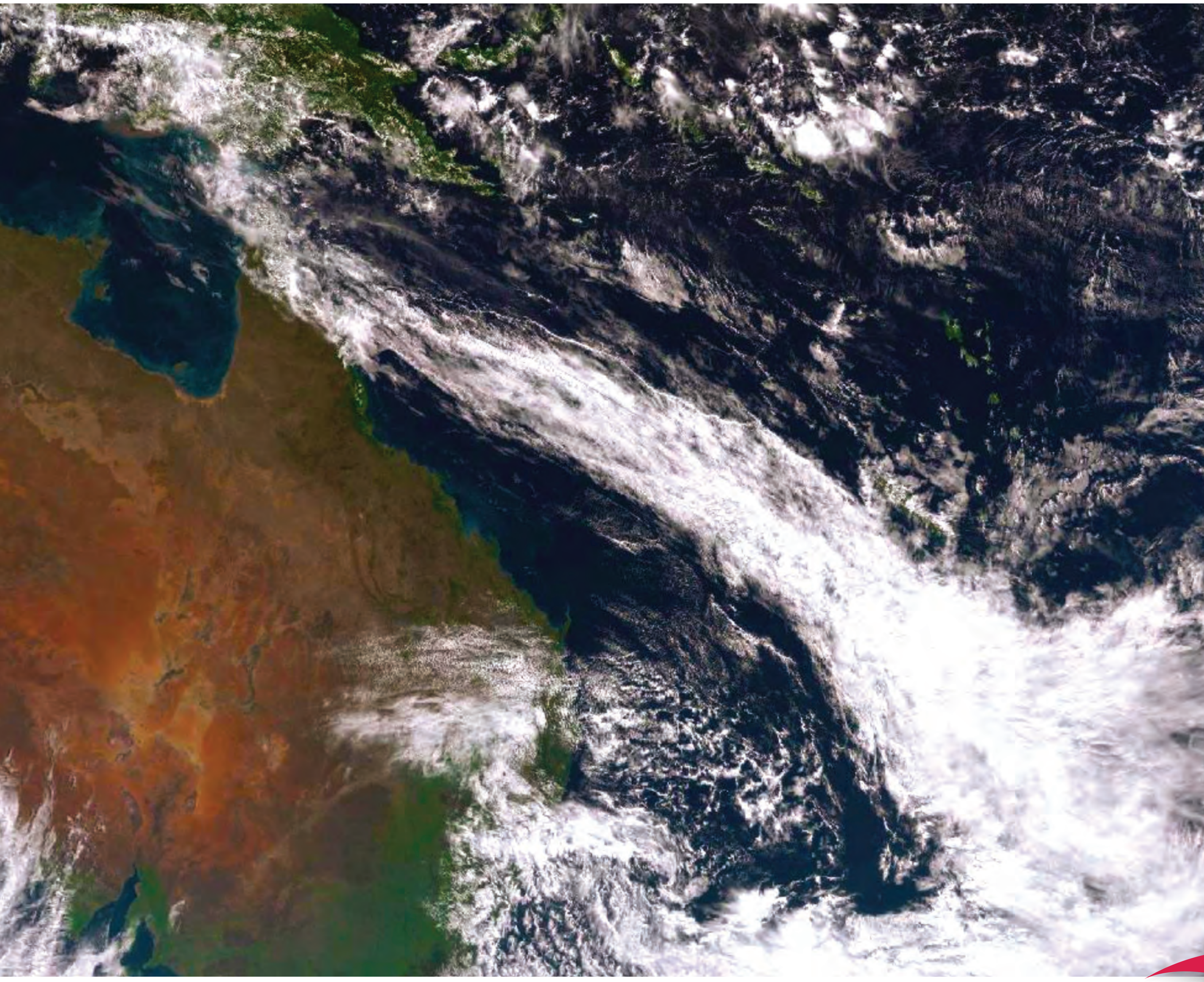
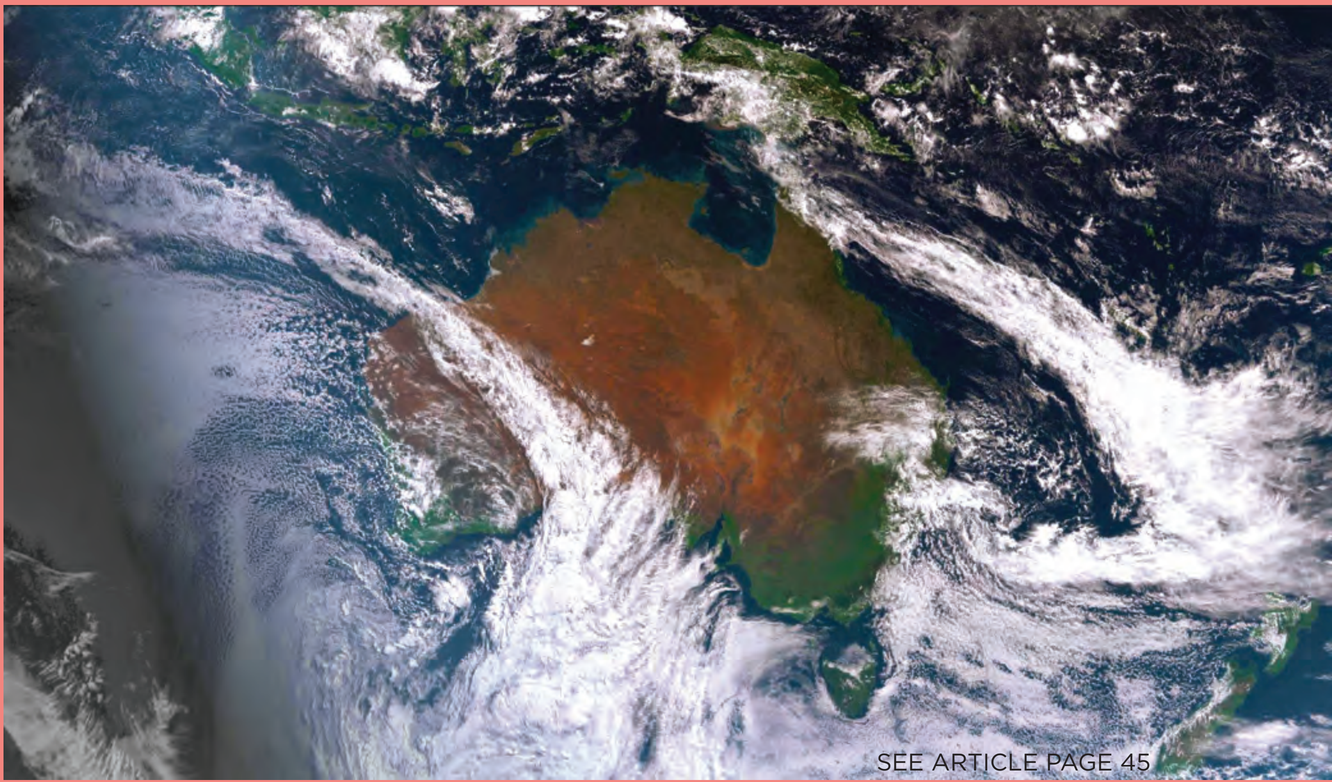
climate extremes
ARC centre of excellence



Report 2020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Centre of Excellence for Climate Extremes Annual Report 2021

The ARC Centre of Excellence for Climate Exremes is financially supported via a grant from the Australian Research Council 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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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.

PREETHI PAUL

Aims and Objectives

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

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

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

World-Class Research

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

An Outstanding Environment

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

Exceptional Infrastructure

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

Transformative Collaboration

We strive to achieve a rich national collaborative environment as a foundation for our research, and we 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 provides 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

The ARC Centre of Excellence for Climate Extremes (CLEX) is primarily funded by the Australian Research Council (ARC). We operate across five Australian universities and a suite of outstanding national and international Partner Organisations. The establishment of the Centre of Excellence – 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 directly affecting Australian natural and economic systems. With this increased evidence-based understanding as our foundation, the Centre will improve the 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 established industry partnerships: 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. To this, in 2020, we added Sydney Water. We have also partnered with the Bush Fire and Natural Hazard Cooperative Research Centre, the Indian Institute of Meteorology, the Monash Climate Change Communication Research Hub and TROP-ICSU (Trans-disciplinary Research Oriented Pedagogy for Improving Climate Studies and Understanding project).

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

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

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

STEVE SHERWOOD

From the Chair of the Advisory Board

It goes without saying that 2020 was a year that presented many unanticipated challenges. Bushfires, drought, the Covid-19 pandemic – along with associated lockdowns and disruptive restructuring on Australian university campuses – formed the backdrop to the year that was. Despite this confluence of external difficulties, the Australian Research Council's (ARC) Centre of Excellence for Climate Extremes (CLEX) set a course through the storm and continued to undertake transformative research.

Centre researchers published over 240 papers in 2020, which would be an extraordinary achievement even in a 'normal' year. As always, the vast majority of these papers appeared in top journals, attesting to the quality of the Centre's research as well as the sheer volume. Many highlights of that research were showcased at the virtual annual workshop in November.

While an online event can't harness all the benefits of a face-to-face meeting, by all accounts this was a highly successful example of what's possible with the creative adoption of innovative technologies.

In October I was honoured to join with other members of the Advisory Board and a range of CLEX stakeholders to participate in the ARC's formal mid-term review of the Centre. I thank all who were involved in the review process and look forward to the panel's report being tabled at an upcoming Advisory Board meeting. Discussions during the review process were positive and encouraging regarding the Centre's research outputs, impacts on the wider climate science community and on the robustness of CLEX's operations and cohesiveness as a community of scholars.

This foundation of cohesiveness and sense of community undoubtedly supported the Centre of Excellence through 2020. The Centre leadership, especially Andy Pitman, Melissa Hart, Todd Lane and Stephen Gray, worked tirelessly to minimise the inevitable disruptions of transitioning to remote work. They also displayed innovation and unwavering commitment in providing practical and moral support to every member of the CLEX community, from brand new students to senior Chief Investigators.

On behalf of the Advisory Board I commend the Centre on its resilience and success throughout 2020 and wish the Centre well for a less challenging 2021. ■

Dr Tony Press
Chair, CLEx Advisory Board

Director's Report, 2020

To state the obvious, 2020 was a tough year for everyone at the ARC Centre of Excellence for Climate Extremes (CLEX). It was extremely hard on individual students whose PhDs and Masters degrees were disrupted. It was equally tough on research fellows in the Centre, many of whom became isolated from friends and families. The Chief Investigators struggled with isolation and trying to support their students and research fellows. The CLEX administrative team, our media team, our Knowledge Brokers and our Computational Modelling Systems team all struggled with similar challenges. Many of you will look at those challenges and say, 'all of the above'.

A major component of CLEX is based in Victoria, and really only those of you in Victoria knew what that was like. Some of you existed in apartments on your own, or in a share house, or with a partner, or with a partner and kids, and some of you suddenly had to juggle home learning responsibilities.

And so, first and foremost, I would like to congratulate you all on making it through 2020. That is an achievement worthy of congratulations and celebrations and at some point I hope we can celebrate together.

I am often asked what the key objective is for the Centre of Excellence in 2021. Our university partners primarily want high-impact publications and additional research income. Our funders and stakeholders want us to be a beacon for climate extremes research with high-impact publications, impact and engagement with industry and government and so on. The Chief Investigators want that next question answered, the research fellows want the next model to run or the next data set to be published and the PhD students often just want to cope with the next deliverable.

So, what do I want? I think 2020 had a profound impact on the research community. I do mean profound, and I doubt we have begun to quantify the long-term consequences. So, I want the buzz back. I want to see that glint in a PhD student's eye when they have a neat idea that their supervisor has not understood yet. My PhD supervisor was a great fan of Tigger ... the "bouncy, bouncy, fun, fun, fun" Tigger. I want my Chief Investigators, research fellows, students and so on to get some of their bounce back. That is my main priority for 2021.

Elsewhere in this report is the documentation of some pretty remarkable achievements. There are papers published in hard-core journals which represent outstanding research achievement. There are papers in high-impact journals, data sets published, new code published, PhDs submitted, promotions gained and prizes won. Congratulations to all of you; I know how hard these were to win and your successes are celebrated.

I will only highlight one success for 2020. The leadership of many of you via our response to COVID was outstanding. It has held groups together, supported individuals and supported each other. There has been outstanding leadership, which is generally hidden, from all levels of CLEX, right from the PhD students to the greying professors. In particular, members of the Centre Executive have met weekly through 2020 to help me cope, and your support has been exemplary. To all of you who have asked another if they are ok; who have made a Zoom call, slacked, skyped and even "telephoned", you are all deserving of a huge vote of thanks.

So, how do we get our bounce back? Video conferencing is awesome, but we will not get our bounce back via Zoom. We need to physically meet again and re-learn person-to-person interactions that have gone missing. We might get together in small research-focused groups, gradually growing until we can run our Graduate Winter School again, or the Centre workshop. We have to be COVID-safe, but we will manage this. I am hoping to start by visiting nodes soon to connect with students and research fellows. So, here's to a celebration of research in 2021, research undertaken in collaboration. ■

Andy Pitman, AO

Director

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.

climate extremes
ARC centre of excellence

Strategic Objectives:	World class research focused on climate extremes		An outstanding environment for all Centre activities		Exceptional research infrastructure		Transform collaboration at all scales		Research that engages and has impact	
Success strategy	**Our research program**		**An outstanding culture for all**		**Our research infrastructure program**		**National climate science fabric**		**Our outreach program**	
Strategic Actions we will:	1.1	Focus research on delivering four research programs: Extreme rainfall, heatwaves and cold air outbreaks, droughts and climate variability & teleconnections	2.1	Develop a researcher development program led by a Graduate Director	3.1	Establish an infrastructure team to advise on modelling and data systems	4.1	Establish structures that avoid silos and encourage cross-institutional research	5.1	Establish a knowledge brokerage team to deliver outreach programs
			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
	1.2	An uncompromising focus on research excellence at all levels	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
	1.3	Engage nationally and internationally to ensure impact	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
	1.4	Identify gaps in our research and attract additional funding to resolve them	2.5	Be an exemplar providing a superb environment for all students and staff	3.5	Develop a strategy for observations, models, and reanalysis data	4.5	Contribute strongly to Australia's Science and Research Priorities	5.5	Communicate our research to government, schools, businesses, etc.

Partnerships and Engagement

Our Partners

Administering Institution

The University of New South Wales

Collaborating Institutions

The Australian National University

Monash University

The University of Melbourne

The University of Tasmania

Australian Partner Organisations

Bureau of Meteorology

CSIRO

Managing Climate Variability Program

National Computational Infrastructure

NSW Department of Planning, Industry and Environment (formerly OEH)

Risk Frontiers

Sydney Water

International Partner Organisations and Collaborators

ETH Zurich

Geophysical Fluid Dynamics Laboratory (USA)

LMD – Centre National de la Recherche Scientifique (France)

Max Planck Institute for Meteorology (Germany)

NASA-Goddard Space Flight Center (USA)

National Center for Atmospheric Research (USA)

UK Meteorological Office (UK)

The University of Arizona (USA)

The Australian Research Council 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.

In spite of the curtailment of travel in 2020, we have maintained ongoing cooperation with our key research partners. Our Centre has a long track record of meeting virtually and this continued throughout 2020. Frequent discussions, at both the researcher-to-researcher level and at the organisational level via representation on our Advisory Board, have informed our strategic and implementation plans at all levels. Joint efforts around the Australian Community Climate and Earth System Simulator (ACCESS) were buoyed in October with the Federal Government's announcement that ACCESS would be recognised as national research infrastructure, thus securing funding of $7.6m for the next three years for the strategic development and operational oversight of Australia's core climate modelling capability.

We continue to work closely with the National Computational Infrastructure (NCI) for the provision of our day-to-day high-performance computing and data needs, as well as engaging with NCI on strategic considerations linked to ongoing investment in national high-performance computing infrastructure. CLEX has collaborated with CSIRO and NCI to port a version-controlled ACCESS ESM1.5 and ACCESS CM2 to NCI and help make it available to researchers. These efforts have significantly reduced the time taken for a PhD student or research fellow to begin to conduct their research.

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

Prior to the closure of international borders, CLEX was honoured to host a visit by Dr Hugh Morrison from the National Center for Atmospheric Research. Dr Morrison visited researchers and and gave seminars at UNSW, Monash, the University of Melbourne and the Bureau of Meteorology during his time in Australia. Dr Morrison also put together a bespoke lecture series on cloud microphysics.

A silver lining that emerged from 2020 was our success in getting international speakers to give virtual presentations at our annual workshop see page 27. Feedback from the workshop was that people enjoyed hearing from international experts and that our early career researchers, especially, would like talks to be followed by online discussion forums. This has led the Centre to form a new committee in 2021 to curate a monthly seminar series where research partners, stakeholders and end-users of our science will present on topical issues and then engage in online forum discussions.

Despite no international travel through virtually all of 2020, international collaboration has been maintained. In some ways, the need for US and European colleagues to provide videoconferencing to international groups enabled easier engagement with our researchers, albeit at very challenging times of the day. As a consequence, papers with strong international engagement have continued to be published. There are multiple examples, among them Bador et al. (2020), which included authors from the Max Planck Institute for Meteorology (MPI-M) in Germany and the UK Meteorological Office. Brown et al. (2020) included authors from the National Centre for Atmospheric Research; the Institut Pierre Simon Laplace, France; NASA; and MPI-M, while Kiss et al. (2020) included authors from CSIRO, the Bureau of Meteorology, the Geophysical Fluid Dynamics Laboratory and NCI.

We do not report destinations for international travel in this report for obvious reasons. We very much hope this will be resolved in 2021 so we can re-establish person-to-person collaboration via significant visits by students, research fellows and our named investigators this year. ■

Knowledge Brokerage Team

The CLEX Knowledge Brokerage Team (KBT) is a key part of the outreach program at the ARC Centre of Excellence for Climate Extremes (CLEX). It exists to enhance the impact of the Centre beyond academia.

One of the KBT's aims is to make sure the work of CLEX researchers is communicated to Australian governments and business sectors. A key tool used to do this is a series of CLEX briefing notes. The impacts of COVID-19 meant that just a few notes were written in 2020. However, a joint note written with the National Environmental Science Programme's Earth Systems and Climate Change Hub on a new assessment of how sensitive the Earth's temperature is to atmospheric carbon dioxide was particularly well-received by public servants and the private sector. The KBT also ensured that CLEX expertise was communicated through documents led by external stakeholders. The team helped IAG, Australia's largest insurer, update its major Severe Weather in a Changing Climate report by drawing its attention to relevant CLEX publications. The report assessed the latest climate science as at July 2020 and examined the effect climate change will have on extreme weather events across different parts of Australia, to enable businesses, governments and the community to understand and plan for impacts. In addition, KBT's Leader, Dr Ian Macadam, contributed to a paper in *Nature Food* on sources of uncertainty in the modelling of wheat yields under future climate conditions, as part of ongoing collaboration with the NSW Department of Primary Industries.

In 2020, the KBT continued to represent CLEX at meetings of significant stakeholders. For example, Dr Macadam participated in a European Union-Australia bilateral knowledge exchange workshop on Services and Science Supporting Climate Action, held in Melbourne in March 2020. This brought together public- and private-sector experts from the EU and Australia, including from CLEX Partner Organisations (for example, CSIRO, the Bureau of Meteorology (BoM), the NSW Department of Planning, Industry and Environment) to discuss the development and use of web-based resources to enhance the provision of climate intelligence.

Work started by the KBT in 2019 on the provision of climate data beyond academia bore fruit in 2020. In December, a new Climdex data portal was released. This enables stakeholders with an interest in climate monitoring and/or model evaluation (for example, the World Meteorological Organisation and actuarial organisations in the US and Canada), as well as researchers, to more easily access a larger range of global datasets on extremes of daily temperature and precipitation. Climdex's provision of these datasets relies on close collaboration between CLEX, the UK Met Office and the US National Oceanographic and Atmospheric Administration National Centers for Environmental Information.

Also released in 2020 was an enhanced version of the CLEX-supported WeatheX app. This allows members of the public to report extreme weather events in real time. The data collected can be used by weather forecast providers to assess their forecasts of extreme weather and by insurers to support the timely assessment of insurance claims. The original version of the app was developed by Monash University. The development of the new version was guided and funded by a group of organisations brought together in 2019 by the KBT, including Monash University, BoM, IAG, NSW Government and Risk Frontiers.

One of the highlights of 2020 for the KBT was progress made in developing educational resources on climate and weather science for secondary schools. School students are often exposed to climate and weather science only through non-quantitative subjects. CLEX aims to highlight these sciences in STEM (Science, Technology, Engineering, Mathematics) subjects. CLEX's strategy in this space is to work with partners to develop curriculum-aligned resources that meet the needs of teachers.

Partnerships put in place in 2019 facilitated the running of a Climate Across the Curriculum workshop at the Australian Meteorological and Oceanographic Society 2020 Conference in Fremantle. This brought scientists at the conference, including CLEX researchers, and teachers in the Fremantle area together to generate ideas for lesson plans involving climate and weather science. The workshop resulted in the production of three lesson plans by the KBT in partnership with the Monash Climate Change Communication Research Hub and the TROP ICSU (Trans-disciplinary Research Oriented Pedagogy for Improving Climate Studies and Understanding project) international repository of climate change teaching resources. CLEX Research Associate Dr Sanaa Hobeichi was instrumental in this effort and is now seconded one day per week to the KBT as a School Resources Developer. She is leading the organisation of a second Climate Across the Curriculum workshop at the Australian Meteorological and Oceanographic Society 2021 Conference. This conference will be online, which will enable CLEX to bring the successful model of the Fremantle workshop to teachers and scientists across the country. ■

TIMELINE OF ACHIEVEMENTS

JANUARY 2020

FEBRUARY 2020 — CLEX co-convenes the "Climate across the Curriculum: Educational Resources for Teachers Workshop", leading to the release of lesson plans for teachers

MARCH 2020 — KBT represents CLEX at the "Services and Science Supporting Climate Action" EU-Australia bilateral knowledge exchange workshop in Melbourne

APRIL 2020 — Release of CLEX Briefing Note "Research on the Antarctic stratospheric polar vortex is important for Australia's seasonal forecasts"

MAY 2020

JUNE 2020

JULY 2020

AUGUST 2020 — Version 1.1.0 of CLEX-supported WeatheX weather reporting app released

SEPTEMBER 2020 — Contribution of CLEX acknowledged at launch of 2nd Edition of IAG report "Severe weather in a changing climate"

OCTOBER 2020

NOVEMBER 2020 — *Nature Food* paper "Sources of uncertainty for wheat yield projections under future climate are site-specific" led by NSW Department of Primary Industries with CLEX KBT co-author published

NOVEMBER 2020 — Release of joint CLEX - NESP Earth Systems and Climate Change Hub Briefing Note "How sensitive is the Earth's temperature to the amount of carbon dioxide in the atmosphere?"

DECEMBER 2020 — Release of re-engineered Climdex data portal for extremes of temperature and precipitation

Media and Communications

Highlights

- Social media campaign around launch of WeatheX v2.0 leads to 270 reports of single thunderstorm event in Queensland
- Dr Sarah Perkins-Kirkpatrick spent a week in the news.com.au newsroom as part of the Time As Now series
- Continued cooperation between Centres of Excellence resulted in Q&ARC social media video series and the largest media communication workshops to date
- Successful internal communications restructure and focused use of social media channels combine to boost morale and keep lines of communication open across the Centre of Excellence during COVID-19 pandemic.

The challenges of 2020's coronavirus pandemic were felt right across the ARC Centre of Excellence for Climate Extremes (CLEX) and, naturally, it had an impact on our media and communications. As COVID-19 took hold across the world, it also consumed huge swathes of the media footprint in both social and traditional formats. As a result, our external media growth continued but at a slower rate.

However, the greatest impact on our communications was felt internally. As students and researchers found themselves working from home and suffering from unexpected stresses caused by the pandemic, our internal communications became the pre-eminent concern. We changed the form of our internal Weekly Update, moving virtual events to the top and creating dedicated areas for online meet-ups and links to professional counselling support at each node. We also made it a focus of the news section to celebrate every triumph, no matter how small, so that it gave a welcome boost to spirits and created the opportunity for CLEX personnel to engage with each other around positive news.

Virtual became the new normal, with combined Centre of Excellence communication workshops moving online. Social media campaigns, such as Q&ARC, which used footage shot on mobile devices in an intentionally rough-and-ready way, were delivered in new ways through content driven by our researchers. We also explored the power of social media to activate the public around our research, with the release of version 2 of the WeatheX app in October. With that launch we stepped away from traditional media, using social media, particularly Facebook, as the lead form of promotion. The results were outstanding and led to 270 reports of a single thunderstorm in south-east Queensland.

We also explored a new platform, Cimpatico, producing a pilot program around the challenges of climate science as part of an online television channel called Climate Australia.

Overall, the challenges of 2020 led to new partnerships and new approaches that will continue to be employed long after the pandemic has passed.

CLEX Website

The website saw modest growth in 2020. Over the course of the year, we have seen:

- 33,661 unique users
- 50,425 sessions
- 86,772 page views
- Top 5 countries: Australia (40.01%), US (20.89%), India (4.46%), UK (3.57%) and Germany (3.04%).

The website content has grown to now include 592 posts and 160 pages, a growth of 198 items since 2019. Aside from our home page, the most popular page on the website continues to be the communications article, 10 Tips to Write an Opinion Piece People Actually Read, followed by an article for students, How to Become a Climate Scientist. These show the importance of evergreen content that will continue to be relevant to our researchers and visitors to the website. The most popular news articles on the website included the media release, Heatwave Trends Accelerate Worldwide; Briefing Note 9, Does Global Warming Cause Droughts, Drying or Increased Aridity?; and the research brief, How Warm Water Reaches Antarctica.

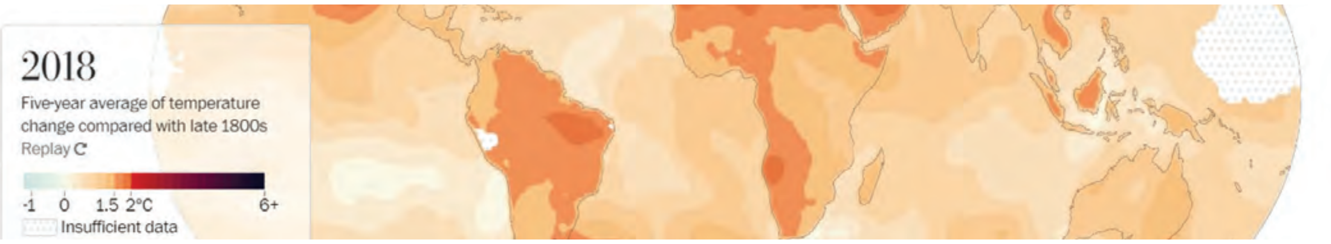
In the coming year, the CLEX website will continue to fulfil its foundational role for our research in concert with social media to reach our peer networks and the public. We also intend to increase embedded video content, with a number of partnerships and projects currently under discussion that will enable us to produce meaningful content for a wide audience.

Social Media

Our social media presence continues to grow across all platforms. Our Twitter followers have now increased to 2247, with more than half a million impressions; our Facebook page grew to 1463 followers; and the Instagram account run by students and early career researchers now has 277 followers.

As noted in previous reports, our Twitter feed is aimed at peer networks and Facebook focuses primarily on our internal cohort and immediate stakeholders, while Instagram is aimed at a younger audience interested in science. The most popular posts in each of these sectors reflect the sector engagement for each of these audiences.

The highest engagement for our Twitter posts was the promotion of Julie Arblaster to full professor and a technical but fascinating modelling paper by Dr Martin Jucker on storm representations in two of the world's major climate models. On Facebook, Professor Arblaster's promotion also rated highest. This was closely followed by congratulations to promotions for Graduate Director Melissa Hart, Professor Jason Evans and a presentation at a summer school by CLEX Undergratuate Research Scholar Fabian Circelli. Overall, the internal triumphs of CLEX personnel rated highest, showing how important this was during the pandemic for Centre morale. As for Instagram, extreme weather and unusual video animations were by far the most popular posts, with the top two posts being a storm tossing up foam in South Africa and a satellite animation of ship tracks in the clouds.



The real power of social media was demonstrated with the launch of WeatheX v2.0, a citizen science app that is used to report on storm events in real time. The new version came out in October, at the beginning of Australia's storm season. It added Twitter report functionality, local area storm warnings and the capacity to upload photos on to social media feeds. When the original app was released, we focused primarily on mainstream media to get the word out. This time around, the key focus was to add more users. For this reason, we directed our engagement strategy around Facebook pages where there was already a large number of people engaged in discussing storms or weather more generally. ABC's Weather Obsessed page was extremely supportive and a number of storm-chasing websites added posts about the new version of the app. We also made Dr Joshua Soderholm available for Facebook live broadcasts. We saw this approach bear fruit when a line of storms passed through south-east Queensland a few days later. In the space of a few hours, we received more than 270 separate reports, the most for any single storm event with the app.

Between the success of the promotion of the WeatheX app and our understanding of the audiences we have cultivated on social media, we now have a clearer way ahead for growing our accounts and some new ideas to explore in 2021.

Media Engagement and Training

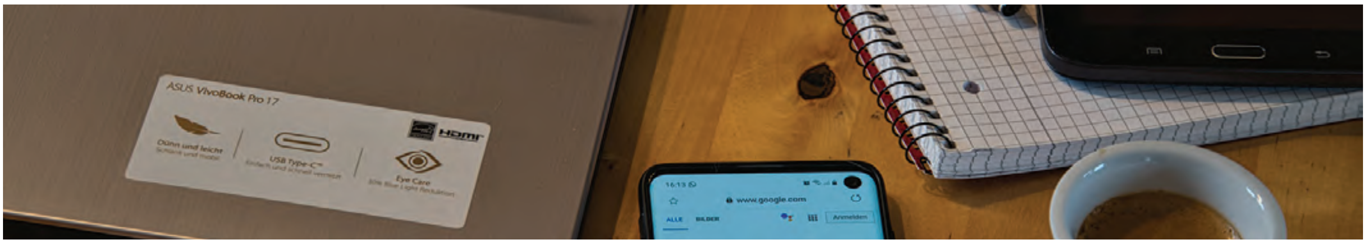
Overall, we saw a slight decline in the number of media stories for the year, with 351 stories by our researchers before syndication, despite a strong start in January that revolved around Australian bushfires and their relationship to climate change. This slight decline was primarily due to the COVID-19 pandemic consuming an extraordinary number of column inches for most of the year. However, many of the stories that did break through have been in high-profile media outlets, including international titles like *The Washington Post*, *BBC Online*, *NBC News*, *Los Angeles Times*, *The New York Times*, *Bloomberg News*, *India Times*, *The Independent* (UK), *Fox News*, *CNN*, *Japan Times*, *CBS News* and *The Globe and Mail*, along with every national and major metro media outlet in Australia.

One of the highlights of our year was seeing Dr Sarah Perkins-Kirkpatrick spend a significant amount of time in the news.com.au newsroom to take part in a series called Time Is Now: How Australia's climate is changing our way of life. The series was the result of a special partnership with the Judith Nielsen Institute for Journalism and Ideas and the Australian Science Media Centre, where the aim was to bring scientists into newsrooms to communicate important scientific issues of the day. Dr Perkins-Kirkpatrick was the inaugural researcher in this partnership and was selected because of her extensive communication history with the Centre of Excellence. This collaboration led to five stories, multiple videos and a lengthy opinion piece all in the space of a week.

We also saw our researchers featured in a series by *The Washington Post*, 2°C: Beyond the Limit, that was awarded a Pulitzer prize.

The Centre's research featured prominently in its own right throughout 2020, with prominent media around our research into the Indian Ocean dipole and its influence on Australian rainfall; a paper on the increasing frequency and intensity of heat waves globally; a major study that, for the first time in 40 years, narrowed the range of the climate sensitivity to carbon dioxide; research that showed how the ocean's strongest currents are rapidly warming; and much more.

We were also delighted to see PhD student Kimberly Reid take an exceptionally active approach to media when she recognised the formation of atmospheric rivers over Australia as extreme weather events were being reported. Atmospheric rivers are the primary focus of Kimberley's research. By contacting the *Sydney Morning Herald* during one of these events, she was able to highlight her research and be



recognised by others in the media as being an expert on this phenomenon. This meant that, when another atmospheric river formed later in the year, reporters contacted Kimberly. She has two very important papers on atmospheric rivers and their impacts on extreme weather events coming out in 2021, so we certainly expect to hear more from her in the future.

Kimberly had previously participated in a combined Centres of Excellence media communications workshop and this certainly seemed to help her during interviews. We on the media team were able to produce two of these workshops for around 55 researchers from 11 Centres of Excellence, despite being off-campus for much of the year. These workshops continue to get excellent feedback from participants and taking them online did not diminish their value in the slightest.

The regular contact between the media and communications personnel at the various Australian Research Council (ARC) Centres of Excellence has also enabled us to partner on a number of initiatives. One of these was the aforementioned Q&ARC, a series of videos which were 'hot takes' of our researchers being asked questions while filming themselves on mobile devices. The intentionally lo-fi approach was perfect for social media, and the videos from all Centres of Excellence were shared widely.

Another initiative was the production of a pilot episode for Cimpatico — an online television network. Working with Lee Constable, who leads the Climate Australia channel on this network, Professor Christian Jakob took part in a half-hour program looking at the known unknowns of climate research. In this case it was focused on how climate models can and cannot supporting decision-making around climate change and future extreme events. The program was CLEX-branded and included visuals and animations provided by the Centre. The episode was live-streamed on Facebook and YouTube and then afterwards was edited and packaged with full credits. This edited version can now be found on our website. In 2021 we will be investigating whether it is possible to create an entire series around similar climate science challenges.

Looking Ahead

After the extraordinarily difficult year of 2020, we are hopeful that 2021 will give us more opportunities to increase our communications capabilities. At a fundamental level we will be reinvigorating the website, which will involve a restructure patterned on variations in our research directions. This is likely to be a major task that will consume much of the early part of the year. It is also our hope that we will have the resources to invest more strategically in video, ranging from short, sharp pieces for social media to more extended in-depth discussions with our researchers.

We also expect work to be completed on a major high-resolution piece of modelling that focuses on rainfall over Australia. This work will also incorporate a detailed 3D animation that could be the core of a communications strategy around our research programs.

In 2021 we will likely see a number of new Chief Investigators appointed to the Centre, which creates the opportunity to introduce each of them in a way that capitalises on our various communications channels.

Finally, there is a small hope that we may again be able to meet face-to-face. If this is the case, then it is an opportunity for the CLEX Media and Communications Manager, Alvin Stone, to visit each of our nodes and engage researchers in a series of workshops and meetings.

There is no doubt that 2021 will be a year of change throughout the Centre of Excellence and that this will lead to a range of strategic communications opportunities and challenges. While this is likely to produce a substantial workload there are also many new avenues that may open to us as a result, and we look forward to what should be a very exciting year to come. ■

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 Centre Advisory Board provides strategic oversight and advice to the Centre of Excellence as well as monitoring the Centre's performance against its stated Key Performance Indicators. The Advisory Board met virtually in February and September 2020.

In 2020 the Advisory Board welcomed two new members: Dr Jaci Brown, Research Director for the Climate Science Centre at CSIRO's Ocean and Atmosphere and Dr Bertrand Timbal, Head of Research, Bureau of Meteorology.

Advisory Board Members in 2020

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

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

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

Dr Jaci Brown, Research Director, CSIRO Climate Science Centre

Dr Jaci Brown is the Research Director for the Climate Science Centre in CSIRO's Ocean and Atmosphere Business Unit. Her research has spanned tropical oceanography, climate projections, fisheries, high-resolution ocean defence tools and seasonal atmospheric processes in Australia. Dr Brown's previous role was as a team leader in the Agriculture and Food Business Unit. Here, she led the Weather and Climate Decisions team. This team focused on delivering actionable weather and climate knowledge to stakeholders.

Professor Ana Deletic, Pro-Vice Chancellor Research UNSW

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

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

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

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

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

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

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

Dr Nick Post, Assistant Secretary Climate and Adaptation Services, Department of Agriculture, Water and Environment.

Dr Nick Post is Assistant Secretary in the Climate and Adaptation Services branch of the Department of Agriculture, Water and Environment.

Dr Post is an experienced senior bureaucrat, having held numerous positions in defence and intelligence prior to assuming his current position.

Dr Bertrand Timbal, Head of Research, Bureau of Meteorology

Dr Bertrand Timbal moved to Australia and the Bureau of Meteorology in 1996, soon after completing his PhD at the French National Meteorological Service (Meteo-France) in 1994. After a three-year stint leading the Climate branch in the Centre for Climate Research Singapore, Bertrand rejoined the Bureau of Meteorology (BoM) in 2020 as the General Manager for the research program, Science and Innovation Group (SIG). In this role, Bertrand leads a program of 130 of scientists, support scientists and science managers, all delivering on the four objectives of BoM's Research and Development Plan.

Dr Jon Petch, Head of UK Meteorological Office Science Partnerships

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

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

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

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

Centre Executive

The Centre Executive is made up of the Centre Director, who carries overall responsibility for day-to-day leadership of the Centre and its research; the Deputy Director; the Director of Engagement Impact and Partnerships; the Chief Operating Officer; the Graduate Director; and the Manager of the Computational Modelling Systems team.

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

Centre Committees

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

Early Career Researcher Committee

Chairs: **Dr Diego Saúl Carrió Carrió and Mengyuan Mu**

The ECR committee is composed of one student and one postdoc representative from each of the five CLEX nodes (UNSW, ANU, Monash, Unimelb, and UTAS). The main functions of the committee include:

- Liaising between ECR members and the CLEX executive committee;
- Career development advice;
- Facilitating opportunities for networking and socialising
- Facilitating communication between ECR members and social media;
- Facilitating communication between ECR members and CLEX executive committee to fund potential ECR development projects.
- Organising and promoting seminars and workshops focusing on topics important to ECR, such as career development (including alternative career pathways), mentoring, funding opportunities, grant and journal writing, media training, communication skills, time management, peer reviewing;

The committee remained active in 2020 in spite of the challenges of COVID-19 and associated lockdowns. An important event on our calendar each year is the ECR day that coincides with the CLEX annual workshop. Like the workshop its self, the ECR day was run online. With the drama and instability of 2020, many of our ECRs have faced unprecedented challenges including loneliness, homesickness and the mounting uncertainties for their future careers. That latter concern may be why the majority of ECRs wanted this year's virtual ECR workshop to focus on the *Future in academia and planning your research career*. With this in mind, the ECR committee arranged this year's workshop as an interactive discussion panel where five professionals with diverse backgrounds introduced their career trajectories.

Over 50 ECRs asked more than 20 questions of the five speakers – Nathan Bindoff (AAPP), Matthew England (UNSW), Terry Bailey (IMAS), Amelie Meyer (IMAS), and Ailie Gallant (Monash Uni). Their different backgrounds in academia and industry meant they answered these questions from a variety of perspectives ranging from complex oceanography to environmental and climate change policy.

After the workshop, the ECR committee organised an online ECR trivia game. Even though we could not physically get together for this ECR day, we still had plenty of fun and felt connected to our colleagues across all five nodes. As this year comes to a close, we all look forward to the next physical reunion of CLEX ECRs in 2021.

Diversity and Culture Committee

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

Members: **Julie Arblaster** (Monash), **Hakase Hayashida** (UTAS), **Mike Roderick** (ANU), **Steven Sherwood** (UNSW), **Claire Vincent** (U. Melb)

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

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

In 2020 the committee was strongly focused on guiding the Centre's COVID-19 response, which is outlined in detail on page 26 Of course, even in the midst of the pandemic we maintained a focus on implementing the key pillars of our Equity Plan.

The highlights of our year included:

- The 2020 CLEX Career Advancement Award for Women and Other Underrepresented Groups was awarded to Dr Nina Ridder
- We continued to advocate for traditionally disadvantaged members of our community
- Under Prof Melissa Hart's guidance, we proposed the introduction of bridging scholarships for international students whose stipends cease upon submission of their theses
- Members of the committee enhanced their knowledge and skills as practitioners in the equity, diversity and inclusion space by attending online training sessions run by home institutions and panel sessions presented by the Diversity Council of Australia.

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), **Craig Bishop** (UMelb) and **Ben Evans** (NCI)

The CLEX Infrastructure Committee's primary role is to aid the Computational and Modelling Support (CMS) team in the prioritisation and delivery of the services it provides. This includes facilitating discussion and decision-making around which modelling systems and data sets should be considered in or out of scope, as well as identifying emerging modelling systems or data sets that offer new opportunities for CLEX. The committee is also tasked with helping the CMS team allocate compute and storage resources to CLEX research programs – particularly where there are competing requests – and liaising with NCI and other relevant national infrastructure bodies.

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

This year the committee discussed issues such as:

- the porting of models and other tools to the Gadi supercomputer
- implementation approach for the ERA5 ARC LIEF proposal
- Last Millennium simulations with the ACCESS ESM
- CABLE and JULES land surface model integration
- prioritisation of requests for in-depth CMS team engagement and new data set hosting
- strategies for improving the efficiency of existing storage.

Outreach Committee

Chair: **Peter Strutton**, UTAS

Members: **Nerilie Abram** (ANU), **Dietmar Dommenget** (Monash), **Karla Fallon** (U. Melb), **Christian Jakob** (Monash), **Ian Macadam** (UNSW), **Amelie Meyer** (UTAS), **Alvin Stone** (UNSW)

The CLEX 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*. The committee works closely with the Knowledge Brokerage Team (KBT), led by Ian Macadam, and the CLEX communications team, led by Alvin Stone.

Outreach efforts started strongly in 2020, with a workshop for educators at the Australian Meteorological and Oceanographic Society annual conference in Perth. The details of this session are reported by the KBT elsewhere in this report. The main outcome was significant progress towards the development of lesson plans for schools and the secondment of CLEX researcher Sanaa Hobeichi one day per week to the KBT as a Schools Resources Developer. This was a very positive step for CLEX outreach efforts, representing the culmination of discussions within the committee about the direction this effort would take.

The KBT continued to produce briefing notes in 2020, though the rate at which these were produced was affected by the COVID-19 pandemic. The Outreach Committee acted as a sounding board for briefing note pitches and also provided input on drafts. The KBT continues to refine the topics these briefing notes should cover, as CLEX becomes more aware of the uptake of these notes by stakeholders. Briefing notes also became more visually engaging in 2020, thanks to the efforts of Jenny Rislund.

On the topic of engaging graphics, the Outreach Committee has recommended the hiring of a graphic designer to increase the visual impact of:

- stakeholder documents such as briefing notes and reports
- media releases and social media posts
- school resources
- the annual report
- potential future assessment reports.

This person, who will likely be hired in 2021, will also produce synthesis graphics for briefing notes and outreach more generally.

Moving forward, the Outreach Committee looks forward to developing deeper CLEX engagement with government and industry, in areas of emerging climate challenges.

Centre Business Team

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

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

In addition to the underpinning work of the CLEX business team, our Media and Communications Manager Alvin Stone (UNSW) continues his superb work of profiling the Centre's research and generously sharing his time and expertise with other communicators in the national Centres of Excellence community.

Our Knowledge Brokerage Team is responsible for the translation of the Centre's research to a range of end users. You can read more about the great outcomes emerging from the work of Dr Ian Macadam and Dr James Goldie elsewhere in this report.

Leadership Development

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

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

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

Equity and Diversity

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

As noted earlier in this section, the Centre's Diversity and Culture Committee spearheaded a range of initiatives in 2020 by way of implementing the three key objectives of the CLEX equity plan. Those objectives cover recruitment, inclusivity and wellbeing and culture.

CLEX Response to the COVID-19 Pandemic

The Centre of Excellence for Climate Extremes (CLEX) took a proactive and multi-faceted approach in response to the major disruptions caused by the COVID-19 pandemic. Our key focus was to ensure our researchers, especially students and early career researchers (ECRs), had the physical resources and support mechanisms in place to continue their work. We also provided resources and guidance to more senior members of the Centre community, given the added burden they faced in not only coping with disruptions and challenges in their own lives but also being called up on to support others. Below is a summary of the many initiatives we put in place. The CLEX COVID-19 response was highlighted in an article in The Conversation authored by Graduate Director Melissa Hart.

Early in the pandemic

- There was a strong focus on maintaining existing connections between supervisors and their teams
- Where possible, CLEX provided resources to help people work from home
- Supervisors were asked to provide information to the CLEX Cle(v)er database on their students' and ECRs' capacity to work remotely and stay mentally healthy
- We negotiated desk space and support at affiliated institutions for international students stranded in their home countries
- Melissa Hart, Stephen Gray and Chief Investigators actively followed up where there was specific cause for concern
- Weekly ECR drop-in Zoom lunches were established
- Updates from Andy Pitman were circulated with the Centre's weekly bulletin. These were carefully crafted to be CLEX-specific rather than offering general COVID-19 advice, so as not to add to the information overload early in the pandemic.

Ongoing initiatives

- Melissa Hart drafted the above-mentioned *Conversation article* on supporting graduate students through the pandemic
- Stephen Gray drafted a document offering advice to supervisors for looking after their own wellbeing and that of their groups. This was circulated internally and beyond CLEX
- Weekly Hump Day Tips continued, with increased focus on mental health and remote working advice
- A weekly informal meeting of the core leadership group was instigated to catch up and debrief over virtual drinks
- There was wider adoption of tools such as Slack to maintain connection
- Attendance at research program meetings increased throughout 2020
- We offered "writing up" scholarships for students who had submitted theses and don't have a secure income stream upon suspension of their stipends
- Fixed-term contracts that were due to terminate in 2020 were extended to the end of the year
- The winter school and annual workshop were both successfully moved online.

Looking forward

- Attention of the Centre Executive and the Diversity and Culture Committee is starting to turn to re-engagement strategies for existing people and how to induct new staff and students into the Centre. ■

CLEX 2020 Annual Workshop

Back in early February 2020 we shortlisted a small handful of workshop venues just outside of Melbourne and settled on Ballarat for the 2020 CLEX workshop. Little did we know then how the rest of the year would play out. By mid-year hopes of an in-person workshop for 2020 had to be abandoned.

Undeterred, the workshop committee came together to set to work on creating an online workshop that sought to balance opportunities to share our current science, look ahead to future directions and to try to re-create opportunities for networking and serendipitous connections; all the while being mindful of the Zoom fatigue that became a significant part of everyone's 2020 experience.

To meet these aims, the workshop agenda was structured around manageable blocks of time for talks in the morning by Zoom and poster sessions in the afternoon on the "Remo Conference" platform. Morning talks were split between "New Horizons" talks which looked at challenges and opportunities in the scope of the new proposed CLEX research areas: Weather and Climate interactions; Drought; Attribution and Risk; Ocean Extremes and: Modelling. An advantage of this year's online format was that in addition to hearing from internal experts in these fields (Claire Vincent and Ailie Gallant) we were able to invite three international speakers who wouldn't have otherwise been able to join us – Bjorn Stevens, Emanuel Di Lorenzo and Daithi Stone.

We also heard from Dr Tom Mortlock from CLEX partner organisation Risk Frontiers who gave a fascinating talk on risk modelling. A final highlight of our morning Zoom sessions was the pair of breakout sessions that were developed and led voluntarily. Navid Constantinou led a very topical conversation around the experience of staff and students who spent 2020 far from their home countries, friends and families. Pete Strutton and Melissa Hart led an interactive session on concise writing and offering constructive feedback. Both sessions were well attended and feedback from participants was positive.

As always with the CLEX workshop, the week showcased the enormous depth and breadth of work being done in the Centre, especially by our students and ECRS. We had eight superb science talks from the current research programs, 27 one-minute lightning lectures and 62 posters. Our poster sessions took place in a virtual conference venue which enabled participants to freely move between posters and engage via video chat with the poster presenter and others at the same virtual table. The platform also enabled people to break off to chat one-on-one or in a small group of colleagues. The success of this platform was borne out in the post-workshop feedback and in the fact that poster sessions were extended by up to an hour each day due to the fact that people were still engaging with each other.

The success of the entire event was down to the extraordinary work and adaptability of this year's workshop organising committee – Lisa Alexander, Jason Evans, Stephen Gray, Amelie Meyer and Steve Sherwood. Without doubt they managed to create and deliver an online event that far exceeded most expectations. ■

Organisational Chart

Personnel

Director

Professor Andy Pitman
University of New South Wales

Deputy Director

Professor Todd Lane
University of Melbourne

Graduate Director

A/Professor Melissa Hart
University of New South Wales

Chief Operations Officer

Stephen Gray
University of New South Wales

Chief Investigators

Professor Nerilie Abram
Australian national University

Dr Gab Abramowitz
University of New South Wales

Professor Lisa Alexander
University of New South Wales

Professor Julie Arblaster
Monash University

Professor Nathan Bindoff
University of Tasmania

Professor Craig Bishop
University of Melbourne

A/Professor Dietmar Dommenget
Monash University

Professor Matthew England
University of New South Wales

Professor Jason Evans
University of New South Wales

Professor Andy Hogg
Australian National University

Professor Neil Holbrook
University of Tasmania

Professor Christian Jakob
Monash University

Professor Michael Reeder
Monash University

Professor Michael Roderick
Australian National University

Professor Steven Sherwood
University of New South Wales

Professor Peter Strutton
University of Tasmania

Partner Investigators

A/Professor Ali Behrangi
University of Arizona (USA)

Dr Martin Best
Met Office (UK)

Dr Sandrine Bony
LMD/CNRS (France)

Dr Elizabeth Ebert
BoM

Dr Wojciech Grabowski
NCAR (USA)

Dr Stephen Griffies
GFDL – NOAA (USA)

Professor Nicolas Gruber
ETH Zurich (Switzerland)

Professor Hoshin Gupta
University of Arizona (USA)

Dr Robert Hallberg
GFDL – NOAA (USA)

Dr Harry Hendon
BoM

Dr Cathy Hohenegger
Max Plank Institute for Meteorology (Germany)

Dr Reto Knutti
ETH Zurich (Switzerland)

Dr Rachel Law
CSIRO

Dr Simon Marsland
CSIRO

Dr Richard Matear
CSIRO

Dr Gerald Meehl
NCAR (USA)

Mr Sean Milton
Met Office (UK)

Dr Nathalie de Noblet
LMD/CNRS (France)

Professor Dani Or
ETH Zurich (Switzerland)

Dr Christa Peters-Lidard
NASA – GFSC (USA)

Dr Alain Protat
BoM

Professor Joellen Russell
University of Arizona (USA)

Dr Joe Santanello
NASA - GFSC (USA)

Professor Sonia Seneviratne
ETH Zurich (Swtzerland)

Professor Bjorn Stevens
MPI for Meteorology (Germany)

Dr Peter Stott
Met Office (UK)

Dr Ying Ping Wang
CSIRO

Dr Matthew Wheeler
BoM

Associate Investigators

Dr Daniel Argueso Barriga
UIB (Spain)

Dr Linden Ashcroft
U.Melb

Dr Kathleen Beyer
NSW OEH

Dr Josephine Brown
U.Melb

Dr Jennifer Catto
Exeter University (UK)

Dr Christine Chung
BoM

Dr Alejandro Di Luca
UNSW

Dr Randall Donohue
CSIRO

Dr Stephanie Downes
NSW DPIE

Dr Nick Earl
UTAS

Professor Graham Farquhar
ANU

Dr Ailie Gallant
Monash University

Dr Bishakhdatta Gayen
ANU

Dr Joëlle Gergis
U.Melb

A/Professor Donna Green
UNSW

Dr Benjamin Henley
U.Melb

Dr Will Hobbs
UTAS

Dr Pandora Hope
BoM

Dr Yi Huang
U.Melb

Dr Debbie Hudson
BoM

Dr Fei Ji
NSW DPIE

Dr Martin Jucker
UNSW

Dr Jatin Kala
Murdoch University

Dr Andrew King
U.Melb

Dr Andrew Kiss
ANU

Dr Andreas Klocker
UTAS

Dr Angela Maharaj
UNSW

Dr Andrew Marshall
BoM

Professor Trevor McDougall
UNSW

Dr Shayne McGregor
Monash University

Dr Tim McVicar
CSIRO

Professor Patrick Meir
ANU

Professor Katrin Meissner
UNSW

Dr Adele Morrison
ANU

Dr Negin Nazarian
UNSW

Dr Maxim Nikurashin
UTAS

Dr Terrance (Terry) O'Kane
UTAS/CSIRO

Dr Eric Oliver
Dalhousie University (Canada)

Professor Jonathon Overpeck
University of Michigan

Dr Tess Parker
Monash University

Dr Violaine Pellichero
UTAS/CSIRO

Dr Acacia Pepler
BoM

Dr Sarah Perkins-Kirkpatrick
UNSW

Dr Helen Phillips
UTAS

Dr Scott Power
BoM

Professor Peter Rayner
U.Melb

Dr Agus Santoso
UNSW

Dr Robyn Schofield
U.Melb

Dr Alexander Sen Gupta
UNSW

Dr Callum Shakespeare
ANU

A/Professor Steven Siems
Monash University

Dr Martin Singh
Monash University

Professor Scott Sisson
UNSW

Dr Andrea Taschetto
UNSW

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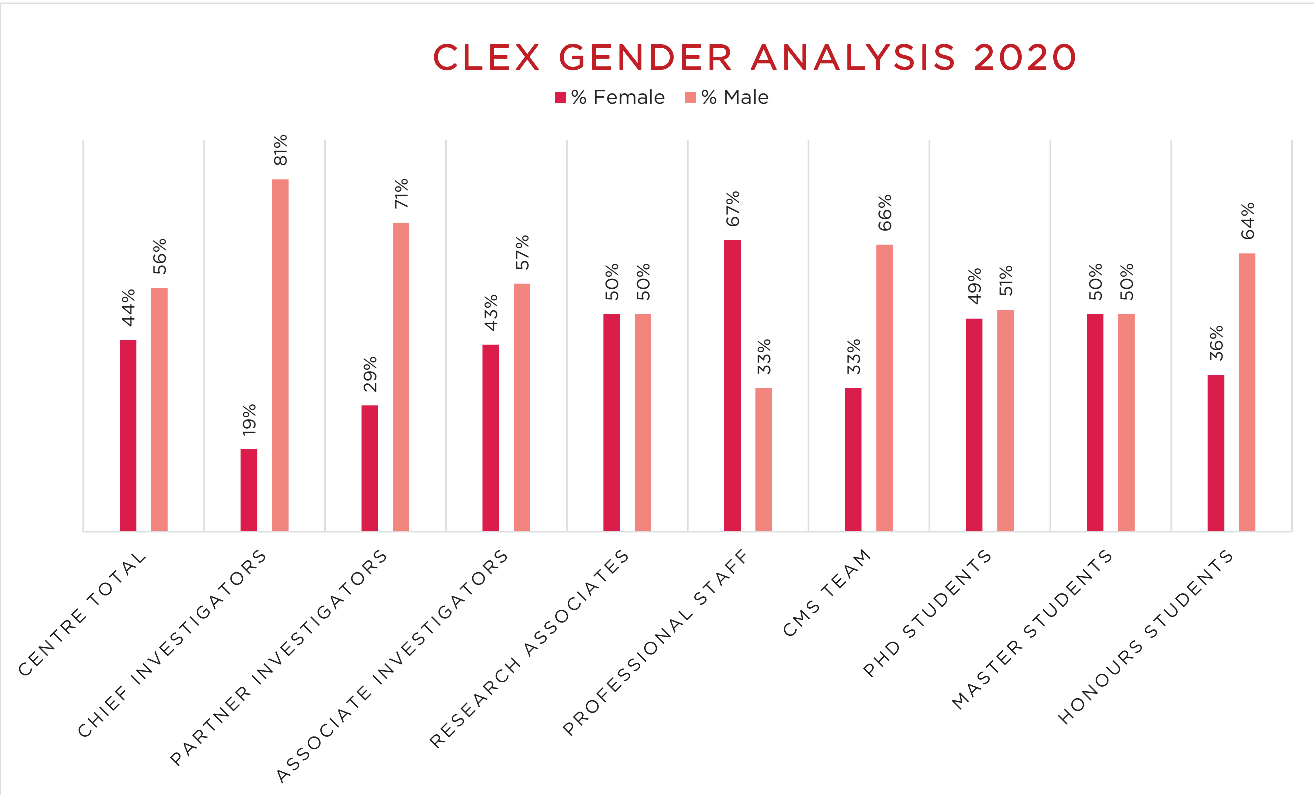


Chief Investigators

Prof Andy Pitman, AO - Director

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

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

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

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

Professor Pitman was appointed an Officer of the Order of Australia in 2019. Other Awards and accolades received by Prof Pitman include: The Royal Society of Victoria's Medal for Excellence in Scientific Research (2019); NSW Scientist of the Year Award (2010), the Australian Meteorological and Oceanographic Society (AMOS) Medal (2009), the Dean's Award for Science Leadership at Macquarie University (2005), the Priestley Medal for Excellence in Atmospheric Science Research (2004) and the Geoff Conolly Memorial Award (2004). He jointly won the International Justice Prize for the Copenhagen Diagnosis (2010) and was among Sydney Magazine's list of the 100 most influential people (2010). He is a fellow of AMOS and of the American Meteorological Society.

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

Prof Todd Lane - Deputy Director

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 Professor in the School of Earth Sciences. Between 2010-2014 he was an ARC Future Fellow.

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

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

A/Prof Melissa Hart - Graduate Director

Associate Professor Melissa Hart has used her role as Graduate Director of the ARC Centre of Excellence for Climate System Science to lead and develop a national, cross-institutional graduate program which has reimagined the traditional Australian PhD. With a vital combination of breadth, depth, support and collaboration, the program has provided over 120 graduate students with the skills, knowledge and experience fundamental to developing world-leading climate science researchers.

A/Prof Hart completed her Bachelor of Science (Hons) in 2001 and her PhD in Atmospheric Science in 2006, at Macquarie University. During her PhD studies she worked part-time at the well-respected air quality consultancy Holmes Air Sciences (now Pacific Environment). She then spent two years as a postdoctoral researcher at Portland State University, Oregon, working on the National Science Foundation-funded Feedback between Urban Systems and the Environment (FUSE) 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, along with quantification of the magnitude of the Urban Heat Island. She is also working in the area of air pollution meteorology, particularly air pollution impacts from hazards reduction burns.

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

Prof Nerilie Abram

Professor Nerilie Abram uses palaeoclimate records to study how Earth's climate has behaved in the past to provide a long-term perspective on recent climate change. She has a particular focus on reconstructing climate variability in the tropical Indian Ocean and Antarctica and how this impacts Australia's rainfall patterns. Her work also involves proxy-model comparisons to assess forcing mechanisms behind natural and anthropogenic climate changes and helping to test climate model performance in historical and last-millennium experiments.

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

A/Prof Gab Abramowitz

A/Prof 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's research looks at questions such 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?

A/Prof Abramowitz is also leading the development of model evaluation.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.

Prof Lisa Alexander

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 Met Office Hadley Centre, with a year on secondment at Australia's Bureau of Meteorology.

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

For her contributions to this area of research, Prof Alexander was awarded the 2011 Priestley Medal by the Australian Meteorological and Oceanographic Society and the 2013 Australian Academy of Science Dorothy Hill Award. In 2020 she became a fellow of the Australian Meteorological and Oceanographic Society. Prof Alexander contributed to the Intergovernmental Panel on Climate Change (IPCC) assessments in 2001, 2007 and 2021 and to its 2012 Special Report on Extremes. She was a Lead Author of the IPCC's 5th Assessment Report. Prof Alexander also chairs a World Meteorological Organisation Expert Team, is a member of the International Association of Meteorology and Atmospheric Sciences Executive Committee and sits on the Joint Scientific Committee of the World Climate Research Programme.

Prof Julie Arblaster

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

Professor Arblaster's research interests lie in using climate models as tools to investigate mechanisms of recent and future climate change, with a focus on shifts in the Southern Hemisphere atmospheric circulation, tropical variability and climate extremes. She is particularly interested in the interplay between the predicted recovery of the Antarctic ozone hole over coming decades and greenhouse gas increases in future climate projections, with its potential impacts on the surface, ocean circulation and sea ice. Recent work has also focused on explaining extreme events in Australia – such as record-breaking temperatures and rainfall – from a climate perspective, both in terms of the role of human influences and the diagnosis of the climate drivers. Prof Arblaster's research incorporates the use of observations, multi-model datasets and sensitivity experiments with a single model. Her strong collaboration with the National Center for Atmospheric Research and her participation in various international committees and reports enhances her engagement with the latest advances in climate research internationally.

Prof Arblaster was awarded the 2014 Australian Academy of Science Anton Hales Medal for research in earth sciences and the 2018 Priestley Medal from the Australian Meteorological and Oceanographic Society. She was an active member of the World Climate Research Programme's Stratosphere-troposphere Processes and their Role in Climate scientific steering group from 2011-2016 and served as a Lead Author of the Intergovernmental Panel on Climate Change 5th Assessment Report and the 2014 WMO/UNEP Scientific Assessment of Ozone Depletion. Prof Arblaster has also served on national committees, including the National Climate Science Advisory Committee, the Australian Academy of Science's Australian Climate Science Capability Review and the National Committee on Earth System Science.

Prof Nathaniel Bindoff

Professor Nathaniel Bindoff is Professor of Physical Oceanography at the University of Tasmania, 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. His 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 research group has contributed to the development of some of the largest and highest-resolution model simulations of the oceans for the scientific study of mixing in the oceans.

Prof Bindoff contributed to the IPCC's winning of the Nobel Peace Prize in 2007, shared with Al Gore, and he was 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 the 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 more than 10,000 citations.

Prof Craig Bishop

Melbourne-born Professor Craig Bishop was awarded a bachelor's degree with honours and a PhD in Applied Mathematics from Monash University. His innovative ensemble-based data assimilation and ensemble-forecasting techniques are now used by leading environmental forecasting agencies such as the European Center 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. 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.

After completing his PhD, Prof Bishop held a postdoctoral position 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 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 in Monterey, California. There he was awarded six outstanding contribution awards, three National Research Laboratory (NRL) Alan Berman publication awards and one NRL Edison patent award. He returned to Australia as Professor of Weather Prediction at the University of Melbourne, in June 2018.

Prof Bishop is a founding co-chair of the World Meteorological Organization's Working Group on Predictability, Dynamics and Ensemble Forecasting and 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. Prof Bishop was elected to the International Commission on Dynamical Meteorology in 2010 and as a fellow of the American Meteorological Society in 2012. In 2015, he served as the PhD-student-elected Distinguished Visiting Scientist of the University of Reading's internationally renowned Department of Meteorology.

A/Prof Dietmar Dommenget

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

A/ Prof Dommenget joined the 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 with an adjoint 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. Since 2010, he has been at Monash University in the atmospheric and climate science group of the School of Earth, Atmosphere and Environment.

A/Prof Dommenget's research focuses on large-scale climate dynamics and climate modelling. He works with climate models at all levels of complexity, with most of that work being centred on the development, conducting and analysis of coupled general-circulation models. 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, and he is also known for his work on the interpretation of patterns and modes of climate variability. 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, from 1992-1994. He was a research scientist in CSIRO's Climate Change Research Program from 1994-1995 and a CSIRO Flagship Fellow in 2005. Prof England has been with the University of New South Wales since 1995, where he held an ARC Federation Fellowship from 2006-2010. He commenced an ARC Laureate Fellowship in 2011. In 2014, he was elected a fellow of the Australian Academy of Science and in 2016 a fellow of the American Geophysical Union.

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

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

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 220 peer-reviewed journal papers. He has been a Contributing Author for two Intergovernmental Panel on Climate Change Assessment

Reports. He was the Convening Lead Author of the 2009 Copenhagen Diagnosis. He has supervised more than 25 PhD students through to graduation and taught more than 3000 undergraduate students. He was an associate editor for *Reviews of Geophysics, 2005-2009*, and an associate editor for the *Journal of Climate*, 2008-2015.

Prof Jason Evans

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 US. 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 on the Scientific Advisory Team of the Coordinated Regional Climate Downscaling Experiment (CORDEX), an element of the World Climate Research Programme. He is also region coordinator of the CORDEX Australasia domain. He was 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 a member of the editorial team 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 awarded 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 awarded 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. He was awarded the Australian Meteorology and Oceanography Society's Priestley Medal for mid-career excellence in climate and related sciences in 2017.

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 ARC postdoctoral fellow. He is currently based at ANU's Research School of Earth Sciences.

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

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

Prof Neil Holbrook

Professor Neil Holbrook completed his Bachelor of Science (Hons) in applied mathematics and physical oceanography at the University of

Sydney, in 1990. He was awarded his PhD in applied mathematics/ physical oceanography, also at the University of Sydney, in 1995. He is one of Australia's original National Greenhouse Advisory Committee PhD scholars.

Following a brief postdoctoral fellowship at Macquarie University, in the Climatic Impacts Centre, Prof Holbrook was appointed a lecturer in atmospheric science at Macquarie University, in 1996. In 2008, he commenced at the University of Tasmania as an associate professor in climatology and climate change. He was promoted to Professor of Ocean and Climate Dynamics in 2018 and is currently head of the Centre for Oceans and Cryosphere within the Institute for Marine and Antarctic Studies at UTAS.

Prof Holbrook uses his expertise in ocean and climate dynamics on sub-seasonal to multi-centennial time scales to better diagnose the important mechanisms underpinning climate variability and extremes as well as climate change. His current research focuses on understanding the causes and predictability of marine heatwaves, based on the analysis of observations and a hierarchy of model complexities and experiments. He has published extensively in the international literature on the ocean's role in climate, climate variability, climate extremes and climate change.

Prof Holbrook is an elected fellow of the Australian Meteorological and Oceanographic Society and an associate editor of the *Journal of Southern Hemisphere Earth Systems Science*. He has previously served as president of the International Commission on Climate of the International Association of Meteorological and Atmospheric Sciences/International Union of Geodesy and Geophysics (2011-2019). He was an associate editor of the *Journal of Climate* (2006-2008), and he led Australia's National Climate Change Adaptation Research Network for Marine Biodiversity and Resources (2009-2013).

Prof Christian Jakob

Professor Christian Jakob was awarded his PhD in Meteorology by 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 Australian 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 the current Co-chair of the World Climate Research Programme's (WCRP) Digital Earths Lighthouse Activity. Before that, he co-chaired the WCRP Modelling Advisory Council (2012-2017) and led the prestigious Working Group on Numerical Experimentation (2008-2012). 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.

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

Farewell Michael Roderick

In June 2020, the ARC Centre of Excellence for Climate Extremes bade farewell to Chief Investigator Prof Michael Roderick, after he retired from academia with plans to spend his golden years pursuing elusive trout.

Mike was co-leader of the CLEX Drought program and prior to that held the same position in the ARC Centre of Excellence for Climate System Science. He has had an extraordinary career where, as Director Prof Andy Pitman noted, has had a remarkable capacity to ask seemingly simple questions that have profound implications. Shortly before he departed, Mike delivered a virtual seminar on drought, bushfires and climate that broke records for attendance at ANU's Research School of Earth Science. It is a direct reflection of the esteem in which Mike is held.

Mike came to climate science via a circuitous route. He grew up in Queensland cattle country and graduated from university with a degree in surveying. That work took him to northern Australia for four years before he decided to pursue a PhD in satellite remote sensing and environmental modelling, which he finished in 1994.

Over the ensuing years his investigations turned to evaporation. His growing understanding of how water moves through the landscape at micro and macroscopic levels has transformed the way the climate science community views drought and its causes. Importantly, his work has made many in researchers recalibrate the way we use drought indices in climate models and how drought may change in a warmer world. As an example, the formerly easy acceptance that droughts would increase in area with global warming is now less clear as the simple questions he asked about drought metrics and evaporation through his research have produced an increasingly complex and nuanced understanding of drought processes.

One of Mike's most notable characteristics is his capacity to explain these complexities in a manner that is instantly accessible. Most of us can easily picture Mike leaning against a lectern with a half-smile, drawing the audience through his thinking in slow careful steps, pausing occasionally to deliver a wry observation along the way, all the while challenging us to think in new ways. This same approach that has seen him become valued mentor to students and early career researchers who have gone on to have spectacular careers in their own right. Mike has been acknowledged by his peers with a John Dalton Medal from the European Geophysical Union, was elected as a Fellow of the American Geophysical Union, received an Australasian Science Prize and much more.

While these are impressive national and international achievements that will stand as an indelible legacy of his work, for many of us at the Centre the true testament to his influence is how he has impacted those around him. He may now be away terrorising trout in Australia's streams and rivers but his foundational research and his challenge to question everything we take for granted will continue to inform us all years to come. ■

topics, including fronts, tropopause folding, extratropical cyclones, Rossby waves, heat waves, tropical cyclones, gravity waves, solitary waves, convection, boundary layers, bushfires, the Hadley and Walker circulations and the Madden-Julian Oscillation.

Prof Reeder has been the principal supervisor for more than 40 graduate students. He is a past president of the Australian Meteorological and Oceanographic Society (AMOS) and a fellow of AMOS. He is a winner of the AMOS Distinguished Research Award and the Loewe Prize (Royal Meteorological Society, Australian branch) and has given the AMOS Clarke Lecture.

Prof 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 NASA-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. He moved to Australia at the beginning of 2009, where he is Professor and Deputy Director of the Climate Change Research Centre at the University of New South Wales.

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

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

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

Awards received by Prof Sherwood include the 2002 National Science Foundation CAREER award and the 2005 American Meteorological Association's Clarence Leroy Meisinger award. In 2014 he was a Eureka Prize finalist and in 2015 he commenced an ARC Laureate Fellowship. Aside from giving numerous invited presentations at scientific meetings or colloquia worldwide, Prof Sherwood has given many public presentations, including a briefing in the US House of Representatives, along with television and radio appearances and public lectures at many venues.

Prof Peter Strutton

Professor Pete 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 an assistant professor with the State University of New York's Marine Sciences Research Centre and from 2004-2010 he was an assistant, then associate professor at Oregon State University's College of Oceanic and Atmospheric Sciences. In 2010, he returned to Australia on an ARC Future Fellowship. Since then he has risen from associate professor to full professor at the Institute for Marine and Antarctic Studies, University of Tasmania.

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 in 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 Prof Strutton contributes to the Climate Variability program, and he is also contributing to projects in the area of marine heatwaves. His research concentrates on the drivers of observed changes in biogeochemical cycles, including oxygen, carbon and nutrients, with a recent and continuing focus on eddies.

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

ANDREW MARSHALL DERWENT RIVER TAS

Research Overview

In the following chapters, we report research progress against each of the research programs in the ARC Centre of Excellence for Climate Extremes (CLEX). There are many highlights: new estimates of climate sensitivity constrained by observations, a new explanation for the extreme Australian weather in late 2019, new predictions of future drought risk – and even links between the Montreal Protocol and the rate of global warming.

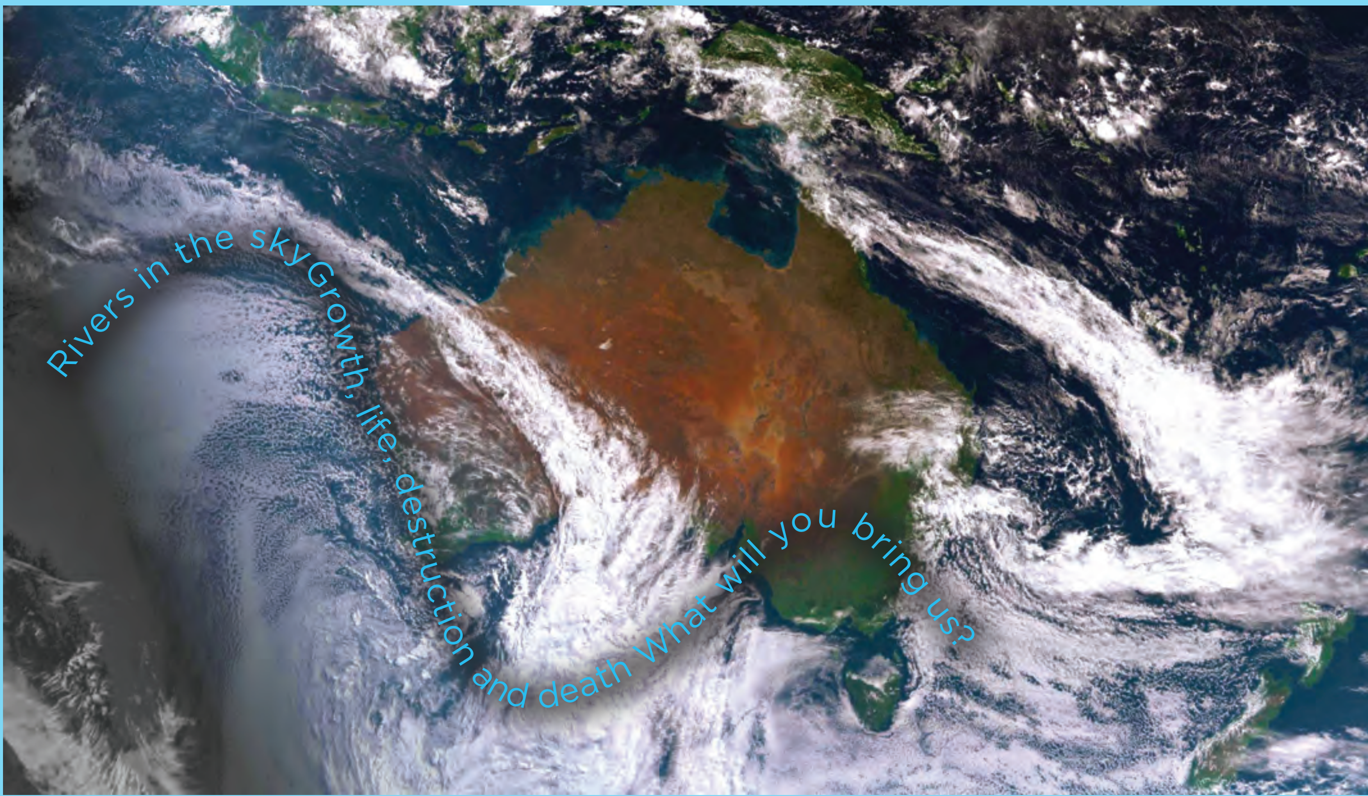
Amongst our research achievements are some important capabilities developed and discoveries made for the users of Centre research. Our climate sensitivity work has real policy implications as it narrows uncertainty in climate sensitivity, which feeds into allowable emissions by countries to meet the Paris agreement. The Centre of Excellence coordinated the Climate Processes Research in Australia report to the Federal government, led by Christian Jakob, in response to a request by the National Climate Science Advisory Committee. We have multiple inputs into State government needs around climate science, in particular in Tasmania, Victoria and NSW. We also worked intensively with government to achieve a positive outcome around the Australian Community Climate and Earth System Simulator National Research Infrastructure announced in the 2020 Federal budget.

CLEX research focused on attributing changes in extreme rainfall has real implications for water resource managers. Both water managers and risk managers will find our work around the number and nature of tropical cyclones important, and a new climatology of compound events helps link heavy rainfall with strong winds. An analysis of Australia's extreme weather in late 2019 has indicated alternative hypotheses around the causes of that weather; new data sets linked with WeatheX are building new knowledge of where extremes occur; and integration of radar data into our research provides new links to engage with industry. Work in the Sydney basin points to population growth being the dominant driver of water demand in the future, with climate change contributing a small but significant additional pressure.

We are also building the capacity to improve our future predictions of important phenomena. Links between climate change, ocean heatwaves and fisheries are being developed. Links between the representation of terrestrial processes, drought and the prediction of when forests will die is underway. Very high-resolution atmospheric modelling is a transformative capacity development that allows us to examine the emergence of phenomena in the atmosphere, while new techniques and new resolution in the ocean is demonstrating how we can improve the prediction of both trends and variability.

The research that enables these policy and industry links is documented in the pages that follow, research program by research program. Any of these are very closely linked with Partner Organisations, and much of the global modelling is dependent on maintaining strong research links with these groups. Those links, and the benefits they bring, are also highlighted in this annual report. ■

Kimberley Reid takes her research to a wide audience



Coronavirus quarantines may have cut many of us off from the rest world but that didn't stop PhD student Kimberley Reid from becoming a very active science communicator around her research in 2020. Kim's research focuses on a little studied area of Australia's climate, atmospheric rivers. These systems drag huge amounts of rain from the tropics southwards to the temperature regions of Australia but after consecutive drought years they had been few and far between.

2020 changed all that, with the return of close to normal rainfall patterns for many parts of Australia from late February and then the development of a La Niña in the latter half of the year.

When, in early May, a weather map showed a large storm system approaching Western Australia packing 185km/h winds Kim immediately spotted the tell-tale signs of an atmospheric river. It was an opportunity to put her research in front of the Australian public. Taking the initiative, she contacted the Environment Editor for Sydney Morning Herald, Peter Hannam, and outlined its characteristics. The result was a story, 'Atmospheric river' 2000km long wallops Western Australia, heads east, that described in detail what they were and why they mattered.

When two atmospheric rivers formed simultaneously in August, reporters already had Kim on speed dial, with the ABC using her as the main expert for a story Atmospheric rivers form in both the Indian and Pacific Oceans, bringing rain from the tropics to the south.

But Kim didn't just communicate to mainstream media. She continues to write blogs for the Centre's website that not only look at her research (Atmospheric rivers – what's in a name), but which have also explored the challenges of being a PhD student and even shared her thoughts about how environmental messages are seeping out of video games.

Her willingness to engage in outreach at every level has seen her take a role on the organising committee for 32nd Victorian Universities Earth and Environmental Science Student Conference.

In a delightful footnote to the year Kim won first place in a Haiku Thesis Competition based on her thesis, Impacts of Atmospheric Rivers in Australia and New Zealand. The Haiku reads:

Rivers in the sky

Growth, life, destruction and death

What will you bring us? ■

RP1:
Extreme Rainfall

Highlights

- International analysis for the first time in 40 years narrowed the range of climate sensitivity
- Climate Processes Research in Australia report for the National Climate Science Advisory Committee, led by Christian Jakob, was a key document for the future infrastructure and direction of climate research in Australia
- Released for climate research community use: version 1 of the Aus400 data set, a detailed 400m grid atmospheric simulation that is the highest resolution simulation over Australia ever produced
- Citizen science app, WeatheX version 2 was released in September 2020 and resulted in 270 different reports from a storm system that passed over south-east Queensland.

No year has been more challenging during the life of the Centre of Excellence for Climate Extremes (CLEX) than 2020. Despite the obstacles that this year has thrown at us, the team at the Centre's Extreme Rainfall research program has still had an extraordinary number of successes and produced a wide range of research.

Without doubt, one of the more impressive papers published this year was the international analysis of climate sensitivity, led by Steve Sherwood and published in *Reviews of Geophysics*. This is a ground-breaking piece of work that has narrowed the range of equilibrium climate sensitivity for a doubling of carbon dioxide compared to pre-industrial times, from 1.5°C - 4.5°C – where it has stood for 40 years – down to a robust estimate of 2.6°C-3.9°C. This is fundamental work that will undoubtedly be a major part of the next Intergovernmental Panel on Climate Change (IPCC) Assessment Report 6, Working Group 1 report. A major component of this work was the examination of paleoclimate and instrumental records, which allowed the researchers to look back at past responses to interpret future changes.

A similar approach of looking backwards to prepare for the future was the basis of a study with Associate Investigators Pandora Hope, at the Bureau of Meteorology (BoM), and Associate Investigator Jo Brown, at the University of Melbourne. Here, our researchers used documentary sources and paleoclimate records to see how modern infrastructure would have coped with past pre-instrumental floods. It found that pre-instrumental flooding in some areas of Australia, particularly in the 18th century, was far higher than that in the 20th and 21st centuries, suggesting we may not be able to cope with future floods, especially once the influence of climate change is factored in.

But when it comes to looking backwards in time to estimate how things may change in the future it is hard to surpass looking back 3 million years to the mid-Pliocene, when temperatures were 2 to 3°C warmer than today but the concentrations of carbon dioxide were very similar. The Extreme Rainfall team, in concert with the Drought research program team, examined these past conditions to better understand how atmospheric circulation may change with expected global warming and what this will mean for rainfall. Together, they found that there would be drier conditions in the tropics and subtropics of the Southern Hemisphere, but that at the same time Australia itself may see an intensification of its monsoon season. This suggests the idea of Australia as a country of drought and flooding rains will only grow more extreme in the future if climate change continues at its current pace.

This study was reinforced by another that looked specifically at monsoons and how they will change, using a period 6000 years ago as a reference point. The researchers modelled this past era to simulate how monsoons changed at this time and then compared this to simulations of monsoonal changes in the future under a high-emissions scenario. This simulation showed that changes to atmospheric circulation led to an intensification of the monsoon season, primarily caused by thermodynamic factors.

While past conditions can give us indications of a future under a changing climate, our best predictors of the future and even some aspects of the present can still be found by using climate models to disentangle the observational data. A team of international researchers investigated whether increases in heavy precipitation from 1951-2015 could be ascribed to human-caused climate change. Using Coupled Model Intercomparison Project - Phase 6 (CMIP6) models, they found it was difficult in the Southern Hemisphere to disentangle natural variation from greenhouse gas influences because of the high variability. By contrast, the observed increases in extreme precipitation over the global land, Northern Hemisphere extratropics, western and eastern Eurasia and global 'dry' and 'wet' regions, were largely explained by the influence of greenhouse gases.

Model studies like this play an important role in future climate projections as well as attribution but, as we all know, they are not perfect and a big part of our research program's work is evaluating and improving them – particularly their representation of future rainfall, which remains a vexing issue.

Increasing the resolution of climate models has been put forward as a way of better capturing the patchy nature of rainfall. A paper by Margot Bador and colleagues found that simulated precipitation extremes were more intense with increasing model resolution, but to get a systematic improvement of rainfall representation required physics tuning. Adding to the difficulty of modelling precipitation, real-world observations were so variable that it made it difficult to quantitively evaluate model performance.

Research from an international team led by Martin Jucker also revealed the choice of convection-resolving models, when looking at locally forced convection, had a significant impact on results. Focusing on the UK Meteorological Office's United Model (UM) and the Weather Research Forecasting (WRF) model, the team found each model had a preferred convective response, independent of what happened in the real world. The UM produced very strong, small thunderstorms early in the day, while WRF regularly produced an impressive squall line in the evening. The researchers speculated this could be a historical artefact of model development and proposed observational campaigns that could address ways to correct these flaws.

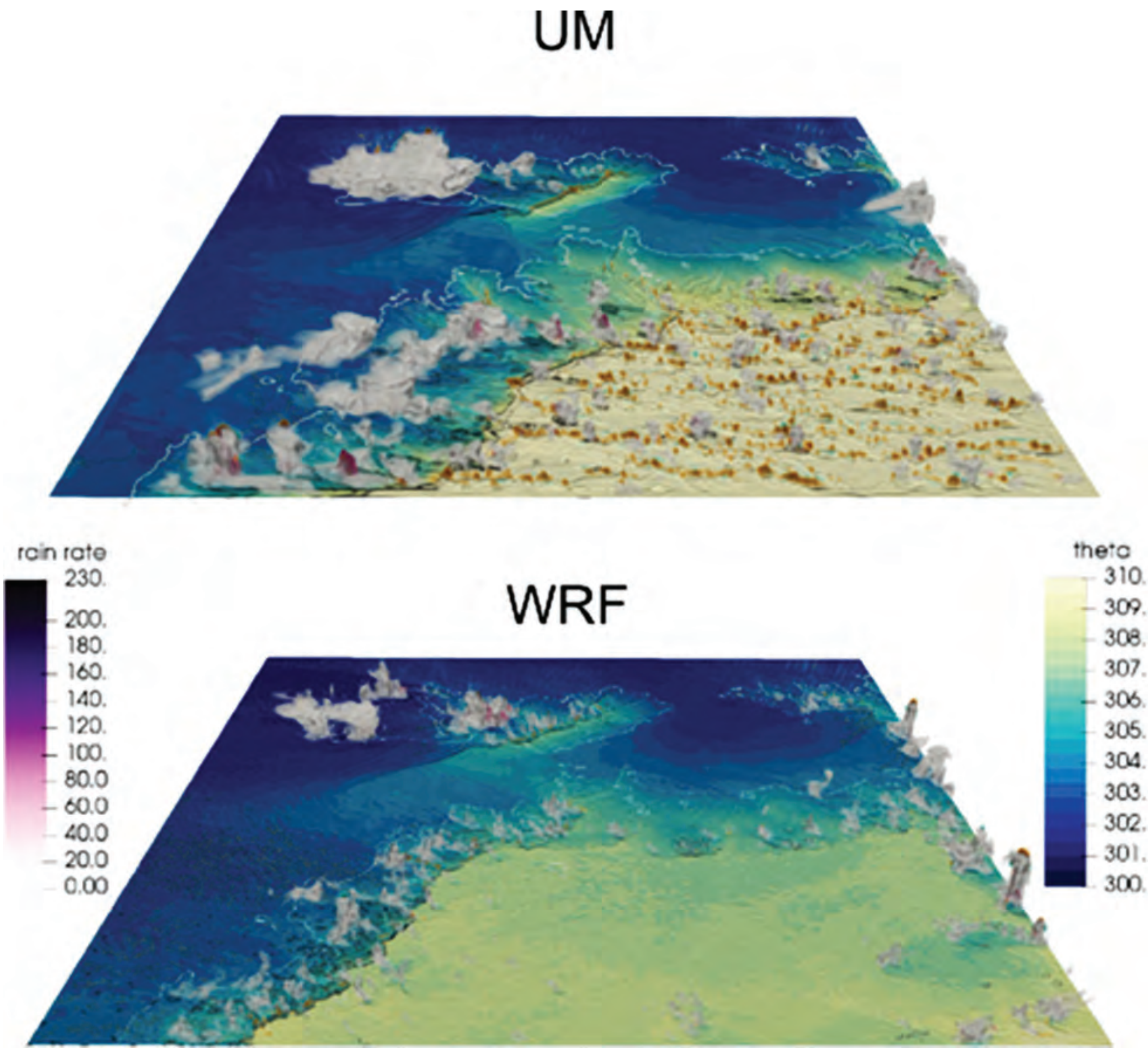


Figure 1: 3D snapshots of surface potential temperature (colour shading), reflectivity (white volume; >10 dBZ), CAPE (black contours at 3, 4, 5×10³ J·kg⁻¹), updraughts (red volume) and precipitation (purple "peaks") for (a) the UM and (b) WRF. The snapshots correspond to 0600 UTC on 02 February 2006

Because precipitation continues to be such a challenge for our models, particularly reproducing tropical precipitation, CLEX researchers examined three generations of models used by the IPCC to see whether the representation of rainfall has improved over time. The results were mixed, with some advances, while in other areas, such as the fraction of precipitation that comes from low-level cloud regimes (warm rain), the models had actually gone backwards. The researchers suggested that large-scale global climate models could be replaced by high-resolution storm resolving models to more accurately capture changes in these more difficult areas. In coming to this conclusion, they noted that improvements in computer processing power meant this was already possible today.

Beyond localised rainfall, modelling high-impact tropical cyclones and how they will change in the future is of growing importance. Pavan Harika Raavi and Kevin Walsh Pavan Harika Raavi and Kavin Walsh examined two parameters used for tracking tropical cyclones – the CSIRO tracking scheme and the Okuba-Weiss zeta parameter – to determine relative performance in simulating tropical cyclone frequency characteristics. They found the Okuba-Weiss zeta parameter corresponded more closely to observations and was able to differentiate between monsoon lows and tropical cyclones.

Our researchers also found that tropical cyclones will likely intensify in a warmer world. Using climate simulations that captured the entire life cycle of a cyclone, from a "seed disturbance" up to a category five event, they found that while there was no trend in the number of cyclones, the speed with which powerful cyclones developed increased. This suggests that rapidly intensifying storms may become more frequent in a future warmer climate and the speed of this increase in intensity will continue to grow as the world's oceans warm.

However, future projections around the number and nature of tropical cyclones relies on a good understanding of ocean temperatures, which are one of the key characteristics that help in their development. And that, according to Margot Bador and colleagues, creates a large area of uncertainty in modelling these cyclones. They found that correcting for the reliability of future sea surface temperatures has a profound effect on cyclogenesis, reducing it by up to 55 percent. The researchers found that this uncertainty in the future patterns of sea surface temperatures could strongly hamper the reliability of projections of South Pacific tropical cyclones. In addition, the researchers found that this strong reduction in tropical cyclone activity was caused by stronger vertical wind shear in response to a South Pacific Convergence Zone equatorward shift.

Another atmospheric phenomenon that is ripe for re-examination is that of atmospheric rivers, which are often associated with extreme flooding events. PhD student Kim Reid has been exploring how atmospheric rivers are defined and identified in climate data and how variation in these definitions explicitly change the number of atmospheric rivers that can be detected through observations and models. She found that when certain definitions were used, or even the order of calculation and resolution processes were changed, that some of the most powerful atmospheric rivers were not detected. This high level of detection uncertainty is something that will need to be resolved across the research community if we are to produce consistent informative research about these important events.

But it's not all bad news for climate models. CLEX researchers and colleagues compared the performance over Australia of the new CMIP6 models to the previous CMIP5 group. The results showed improvements in the latest generation, including better reproduction of land and marine heatwaves and sea-level rise, as well as improved relationships between Australia's climate drivers and rainfall. However, some models continue to show increased sensitivity to greenhouse gas emissions and increased 21st century warming.

While our models may not be perfect, fascinating research by Ewan Short on direct edits by forecasters to numerical weather prediction models suggests humans have their shortcomings, too. These edits are often made to better resolve land-sea breeze and boundary layer mixing. CLEX researchers compared edited and unedited forecast data with weather station observations. The results were nuanced, but broadly showed that when winds were considered at individual stations or averaged over small spatial scales like that of an individual city, the human edited forecast dataset generally exhibited larger errors than unedited model data. However, the human-edited forecast can occasionally produce lower errors than the blended, ensemble average forecast, because ensemble averaging overly smooths the daily varying component of the wind field.

Real-world observations not only allow us to adjust the behaviour of climate models, they also continue to give us insights into our climate and weather that can help us prepare for extreme events. However, one of the key challenges around observations in general, and observations of extreme rainfall in particular, revolves around data sharing between countries. Extremes-relevant data are often restricted because of concerns around the sovereignty of data and commercialisation. As a result, raw data are replaced by 'indices' derived from daily and sub-daily data that measure aspects of extreme precipitation frequency, duration and intensity, because these have far fewer data exchange issues. Recent research by the Extreme Rainfall team examined the advantages and pitfalls of using these indices. It concluded that satellite precipitation products could be used to supplement existing data that uses longer-term in situ measurements. However, more research is required to understand the limitations of the satellite-based estimation process and the challenges of scale between these and in situ measurements.

In follow-up research, CLEX researchers began to look at these issues more closely. The researchers took 22 different precipitation data products and divided them into four categories to evaluate the spread of measurements and determine observational uncertainty. They concluded that none of the datasets by themselves produced a best estimate for precipitation extremes. They suggested the path to getting the most accurate assessment was to avoid using reanalyses as observational evidence and to consider in situ and satellite data (the corrected version preferably) in an ensemble of products. This approach produced a better estimation of precipitation extremes and more plausible observational uncertainties.

Looking at observed precipitation uncertainties in more regional detail, PhD student Loan Nguyen led a study that evaluated the consistency of 13 different observational products of extreme rainfall over Monsoonal Asia. The team found that, while there were broad similarities in the products across the region, large inter-product spread was found in sub-regions such as the Maritime Continent, where ground-based station networks are sparse. The study concludes that the overall quality of the station network has implications for the reliability of both in situ and satellite-based products and that users need to understand how each dataset is produced in order to select the most appropriate product to estimate precipitation extremes to fit their purpose.

One of the best places in the world to get detailed observations of extratropical cyclones is the Mediterranean, which has frequent storm events and a dense network of observational instruments. This network enabled CLEX researchers to examine cyclone-like substructures that can form within massive storms, by focusing on an event that hit the Mediterranean in October 2012. The results showed how the upper atmosphere contributed to the development of the storm and was then amplified again by the terrain below. Together this interaction produced a stable, long-lasting sub-cyclone that by itself caused significant damage. Understanding how each of these characteristics contributed to the development of this storm-within-a-storm can help us to recognise the features that create and sustain these sub-cyclones. With this knowledge, we hope to improve our ability to forecast them and give residents in their path more time to prepare for their impact.

Another massive storm in this data-rich region was Storm Gloria, which struck the Iberian Peninsula in 2020. It gave CLEX researchers insight into which storm-generated waves caused the most damage to infrastructure. Winds contributed the most to the storm surge – around 70 percent along the entire coastline. Atmospheric pressure was generally negligible, while wave set-up itself accounted for up to 40-50 percent of the storm surge in some areas. This is useful information for forecasters that will improve warnings of damaging surf similar to those that hit Australia's lengthy coastline.

While the Mediterranean is well observed, instrumentation on other regions of the world remains sparse. In these regions, other processes are needed to produce the observations that improve the quality of our science. Satellite data are often used to estimate rainfall, but when these estimates are compared with data in areas where rain gauges exist, there is still a significant margin of error. To reduce this error, a CLEX researcher and international colleagues developed a hybrid approach to estimate recent rainfall that combines satellite-based rainfall estimates with satellite-based soil moisture estimates. When this approach was tested against independent rain gauge measurements, it showed notable improvements in a range of metrics when compared to other existing satellite-derived estimates.

Another way of getting useful observations is through radar networks. CLEX researchers developed the Radar Organisation Metric (ROME) that can assess the degree of convective organisation in the tropics. ROME's statistical properties suggest it is able to distinguish between the degree of convective organisation, and it also captures different regimes of the monsoon in Northern Australia. This adds new capabilities that other metrics lack.

And then, of course, we can always improve the number of raw observations – something our citizen science project, WeatheX, which has now moved into its second phase, intends to do. This improved version has proven to be more popular than the first and, as a result, we saw 270 user reports of storms that passed through south-east Queensland in early November. This information is invaluable in helping us understand how these storms develop, comparing what we see on radars with what is happening on the ground. It will also provide important data that will improve our ability to forecast these rapidly developing events. Through our partnership with BoM, IAG, Risk Frontiers and the NSW Department of Planning, Industry and Environment, we expect to see the WeatheX app continue to improve and provide us with valuable data for our research.

But not all observations are on the ground. Another observational study, taken from instruments in ascending balloons, revealed some fascinating interactions between clouds and their environment. The study investigated vertical profiles of horizontal wind speed measured by instruments near Darwin, Australia. This vertical movement influences fair weather and cloudiness over broader areas and it has, until recently, been considered that clouds mostly only respond to the vertical movement. However, the Darwin observations confirmed a recent study of the Atlantic Ocean that showed the clouds themselves can emit waves in a way that is similar to stones being dropped in a pond, and this in turn influences vertical motion and influences the clouds. These findings suggest a two-way coupling of clouds to their environment, with potentially important consequences for our understanding of weather and climate phenomena.

Amidst the research coming out of the Extreme Rainfall program, great strides have been made that will benefit the entire climate community here and overseas. In early November, we announced the release of version 1 of the Aus400 data set for community use. The data set is the culmination of a collaborative project between the Centre of Excellence, BoM and National Computational Infrastructure and is based on a simulation at 400m grid spacing right across Australia, covering a 60-hour period that starts on March 26, 2017. The 400m domain has more than 12.6 billion grid points and at its completion was the largest simulation with the UM ever conducted.

The output shows 3D variables every one hour and 2D variables every 10 minutes. This incredibly detailed simulation captures the period when severe tropical cyclone Debbie made landfall, the passage of a cold front over southern Australia and severe storms in other areas of the continent. This is the highest-resolution simulation of the atmosphere ever produced over all of Australia. It will be used as the basis for a range of scientific endeavours and to create a detailed, animated simulation later in 2021. A workshop to discuss the first results from the analysis of the simulation is planned for Feb/Mar 2021.

The important role that CLEX researchers play in Australia's climate science community was also highlighted by the publication of the Climate Processes Research in Australia report, led by Christian Jakob. The report was produced in response to a request by the National Climate Science Advisory Committee for input to its strategic discussions in the area of climate processes research. Specifically, it summarises the current state of climate processes research in Australia, identifies gaps and provides options for moving the area forward into the next decade. It is a key document that will inform the infrastructure and direction of Australian climate research into the future.

CLEX researchers have played a pivotal role in a Special Issue in *Environmental Research Letters*, Focus on Extreme Precipitation Observations and Process Understanding. This collection of papers was put together as part of a joint initiative by the World Climate Research Programme Grand Challenge on Extremes, the Global Energy and Water Cycle Experiment and the International Precipitation Working Group. It follows on from the development of a global database of precipitation – Frequent Rainfall On GridS (FROGS) – in which CLEX researchers also played a key role. This database contains global gridded daily precipitation products from in situ, satellite and reanalysis products in a common format, enabling researchers to intercompare observed rainfall extremes easily and to begin to understand some of the large uncertainties that exist in our global products.

Of course, we can't conclude our report without mentioning the many individual achievements among the team of extraordinary researchers that make up the Extreme Rainfall research program.

Associate Investigator Ben Henley received a well-deserved Victorian Young Tall Poppy Award in recognition of an extraordinary body of work for an early career researcher. Sopia Lestari was selected as a recipient of the Hadi Soesastro Prize (Australia Awards) for 2020. It's an impressive result for Sopia, as only two Hadi Soesastro Prizes are awarded annually.

Postdoctoral researcher Nina Ridder recently gained a key position in the climate science community when she was elected to the executive committee of Young Earth System Scientists (YESS). The committee helps maintain an overview of YESS and guides the community's activities.

Congratulations also go to CLEX Chief Investigator Lisa Alexander, who has had a very rewarding year. First she was announced as a new fellow of the Australian Meteorological and Oceanographic Society, then she was named by Clarivate as a highly cited researcher in its 2020 list. She has now has been promoted to full professor.

Chief Investigator Julie Arblaster was also made a full professor, this time at Monash University. This makes her the only female professor with a continuing academic position at the Monash School of Earth, Atmosphere and Environment. Julie also joined the CMIP panel. This panel oversees the design and coordination of climate model experiments that feed directly into the IPCC's assessment process, and it is at a critical stage of planning for the CMIP7 round of coordinated experiments.

PhD student Kim Reid, along with colleagues from Earth sciences, was on the committee that successfully ran the 32nd Victorian Universities Earth and Environmental Science Student Conference. Kim's outreach activities have also included a regular

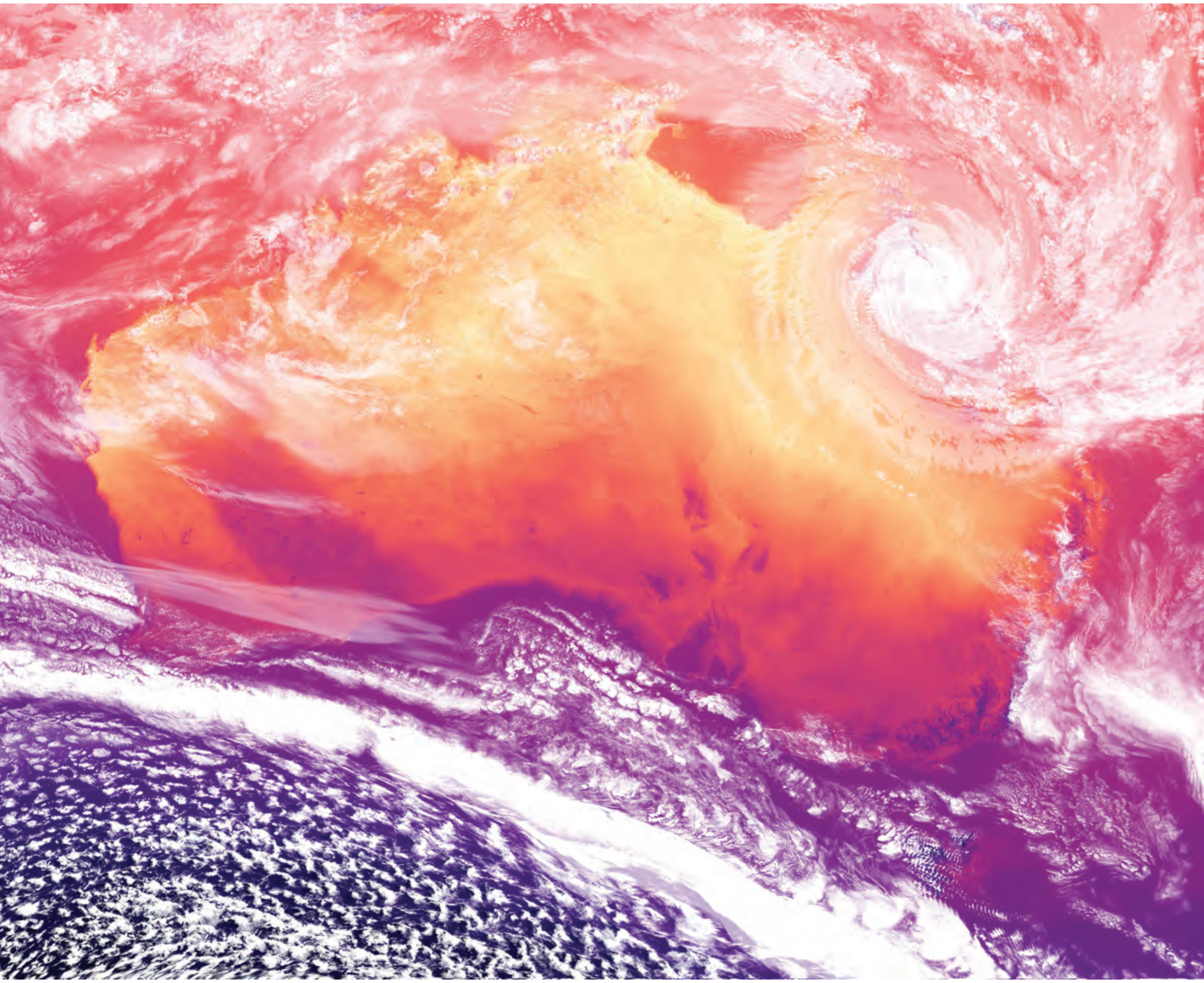


Figure 2: Temperature and cloud graphic generated from Aus400 simulation by CMS team member Scott Wales

blog on the CLEX website that has tackled many topics important to students and young researchers.

We have also had a range of other funding successes. Steve Sherwood, Jason Evans, Fei Ji and Andrew Dowdy received a linkage grant that seeks to better understand and predict wind gusts and their impacts, to aid in planning and adaptation. Associate Investigator Yi Huang received funding from the Joyce Lambert Antarctic Research Fund to study clouds, precipitation and boundary-layer characteristics in sub-Antarctic mesoscale cyclones.

Christian Jakob edited a comprehensive overview of research on clouds and their role in our present and future climate, covering theoretical, observational and modelling perspectives in Clouds and Climate: Climate Science's Greatest Challenge; and to cap it all off, Kim Reid won first place in a Haiku Thesis competition. Her thesis, "Impacts of atmospheric rivers in Australia and New Zealand", was rendered into poetry that seems a perfect way to conclude this report. The haiku reads:

Rivers in the sky
Growth, life, destruction and death
What will you bring us? ■

RP2:
Heatwaves and Cold Air Outbreaks

Highlights

- Research reveals distant cause of record marine heatwaves and improves our ability to forecast them
- International research into IPCC burning embers diagrams finds that major climate change impacts occur at lower global temperatures than previously estimated
- Our research finds prescribed burning days will shift in time but not decrease in number along south-eastern Australia as a result of climate change
- New framework developed for detection and attribution of human-caused climate change in heatwave events
- Extreme weather in Australia was blamed on a sudden stratospheric warming event in late 2019, but RP2 researchers found wind changes over Antarctica were the real cause.

Despite all its challenges, this year has seen the Heatwaves and Cold Air Outbreaks research program team tackle some of the most difficult problems in our field, ranging across the following: unexpected phenomena, like sudden stratospheric warming; a new detection and attribution framework for recognising climate change signals in heatwave events; and a range of new metrics to accurately capture the impacts and improve the modelling of heatwaves.

Perhaps the greatest advances have been made on marine heatwaves, our team working closely with ARC Centre of Excellence for Climate Extremes (CLEX) researchers in the Climate Variability and Teleconnections research program team. Here we have seen significant improvements in our understanding and ability to forecast marine heatwaves.

In the latter part of this year, researchers from both research programs came together to identify the worst marine heatwaves and then reveal the key processes that triggered them and led to their eventual demise. They found that these record-breaking heatwaves tended to occur in summer but, surprisingly, before the annual peak for warmest ocean temperatures had occurred and were most often associated with El Niño events. The key factor that formed these marine heatwaves was a lack of wind and clear skies, usually caused by persistent high-pressure systems. These stalled systems prevented ocean mixing, keeping warmer water closer to the surface. This still, warm water at the top of the ocean had profound impacts on algal growth, a foundation species for ecosystems, but in completely opposite directions, depending on the latitude where they occurred. In tropical regions, marine heatwaves caused a decline in this growth because it prevented nutrients from rising to the surface. However, closer to the poles, where nutrients were plentiful but sunlight less so, marine heatwaves prompted a rapid growth in algal blooms. Both responses have a direct impact on ocean productivity and the fisheries in these regions. This research brings us another step closer to improving our capacity to forecast marine heatwaves and their impacts right around the world.

This also matters to many aquaculture and fisheries industries because marine heatwaves impact the foundations of the ocean food chain, with new research from CLEX showing how nutrient variation, in combination with marine heatwaves, can affect ocean productivity. Marine heatwaves are expected to expand and intensify in coming decades due to climate change, while nutrient-poor waters are projected to expand globally. These findings suggest that weaker blooms during marine heatwaves will therefore become more common and widespread.

These effects of marine heatwaves have resulted in a call from international researchers, led by our program's investigators, that highlights the need for the development of systems to predict marine heatwaves. The authors said there is a need for streamlined and simple information and forecasts that can be widely shared with stakeholders, preferably via a central point where information and news is provided in a consistent and accessible manner. If this were introduced, marine-resource users and managers of fisheries, aquaculture and conservation would be able to take action to minimise damage – such as harvesting or relocating farmed species, or providing short term protections like cooling or shading.

CLEX researchers are already moving on this front. Along with other colleagues, they investigated the large-scale drivers that led to the development of marine heatwaves off southeast Australia, observed from 1994-2016, including the extreme 2015/16 event. They found about half of marine heatwaves in this region were primarily due to the intensification of the East Australian Current Extension, bringing warmer water with it. The slow-moving waves that generated this can't be seen by the naked eye but the change in wave heights they generate can be detected by satellites. This work means it may be possible to forecast major marine heatwave events around Tasmania up to three years in advance.

These observations are useful but, to truly understand and forecast marine heatwaves, we need to improve how we model these events. The fundamental research being carried out on marine heatwaves in 2020 brought together observations of these oceanic heating events and compared them to marine heatwaves produced by climate models at low, medium and high resolutions. They found that, regardless of their resolution, all simulations have weaker, longer and less-frequent marine heatwaves, when compared with the real world. Despite these differences, they found that simulations with medium and high resolutions realistically represented global spatial patterns of these heatwaves. However, the ocean simulations with high resolution were preferable when studying regional patterns of these events. This research will help us to better understand computer simulations of future oceans, under climate change conditions.

While we still have much to learn about marine heatwaves, heatwaves over land are better represented by climate models. This allowed our researchers to investigate if there was a difference in the number of heatwaves over land for exactly the same global average temperature in a world that was still warming compared to a world where the warming had plateaued. Using a novel methodology applied to Coupled Model Intercomparison Project -Phase 5 (CMIP5) projections, CLEX researchers found that the

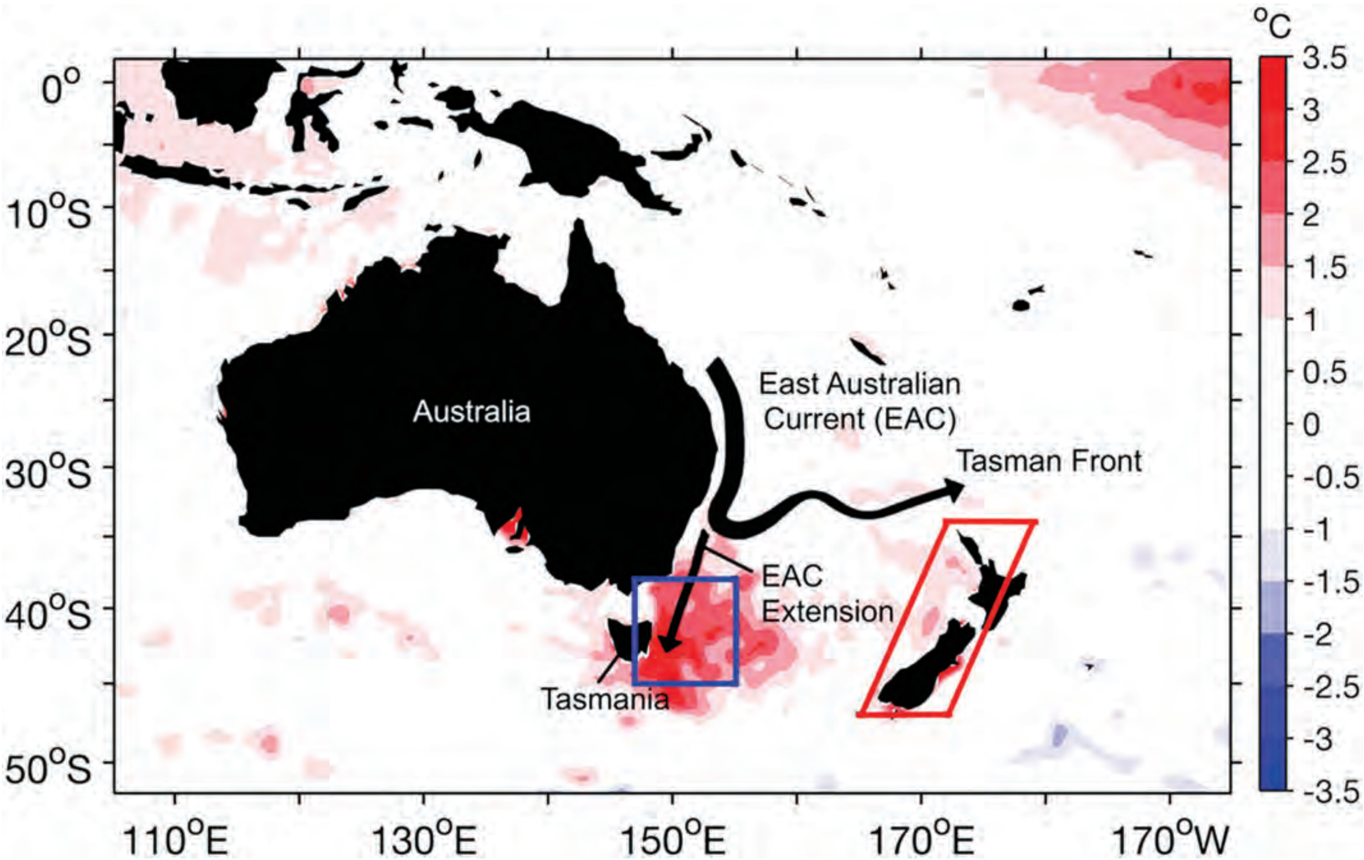


Figure 1: The mean sea surface temperature (SST) anomalies for the 2015/16 austral summer (December–February) relative to the 1982–2011 climatology from NOAA OI SST. The blue rectangle highlights the SEAus region. The red trapezoid defines the region around New Zealand analyzed in this study as a recipient and source of SSH anomalies from Rossby waves. (Li, Holbrook, et al 2020).

the local temperatures experienced by 90 percent of people would be substantially higher in a transient (still warming) climate than an equilibrium climate where the temperatures have plateaued, for the same global temperature. The study demonstrates that it is vital that the use of transient or stabilised climate simulations is explicit in future projections, so decision-makers can best prepare for future warming.

Understanding heatwaves and their impacts at this local level provides the most useful information for these decision-makers. A perfect example of this is a regional study of prescribed burning days in south-east Australia that produced an unexpected result. The study found that along the east coast, from Queensland right round to South Australia, the number of days suitable for prescribed burning would change very little and, in some places, would even increase. What did change was when the weather was suitable, shifting from autumn to winter and early spring. Unfortunately, this also corresponded to changes in inversion layers, which keeps smoke and pollution closer to the ground.

Heatwaves themselves can also be influenced by local conditions, particularly in Australia. Dry soils have been shown to amplify heatwaves in the Northern Hemisphere but surprisingly little work has been done on this effect in Australia. In exploring these knowledge gaps, CLEX researchers found that regions where there is a larger drying trend tend to be more sensitive to land water availability and have more heatwave days. However, they found that the effect of dry soils before a heatwave varies considerably across Australia. The results of this study may require classifying the land into regions where soil water variability affects surface temperatures and where it doesn't. This could be extended to other atmospheric processes to differentiate between local and remote influences.

Perhaps the most policy-relevant decisions need to be made in regard to urban environments, where a greater part of the Australian population lives. With this in mind, our Drought program researchers produced a new cross-scale modelling framework for urban environments that has been applied to calculate how electricity and gas demand will change under future climate change and air-conditioner ownership scenarios. Our researchers used Melbourne as a case study, capturing interactions across building, urban and atmosphere scales at a higher temporal resolution than any location worldwide. The framework developed with this research was also able to undertake century-scale simulations, an order of magnitude longer than previous coupled building-urban-atmosphere studies. The building energy demand, urban climate and global climate modelling systems resulting from this study are open-source, and model outputs are also available across the century at half-hour time steps. This is important and timely research as our energy systems transform.

And then there is that most personal of impacts: how it feels to be subjected to heatwaves and other weather conditions. To date, the scale used by researchers to measure "thermal comfort" has been a primitive one designed for interior use. Its descriptions range from cold (-3), through neutral (0) to hot (3). This fails to take into account the affective state, such as whether something is pleasant or unpleasant, along with many of the other comfort aspects that occur in outdoor environments, including changes in wind, solar radiation and humidity. CLEX researchers, with colleagues from the University of Sydney and Hong Kong Polytechnic, came together to produce more meaningful climate descriptions than simple measures of wind speed, temperature etc. These new descriptions can then be used in research and or public announcements of weather conditions. Together, the researchers created a multidimensional scale using plain language descriptors and then tested it with members of the public. The results showed non-professionals were able to consistently interpret this much more nuanced and evocative multi-dimensional thermal perception scale regardless of whether they were exposed to the actual thermal environment or not. In the future, our weather forecasts may be able to accurately describe how you will feel in the coming days.

While policymakers and individuals may focus on local conditions, our research also has an international reach. Through national and international collaborations, we continue to make strides to improve how climate science is conducted worldwide.

Internationally, detecting and attributing a climate component to extreme heatwave events has become an important area of study over the past decade, particularly in communicating the immediacy of climate change impacts in a way that the climate science community understands. However, recently there has been considerable discussion within this community about the reliability of these attribution studies. To overcome this, CLEX researchers joined a team of international researchers to compile a detailed detection and attribution protocol for future analyses. In addition to building a consistent, robust attribution framework for future researchers to follow, they also produced a plan for communicating these results to the public. The upshot is a foundational process that acts as a reliable framework, highlights potential pitfalls to be avoided and puts in place a consistent process that can now be used by attribution researchers worldwide.

Another international collaboration looked at the burning embers diagrams used in Intergovernmental Panel for Climate Change (IPCC) reports. The burning embers diagrams aim to produce a consistent set of figures that indicate when climate impacts will be felt as global temperatures reach identified temperature thresholds. While the review focused on the clarity of these figures and on producing a consistent structure for the expert elicitation process that informs these impact diagrams, the standardised comparison used by the researchers also produced a separate, unexpected result. The researchers found that, as the science improved across the IPCC reports, a clear trend appeared showing that major impacts such as heatwaves, coral bleaching and the collapse of the West Antarctic ice sheet became more likely to occur at lower temperatures than originally estimated. So, while the review produced new protocols to improve these impact diagrams, it also added further emphasis to the need to take urgent action to prevent the worst impacts of global warming.

A key component of international modelling research is focused on reducing errors and ensuring that physical processes are simulated accurately. As part of this ongoing process, CLEX researchers addressed the error compensation issue for temperature extremes by defining a novel performance metric that identifies those models that can simulate temperature extremes well – and do so for the right reasons. This investigation compared additive errors in CMIP5 and CMIP6 models. We found the overall performance of an ensemble improves when increasing the horizontal resolution, largely due to improvements in synoptic scale variability. We also found that CMIP6 improvements relative to CMIP5 surpasses those expected from the increase in horizontal resolution alone, suggesting model improvements associated with representation of physical processes.

One of the most challenging areas in climate models is downscaling, which is the modelling of climate processes over regional areas. As noted earlier, this scale is important for policymakers to be able to make accurate decisions about adapting to climate in different areas. However, this work uses regional climate models (RCM) that are more expensive in terms of time and computing resources when compared to global climate models (GCM). To determine if RCMs produced more valuable results compared to GCMs, CLEX researchers simulated the Australian climate using both. They found overall, RCMs simulated the Australian climate more accurately than GCMs, particularly for some regions like the heavily populated and economically important east coast. This research was also the first to develop a method that shows where and when RCMs simultaneously add value to modelled representations of the present-day climate, while at the same time making different projections about future climate change compared to GCMs. When RCMs show both of these attributes, it suggests that they confer plausible improvements in future climate projections, relative to GCMs. The researchers called this new quantity the ‘realised added value’ shown by RCMs.

Another new metric developed by the Heatwaves and Cold Air Outbreaks team is cumulative heat. It came from the first comprehensive worldwide assessment of heatwaves down to regional levels, which has revealed that in nearly every part of the world heatwaves have been increasing in frequency and duration since the 1950s. The new, cumulative heat metric reveals exactly how much heat is packed into individual heatwaves and heatwave seasons.

Closer to home, as we move towards the next IPCC report and examine the new range of CMIP6 models that will play a large part in its projections, our researchers have been looking at how well these new models reproduce conditions over Australia. Working with researchers at CSIRO and the Bureau of Meteorology, we found they show small improvements over the previous generation (CMIP5, developed around 2012), including better reproduction of land and marine heatwaves and sea-level rise as well as improved relationships between Australia’s climate drivers and rainfall. The issues around increased climate sensitivity shown in some of the CMIP6 models also appeared in some of our Australian projections, although this aspect continues to be investigated internationally to determine the reason for these differences.

We also focused on a particular event that was blamed for bringing extreme weather, both hot and cold, to Australia in late 2019. A powerful, but relatively rare, influence on Australia’s climate is a phenomenon known as sudden stratospheric warming (SSW), which can slow or reverse the wind direction around the Antarctic. These happen rarely in the Southern Hemisphere but when they do occur, they have predictable and severe weather impacts. It has long been assumed that the sudden upper stratosphere warming is the primary contributor to these predictable extremes. However, CLEX researchers revealed that it wasn’t the SSW itself that led to these impacts but the reversals of winds around the Antarctic that mattered. This suggests that any slowing or reversal of Antarctic winds may have similar impacts regardless of the cause.

SSWs are far more common in the Northern Hemisphere than the Southern Hemisphere, but they occur more frequently at both poles in winter than any other season. The most recent example of a Northern Hemisphere event occurred in 2018. This SSW event was linked to a severe system nicknamed the “Beast from the East”, which brought very low temperatures and heavy snowfall to

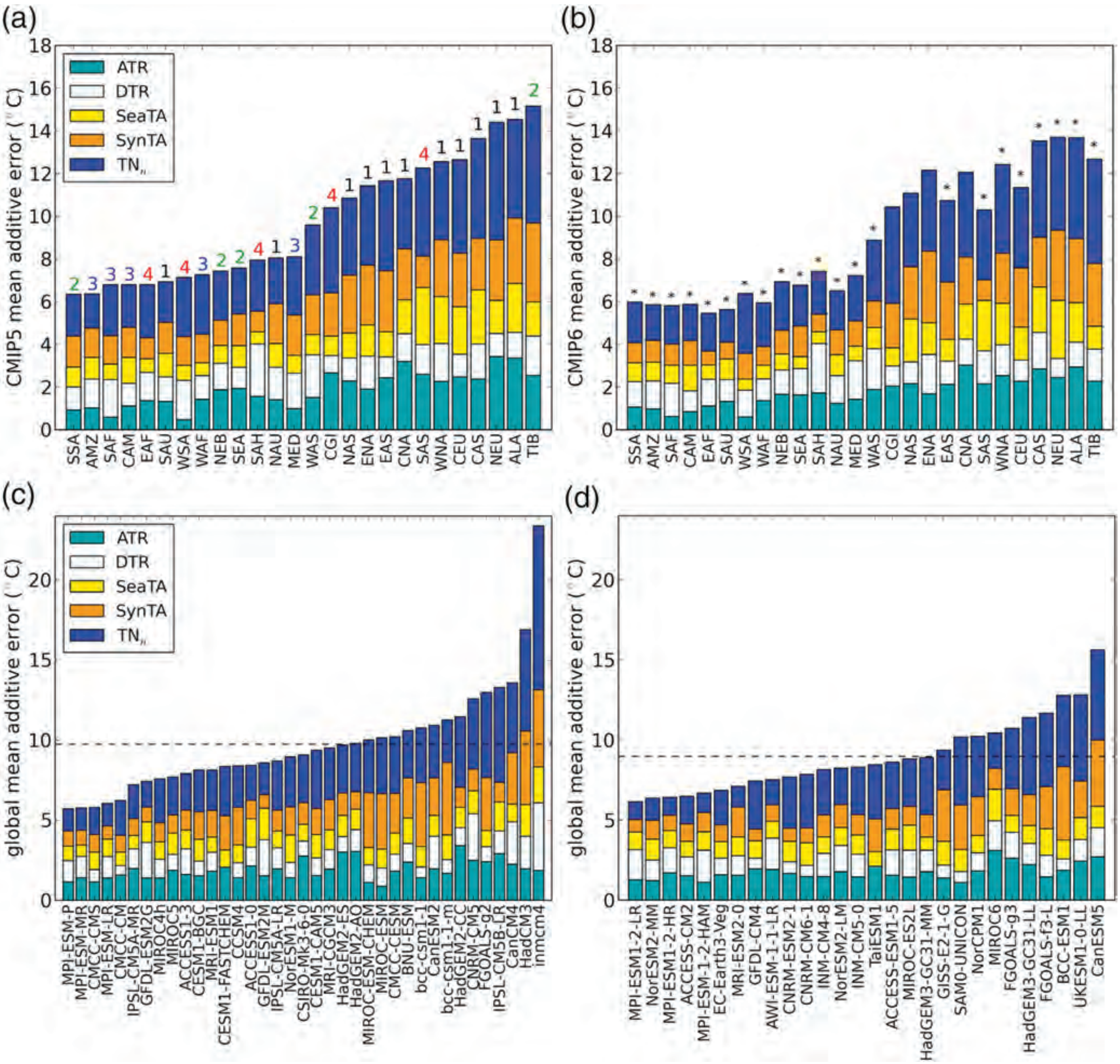


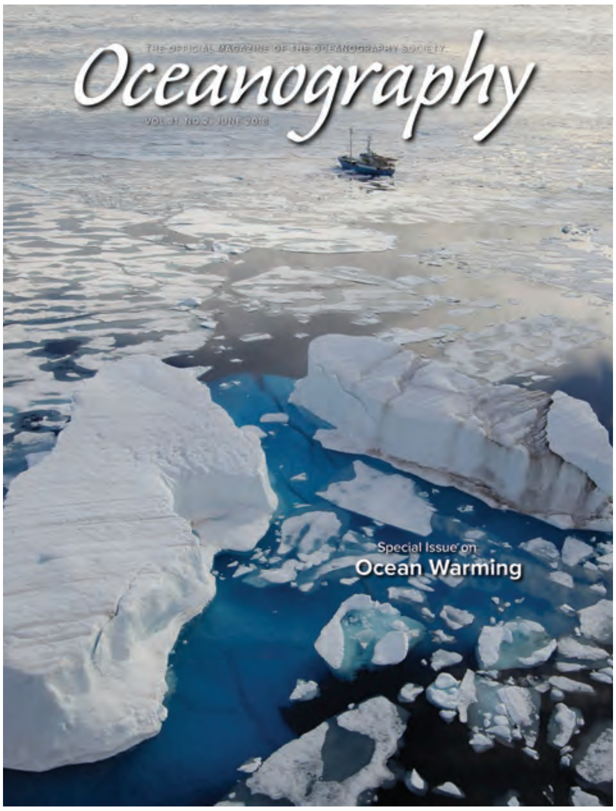
Figure 2: Top panels show ensemble-mean additive errors across SREX regions for the CMIP5 (a) and the CMIP6 (b) ensembles. Numbers 1–4 on top of bars in (a) quantifies the observational uncertainty based on the quartile of the percentage of models with an error lying outside the observational uncertainty range. The asterisk on top of bars in (b) is added when CMIP6 improves on CMIP5 for that specific region. Bottom panels show global-mean additive errors for individual CMIP5 (c) and CMIP6 (d) models. In all panels, the contribution to the total additive error by individual decomposition terms (see Equation 6) is shown using different colors. Figure S3 in the supporting information shows the location/extent of the SREX regions. Di. Luca, Pitman, de Elía (2020)

western Europe. Surprisingly, this link and its impacts had only previously been made through climate model studies. Our researchers working with international colleagues used, for the first time, observations to study the connection and analyse the impacts. The analysis confirmed the link between Northern Hemisphere SSWs and extreme events but the pattern was particularly unusual. The observations showed below-average temperatures tended to precede SSW events, but the intensity of cold extremes, such as the coldest night of the month, was strongest after the SSW event.

As well as finding answers in high-tech climate models and logs of computer data, our researchers have been looking backwards in time, picking through documents in an effort to extend Australia's meteorological record. Joelle Gergis and Linden Ashcroft have been leading a project to dust-off forgotten old weather journals from Adelaide as part of a process to create the longest continuous daily temperature record in Australia– and one of the longest in the Southern Hemisphere. This has also led to the creation of a citizen science project, Climate History Australia, which aims to get Australians involved in transferring the data from journals into the digital realm.

Outreach has been a strong part of a successful year for Linden and Joelle. Joelle was awarded the Australian Meteorological and Oceanographic Society (AMOS) Science Outreach Award after a spectacular 2019 that saw her promote her book, *Sunburnt Country: The History and Future of Climate Change in Australia*. Not to be outdone, Linden – we have just heard – has received the 2020 AMOS Science Outreach Award. Linden has also become Editor-in-Chief of the Geoscience Data Journal which focuses, as the name suggests, on scientific data, producing open-access peer-reviewed data sets.

Our world-leading work on marine heatwaves has also seen our research cited in the WMO Statement on the State of the Global Climate in 2019, published in 2020 – with two papers by our researchers, The role of natural variability and anthropogenic climate change in the 2017/18 Tasman Sea marine heatwave and Categorizing and naming marine heatwaves.



In another form of outreach to the wider community, Sanaa Hobeichi has added CLEX School Resources Developer to her research roles. This new role is part of the Knowledge Brokerage Team led by Ian Macadam. Sanaa will be responsible for ensuring the Centre of Excellence delivers educational resources on climate science and/or weather that are tailored to the needs of secondary school maths and science teachers.

It is a marvel that all these accomplishments have occurred during this extraordinarily difficult year, and it says much for the quality of people within CLEX and our Partner Organisations that make up the Heatwaves and Cold Air Outbreaks program. ■

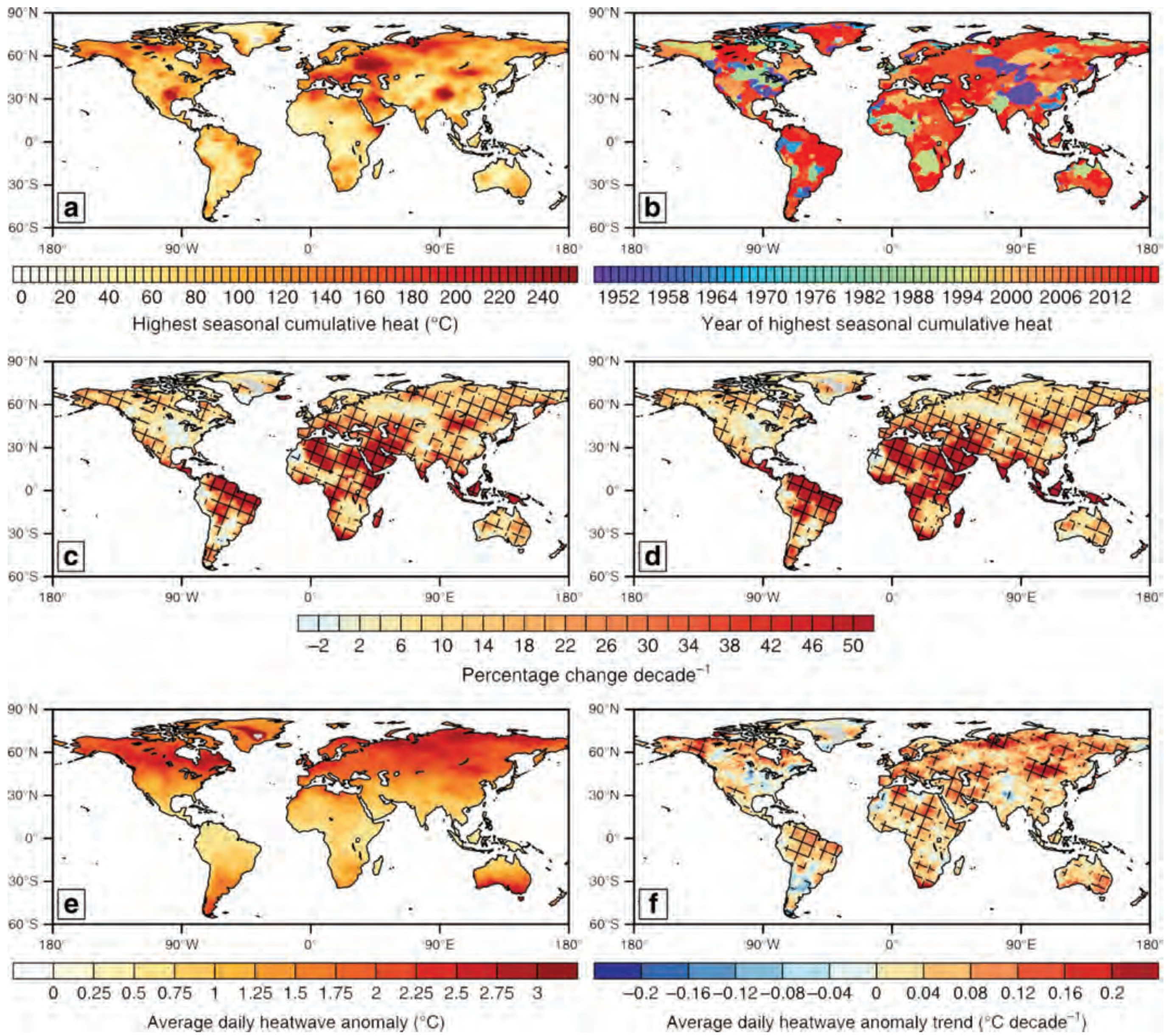


Figure 3: The highest seasonal cumulative heat (sum of anomalies relative to the calendar-day 90th percentile) (a); the year in which this value occurs (b); decadal trends in the percentage change of cumulative heat (c) and heatwave days (d); the average anomaly of a heatwave day (e) and the respective decadal trend (f). All values are calculated for the global observational dataset Berkeley Earth, for 1950–2017. Perkins-Kirkpatrick and Lewis (2020).

Making climate change personal

In 2020, the ARC Centre of Excellence for Climate Extremes moved into a research space that brings climate change impacts into the home. Early Careeer Researcher Mat Lipson produced a world-first, low-cost modelling framework for urban environments that, for the first time, can calculate how our electricity and gas demand will change under future climate change and air-conditioner ownership scenarios. This work was co-authored by Marcus Thatcher at the University of Reading and our own Melissa Hart and Andy Pitman.

This framework means climate researchers can now perform century-long simulations showing how the power demands of cities will respond to climate change and individual heat extreme events. The model combines building energy demand, urban climate, and global climate models using an open-source model that can produce outputs across an entire century and half hour time steps.

Meanwhile, as Mat focused on cities right down to the building level, Dr Negin Nazarian went one step further, investigating climate change impacts on individuals. As part of Project Coolbit, Negin used wearable devices to investigate individual thermal comfort levels and identifying changes to core body temperatures that lead to heat stress. Her most recent research has shown that these devices may be able to account for individual physiologies, activities, and the extreme microclimates created by built environments through the urban heat island effect.

Her results have found that wearable devices had a high degree of accuracy when measuring body core temperature and could quantify the thermal comfort impact on human activity. The next stage of her research is already looking at novel approaches to measure ambient air temperature in real-time.

Together, these wearable devices may make it possible to warn vulnerable people and physically active workers toiling in hot environments when dangerous heat stress develops. They could also help urban planners better design built-environments to minimise the amplification of extreme heat events. As such, these are human-centred approaches to extreme heat events have the potential to build rich and detailed datasets that will save lives and change the way we plan and construct our cities and suburbs. ■

STEPHEN GRAY WARRUMBUNGLES

RP3:
Drought

Highlights

- Research suggests we should invert our approach to droughts; instead of looking at what causes them it may be more useful to understand why drought-breaking rain fails to appear
- Long-term records of Indian Ocean Dipole activity revealed it and ENSO variability played a key role in bringing drought-breaking rains to Australia
- Research reveals origin of Australian rainfall and how this varies during drought
- Major study examining how droughts might change in the future, using CMIP6
- Plant hydraulics explored and coupled into a land surface model to improve the response by the surface to drought
- And while hardly a “highlight”, Mike Roderick retires.

To open this report, we celebrate the career of one of the Drought research program leaders, Prof Mike Roderick who retired in 2020 after a significant and sustained contribution to the ARC Centre of Excellence for Climate Extremes (CLEX). He has been a key mentor to many over this time and has made a career of asking apparently simple questions that turn out to have profound implications. Not surprisingly, Mike didn't leave us with a whimper but a bang. Just prior to his retirement announcement, Mike presented a virtual seminar on drought, bushfires and climate. It attracted more than 350 people and now holds the record for the largest seminar attendance at the ANU's Research School of Earth Sciences. It is a reflection of the esteem in which he is held and we wish him well in his retirement.

As the Drought program has developed over the past few years, we have reached a point where some of our latest research suggests that instead of looking at what causes droughts, it may be more useful to understand why drought-breaking rainfall fails to occur over extended periods. Using Australia's more than century-long observational record, our researchers found that drought-breaking rainfall in south-eastern Australia primarily corresponded with negative Indian Ocean Dipoles (IOD) and La Niñas. Similarly, the likelihood of a drought occurring over the Murray Darling Basin and south-east Australia increased as the length of time between either negative IOD or La Niña events lengthened. This suggests that, if we look at how future droughts may change over these parts of Australia, understanding how climate change affects the frequency and intensity of either negative IOD or La Niña events will be key to improving the robustness of projections.

On far longer time scales, CLEX led an examination of how paleoclimate evidence could provide rich insights into the IOD. We found that strong Indo-Pacific variability was important in breaking droughts over the last 1000 years. Paleoclimate evidence for hydroclimate changes during the last millennium highlights the importance of interannual IOD and El Niño Southern Oscillation variability in providing the rainfall that breaks droughts in regions that are impacted by these modes of variability.

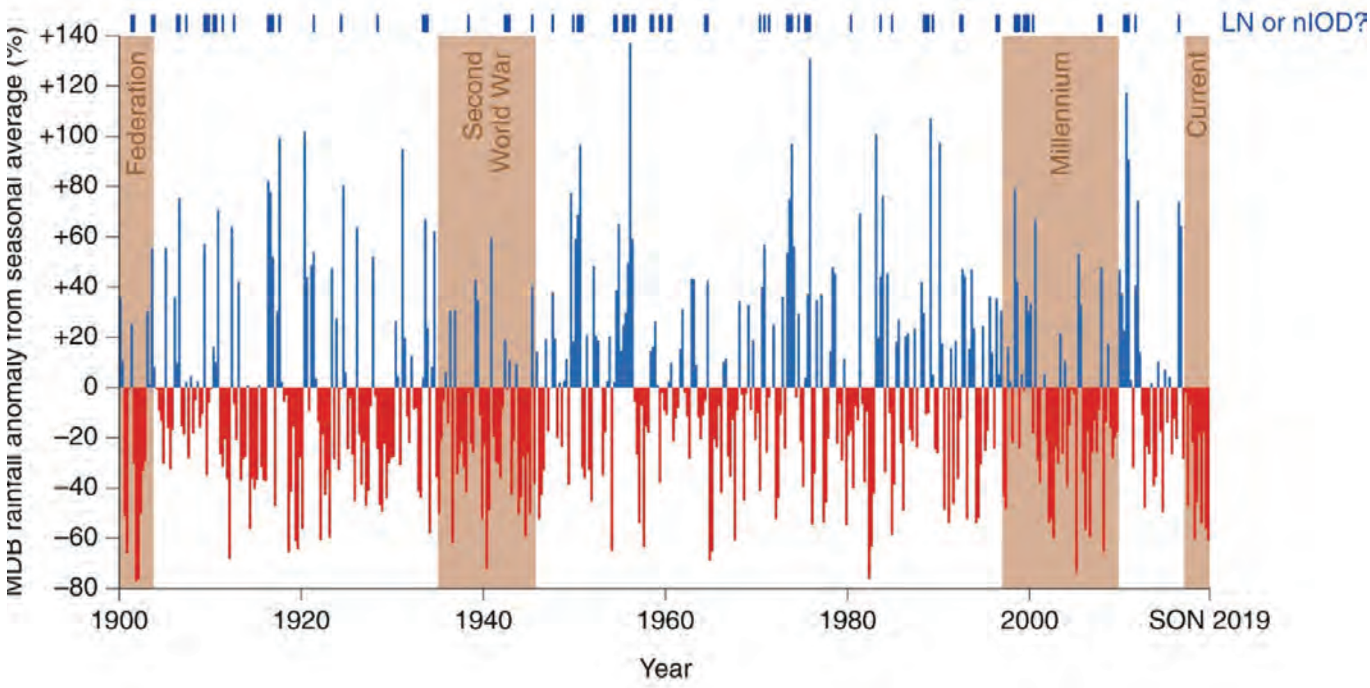
As Australia experiences droughts on a relatively regular basis, our research also extends to understanding how they affect our native vegetation and agricultural crops. It found cultivated lands and grasslands were most sensitive to drought conditions and experienced the most severe impacts. The impact on natural vegetation varied, with it being more robust to drought conditions in areas of high humidity and more sensitive in arid landscapes.

Direct observations with our colleagues at Western Sydney University have also revealed how trees may respond to future higher levels of atmospheric carbon dioxide. The results were unexpected. In the first experiment of its kind applied to mature native forest, as well as the first in the Southern Hemisphere, the researchers exposed a 90-year-old eucalypt woodland on Western Sydney's Cumberland Plain to elevated carbon dioxide levels. As expected, the trees took in about 12 percent more carbon under the enriched CO^2 conditions but they did not grow any faster. A carbon-tracking analysis showed that the extra carbon absorbed by the trees was quickly cycled through the soil and returned to the atmosphere, with around half the carbon being returned by the trees themselves and half by fungi and bacteria in the soil. These findings have global implications: Models used to project future climate change – and the effects of climate change on plants and ecosystems – currently assume mature forests will continue to absorb carbon over and above their current levels, acting as carbon sinks. This suggests those sinks may be weaker or absent for forests on low-nutrient soils.

But when it comes to droughts, it is important to understand how water moves through the system. How plants use and distribute water is an important element in understanding evaporative processes. And as our research continues to show, there is not a one-size-fits-all response in how different plant ecosystems respond to similar changes in conditions. This was highlighted in a paper that looked at how plant hydraulics responded to dryness. Using satellite and field observations, the researchers found that in temperate forests the capacity for vegetation to distribute water to all parts of the plant declined with increased dryness. In contrast, when it became drier in arid areas, the capacity for plants in these environments to shift water to different parts of their system increased. This goes to the heart of the complexities involved in land surface models.

We also need to understand how water moves through the terrestrial environment more broadly. Despite widespread interest in hydrologic variability, there is currently no general climatology of the variability of the water cycle over land and this has limited the development of the underlying science of hydrologic extremes. In an effort to develop a climatology, our researchers used a recently published global hydrologic reanalysis (1 degree, 1984-2010) to present, for the first time, a global climatology of hydrologic variability. The results highlighted the challenges of developing such a climatology, revealing that the variability in streamflow was often greater than the variability in rainfall, while surprisingly, there was much lower variability in the amount of water released by plants through evapotranspiration.

Where the water comes from also matters. PhD student Chiara Holgate



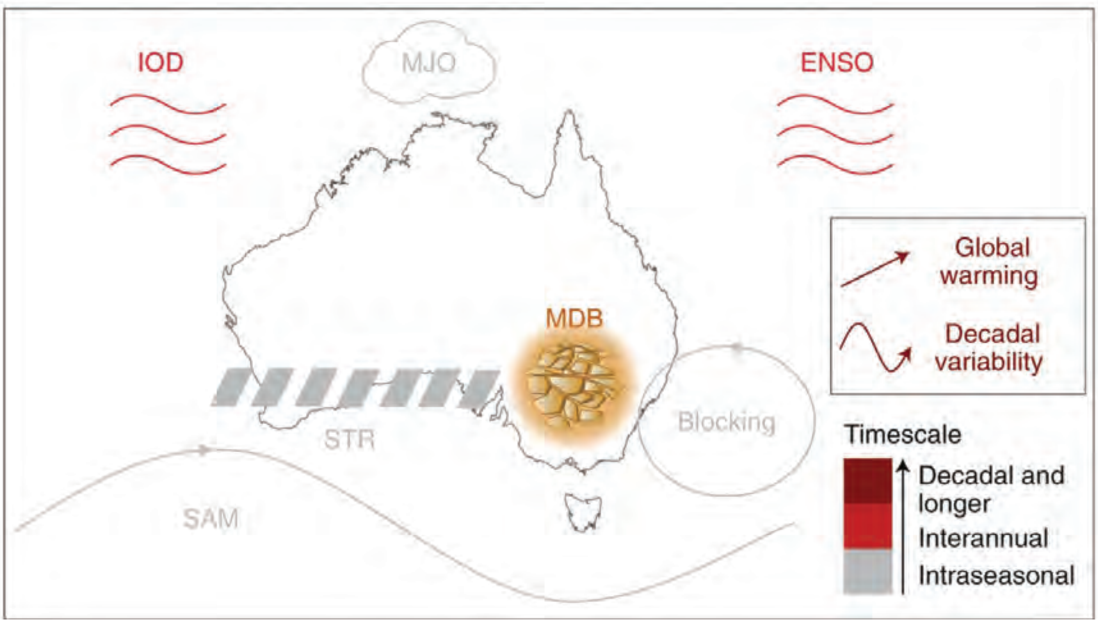


Figure 1: a, Observed seasonal rainfall departures as a percentage of the respective seasonal 1961–1990 climatology. The brown bars mark the times of significant multi-year drought defined following ref. 2. The dark blue bars above the graph indicate whether the season in question is categorized as either La Niña (LN) or negative IOD (nIOD). b, Schematic image showing the climate modes related to rainfall variability in the MDB. Climate modes are coloured by the timescale on which they exhibit variability. STR, Sub-Tropical Ridge (belt of high pressure). King, et al (2020)

revealed the origin of rainfall across Australia. Using meteorological simulations to travel backwards in time, the researchers were able to find out the original evaporation point for much of Australia's rainfall. While it revealed that the majority came from the oceans, it was surprising to find that in some cases very small ocean regions were extremely important to rainfall in key parts of the country. But evaporation over land also matters. In north and north-east Australia and south-east Australia between 18 percent to 25 percent of rainfall originated via evaporation from plants and soil.

The impact of this rainfall, either too much or too little, on vegetation is an area of research of importance to natural and agricultural environments. Comparing observations to global models, drought researchers found that in the short term – periods of up to a month – the models worked well but were less capable of capturing annual responses to rainfall variation. In addition, while the models were very good at reproducing the response of vegetation to a lack of rainfall, they overestimated vegetation response to increased rainfall.

Focusing on Australia's modelling capability has been a major part of our research this year. The Drought program analysed the latest version of Australia's Community Atmosphere Biosphere Land Exchange (CABLE) model coupled with Weather Research and Forecasting (WRF) model for regional applications. The analysis did not identify one configuration that consistently performed the best for all diagnostics and regions. Results were strongly dependent on the region of interest, with the northern tropics and south-west Western Australia being more sensitive to the choice of physics options compared to south-eastern Australia, which showed less overall variation and overall better performance across the ensemble. Comparisons with simulations using the Unified Noah land surface model showed that CABLE in NU-WRF (NASA-Unified Weather Research and Forecasting model) had a more realistic simulation of evapotranspiration.

As the year progressed we continued to work on improving CABLE and other key land surface models. We implemented a new model of plant hydraulics into CABLE to help us robustly project future drought impacts on Australian vegetation. The researchers constrained the vegetations' sensitivity to drought using hydraulic and physiological traits measured in a manipulative drought experiment conducted on Australian tree species originating from across a wide rainfall gradient. The model results agreed well with real-world drought impacts derived from satellite observations. This shows that it is now possible to predict the risk of tree death at large scales, which could have important consequences for conservation and management of Australian forests and woodlands.

The program team has also improved how photosynthesis is represented in land surface models. Drought program researchers and colleagues found that adding vegetation canopy architecture with zenith angle variations significantly improved photosynthesis prediction in light-limited ecosystems. The results closely matched real-world observations and significantly improved photosynthesis prediction in light-limited ecosystems, finding enhanced photosynthesis in the bottom canopy layers.

A key paper investigating model performance compared the observations of evaporation from 20 different sites around the world to how 13 land surface models reproduced this evaporation over the course of a cloud-free day. The researchers found the evaporative processes under cloud-free conditions were poorly represented across the 13 models they examined, with the best-performing model only producing appropriate timing of evaporation and heating in 33 percent of cases examined across the sites. This had a direct impact on the timing of heat exchange with the atmosphere in these models. Investigating further, the researchers concluded the poor performance of the daily cycle of turbulent heat exchange appears to be linked to how models solve for the surface energy balance and redistribute heat into the subsurface.

Our modelling work has also extended to partnerships with the Heatwave and Cold Air Outbreak research program, where we specifically focused on the new Coupled Model Intercomparison Project - Phase 6 (CMIP6) models. In the first instance, we successfully addressed the error compensation issue for temperature extremes by defining a novel performance metric that identifies those models that can simulate temperature extremes well – and for the right reasons. We found there was a noticeable improvement between the current CMIP6 compared to CMIP5 models.

In a second partnership with the Heatwave and Cold Air Outbreak program, we assessed the ability of CMIP6 climate models to simulate the climate of Australia and the new scenarios for 21st-century climate change. They showed small improvements over the previous generation (CMIP5; developed around 2012), including better reproduction of land and marine heatwaves and sea-level rise, as well as improved relationships between Australia's climate drivers and rainfall.

Using the latest CMIP6 models, the Drought program looked at how well these newer models simulated observed drought and how droughts may alter in the future with climate change. The models indicated south-western Australia and parts of southern Australia will see longer and more intense droughts due to a lack of rainfall caused by climate change.

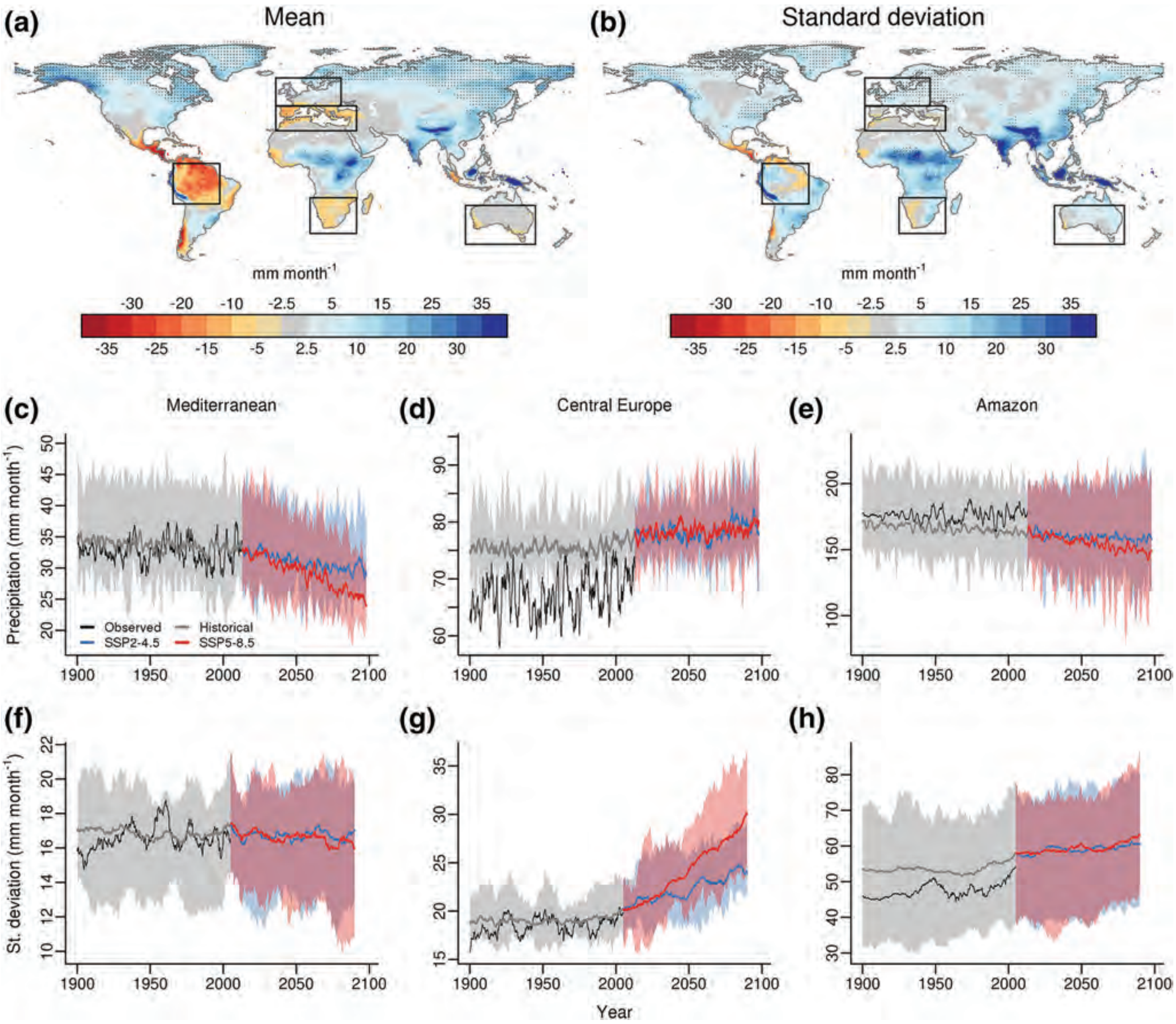


Figure 2: Projected changes in monthly precipitation mean and variability. (a) Projected multi-model mean change in monthly mean precipitation and (b) standard deviation for nine CMIP6 models under the 8.5 W m^{-2} scenario for 2051–2100 compared to the 1950–2014 period. Stippling indicates where the magnitude of the multi-model mean future change exceeded the inter-model standard deviation of the change (24% of land area in a and 21% in b). Data for the historical and future periods were linearly detrended prior to calculating the standard deviation to remove effects from changes in the mean. (c–e) A time series of monthly mean precipitation for the Mediterranean, central Europe, and Amazon regions, respectively, smoothed using a 24-month running window. (f–h) A time series of 10-year running standard deviation of monthly precipitation for the same regions. In (c–f) the shading shows the full model range and the solid lines the mult-model means. For observations, the mean of the three observed products is shown. Ukkola, et al (2020)

But Australia is not alone. Across the globe, several important agricultural and forested regions in the Amazon, Mediterranean and southern Africa can expect more frequent and intense rainfall droughts. While some regions like central Europe and the boreal forest zone are projected to get wetter and suffer fewer droughts, those droughts they do get are projected to be more intense when they occur. The key to these robust results was factoring in rainfall variability and average rainfall. However, this research also highlighted fundamental problems in the simulation of drought intensity. Whether this will increase in the future remains an area of active research.

None of the improvements and assessments of climate models can be verified without robust data sets, so improving these remains a cornerstone of our work. A major challenge in climate science is getting accurate rainfall estimates in areas where ground-based rain gauges are scarce. A CLEX researcher and international colleagues developed a hybrid approach to estimate recent rainfall that combines satellite-based rainfall estimates with satellite-based soil moisture estimates. When this approach was tested against independent rain gauge measurements it showed notable improvements in a range of metrics compared to other, existing satellite-derived estimates.

Another challenge is understanding how energy and water are distributed at the Earth's surface. This is a key part of predicting climate extremes such as drought, heatwaves and flooding. Depending on the landscape and prevailing conditions, rainfall might join rivers, get stored in soils or evaporate. At the same time, absorbed energy from the sun heats the air and soil or powers evaporative processes. While a range of observational data sets of each of these key processes exists, each has its own limitations. Collectively, they do not necessarily obey the laws of conservation of energy or mass. To overcome this restriction, we developed a method for combining multiple observational data sets of the energy and water budgets at the land surface from different sources into a single hybrid data set that conserves energy and mass.

Even that most fundamental need, detecting a developing drought, requires good data that can often be difficult to access. In an ideal world, the best way to assess drought on seasonal to annual time scales – and with an eye to agricultural impacts – would be to base its occurrence on soil moisture measurements. However, direct soil moisture measurements are rarely employed in drought indices because in situ soil moisture observations are sparse in space and time. Therefore, many drought indices have been developed that are based on other variables that can act as a proxy for soil moisture; for example, precipitation or some combination of precipitation and evaporation. All approaches have distinct differences in how they are calculated, how they are affected by uncertainties in the data being used and, ultimately, how they represent drought. What has not been examined is this: whether there is more or less uncertainty in the data using a complex drought index that includes evaporation compared to examining drought using a simpler metric based entirely on precipitation. When CLEX researchers investigated this idea, they found that the uncertainties in the data sets caused by coverage, quality and length of available observations was so great that the precipitation-only index still showed the best ability to detect drought.

This highlighted the importance of the amount and variety of real-world data needed to improve land surface models and make those models outputs more immediately useful to researchers in other fields. Unfortunately, a range of obstructions have created data bottlenecks that mean much of this new data remains inaccessible to those modelling these natural systems. An international group that included CLEX researchers performed a critical review of the information infrastructure that connects ecosystem modelling and measurement efforts. This group has now proposed a roadmap to community cyber-infrastructure development that can reduce the divisions between empirical research and modelling, accelerating the pace of discovery. As part of this review, the team has called for investment in a new era of data-model integration that is accessible, scalable and includes transparent tools that integrate the expertise of the whole community – including modellers and empiricists.

Before the borders closed due to Covid-19, Martin De Kauwe attended the Manipulation Experiment Synthesis Initiative Workshop in Auckland, which also dealt with these precise data challenges. The workshop focused on research carried out over three decades, where scientists carried out ecosystem-scale manipulation experiments to understand and predict future responses of the carbon, water and nutrient cycles to global environmental change. These experiments are one of the key constraints we have on global climate models' predictions and yet models have grossly under-utilised these data when evaluating predictions. We now have more than 2000 of these experiments and the aim of the workshop was to synthesise existing experimental databases to create a single unified database. It is hoped this database will allow us to explore pressing global change questions and better evaluate model predictions in the future.

The importance of these data sets can be seen in how they assist our understanding of the real-world impacts on ecosystems and our agricultural sector. As is becoming clear in our research, there are significant uncertainties around the impacts of future climate changes on crop yields. On the one hand, different climate models can simulate different climate changes when given the same scenario for future atmospheric greenhouse gas concentrations. On the other hand, different crop models can simulate different changes in crop yields when given the same changes in climate. If we are to understand what will happen to the agricultural sector in the future, it is important to determine the levels of uncertainty in these model types. To do this, CLEX researchers examined wheat simulations for two important but climatically different zones of rain-fed wheat production – south-east Australia, with a Mediterranean-type climate, and northern China, with a continental monsoon climate. The researchers found that the relative contribution to this uncertainty due to climate models and crop models varied between the south-east Australian and northern Chinese wheat belts. The primary reason for this was the influence of future changes in growing season rainfall on the wheat yield simulations. Crop model uncertainty was more important in China, where the influence of rainfall is relatively weak and climate models agreed on a future increase in growing season rainfall. However, climate model uncertainty was more important in Australia, where the influence of rainfall is stronger, because some climate models simulated future rainfall increases and some simulated future rainfall decreases. This study supports the practice of using multiple climate models and crop models in assessments of the impacts of future climate changes on crop yields.

Our urban areas also feel the impacts of droughts. Working with the Heatwaves and Cold Air Outbreaks team, the Drought team produced research that generated a new cross-scale modelling framework for urban environments that has been applied to calculate how electricity and gas demand will change under future climate change and air conditioner ownership scenarios. Our researchers used Melbourne as a case study, capturing interactions across building, urban and atmosphere scales at a higher temporal resolution than any location worldwide. The framework can undertake century-scale simulations. The climate modelling systems resulting from this study are open-source, and model outputs are also available across the century at half-hour time steps.

And of course, as a research program we continue with international colleagues to grapple with new problems that for the moment evade a clear understanding. We contributed to a major perspectives piece in *Nature Climate Change* on flash droughts – an area where a lot more research is needed.

Turning its attention far from home, the Drought program also took the opportunity to examine an annual drought in South America and Mexico, to see if it could give broader insight into predicting droughts. This region is unusual as it sees high precipitation rates from May to July and then again from August to October, but between these two peaks, from July to August, rainfall is at its lowest for the entire year. The researchers found there were two key characteristics to this annual drought: the reversal of onshore and offshore winds during the development of the drought and how the wind was forced by the steep mountainous terrain. However, this interaction was so complex that, while the development of the drought was predictable to a point, it was difficult to summarise this development in a single theory. As always, the complexity around what causes droughts continues no matter where you are.

While uncertainty seems to be the theme of drought research in this report, we do have one certainty within the Drought program: the quality of our researchers. Over the past year we have seen a number of those within our program recognised for their excellent work. Ben Henley received a Victorian Young Tall Poppy Award. Andrea Taschetto was promoted to Associate Professor. Meanwhile, in our annual CLEX awards, Manon Sabot was awarded Best Paper by a Student for *Plant profit maximisation improves predictions of European forest responses to drought*, while Nina Ridder won the 2020 CLEX Career Development Award for Women and Underrepresented Groups.

And, of course, it is hard to go past one of the most rewarding parts of academic life, completing a PhD. Congratulations to David Hoffmann who submitted his PhD, The representation of drought in observations and climate models, at Monash University, on August 26. It was a fantastic achievement under Melbourne's lockdown conditions. His supervisors were Ailie Gallant and Julie Arblaster. Nerilie Abram, too, has had an impressive year, being awarded the 2020 Priestly Medal by the Australian Meteorological and Oceanographic Society, winning an ANU Vice-Chancellors award and being promoted to full professor – all well-deserved honours.

Finally, we can't help but draw attention to the Cranky Uncle climate change app developed this year by communications expert and founder of Skeptical Science, John Cook. Cranky Uncle is a smartphone game that uses cartoons and gameplay to interactively explain the techniques used to cast doubt on climate science. It also uses caricatures of climate scientists. Indeed, we have it on good authority that should you download the app you will find our program leader and CLEX Director, Andy Pitman, has had his likeness added to the collection. ■

Chiara reveals the origins of Australia's rainfall

Chiara Holgate completed her PhD in 2020 and in the process of doing so, she left an important legacy that will be the basis of future research by the Centre of Excellence. Combining observations and climate models she used both to travel backwards in time and trace the origin of major rainfall events in Australia between 1979 and 2013. This is vital research that has the capacity to improve short-term weather forecasts, seasonal forecasts and perhaps, most importantly, the long-term impacts of climate change on Australian rainfall.

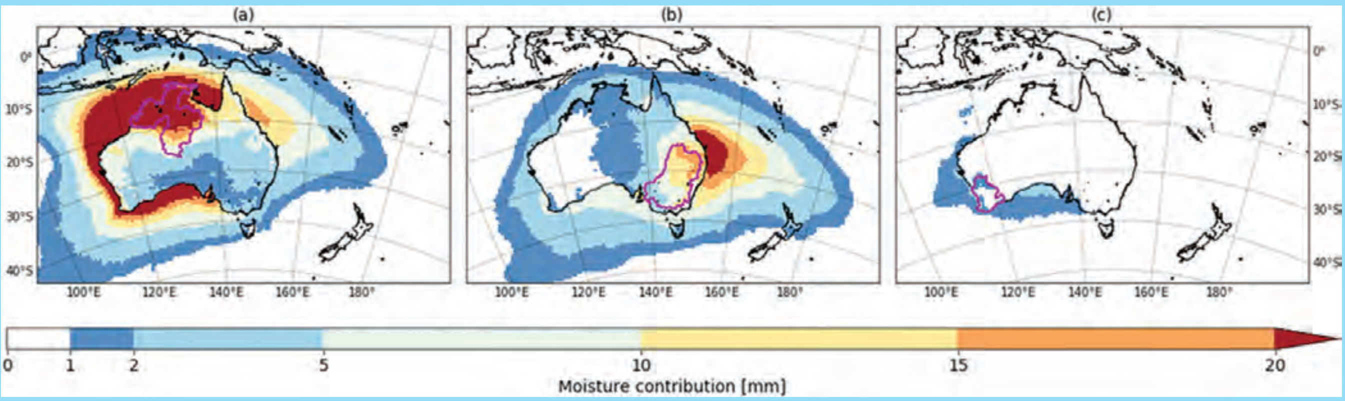
Not surprisingly, the great majority of Australian rainfall – around 75 percent – was the result of evaporation over surrounding oceans. However, there were some very interesting nuances in this result that are likely to have significant impacts on key Australian regions. One of those regions was the south-west of Western Australia, which has already seen large reductions in rainfall. The rainfall for this region came from one very small part of the ocean making it vulnerable to future changes in evaporation or atmospheric circulation that occur in this area.

Another source of rainfall that is particularly important for north and north-west Australia is evaporation from the soil. 25 percent of their rainfall has been evaporated from soils and plants. In comparison, south-east Australia land-based evaporation makes up 18 percent of total rainfall. This tells us that if we were to change the vegetation cover in these regions it is very likely to have a direct impact on rainfall.

Another fascinating finding of this research was that the origin of a rainfall is changing. North-west Australia is now receiving more rainfall associated with ocean evaporation than land evaporation during the spring months. This suggests evaporation over the tropical oceans is increasing.

Meanwhile, the south-east of Australia is now receiving less moisture in winter but more in summer. The origin of this change appears to be an increase in easterly flows of moisture from the Tasman Sea in summer and reduced westerly flows of moisture from the Southern Ocean in winter. This has important implications for agriculture and water resource management in these regions.

Understanding these changes will help give the Centre a better understanding of both the causes and termination of droughts as well as better understanding of floods, hopefully improving their prediction and allowing farmers and water resource managers to make better and more confident planning decisions. ■



Mean summer moisture contribution (mm) to precipitation in (a) Tanami–Timor Sea Coast, (b) Murray–Darling Basin, and (c) South West Coast. (Journal of Climate 33, 20; 10.1175/JCLI-D-19-0926.1).

RP4: **Climate Variability and Teleconnections**

Highlights

- Our researchers produced the world's longest record of IOD events, extending back to 1240
- Significant advances made in understanding marine heatwaves – with the potential to improve our ability to forecast them well in advance
- Collaboratively produced a foundational textbook on ENSO: El Niño Southern Oscillation in a Changing Climate
- New insights into the Southern Annular Mode that question its actual nature
- Found decreases in sea surface salinity could act as a harbinger of extreme rainfall events, using the 2010/2011 Brisbane floods as a case study.

It has been an extraordinary year of research and achievements in the Climate Variability and Teleconnections research program at the ARC Centre of Excellence for Climate Extremes (CLEX). We have seen significant advances in our understanding of marine heatwaves and impressive world-first insights into the powerful role the Indian Ocean plays in Australia and even the world's climate.

A very high-profile piece of research led by Nerilie Abram resulted in the world's longest reconstruction of positive Indian Ocean Dipole (IOD) events, with a record that extended back to 1240. The research, published in Nature, revealed that these historically rare events have become much more frequent and intense during the 20th century, and this situation is expected to worsen if greenhouse gas emissions continue to rise. The study also found that in 1675 a positive IOD event occurred that was up to 42 per cent stronger than the strongest event observed during the instrumental record. Its effects could be seen in historical documents from Asia produced during this period. Importantly, there is a tight coupling between IOD variability and that of El Niño Southern Oscillation (ENSO) variability in the Pacific, suggesting that recent changes to both, likely a result of climate change, could have significant impacts on Australian conditions.

An examination of paleoclimate observations and climate model projections also allowed strong conclusions to be drawn about how human-caused climate change is altering the IOD. All data sources agree that positive IOD events are becoming stronger and occur more often. They further agree that the mean-state of the Indian Ocean is moving towards a more positive IOD-like state, due to enhanced warming in the west compared to the east. Paleoclimate data further demonstrates that IOD variability even more extreme than that recorded in recent decades is possible – and that IOD variability is important in long-term hydroclimate changes, including megadroughts.

Research on changes to the Indian Ocean has become increasingly urgent as we begin to realise its important role in Australia's climate. Recent modelling work by Annette Stellema and other members of the Variability team has found that climate change will lead all circulation features of the South Indian Ocean (including the Leeuwin Current and Undercurrent, North and South East Madagascar Currents and transport through the Mozambique Channel and Agulhas Current) to weaken significantly in the last half of the 21st century, should greenhouse gas emissions remain unchecked. This could have important consequences for regional weather and marine resources.

Highlighting the urgency of this research, we found the ocean temperatures in this region are already 1°C warmer than they were in the mid 20th century. And that warming in this single ocean basin has had global effects. The warming ocean and increased evaporation led to higher rates of precipitation around the ocean basin. The heat dissipation caused by this increased rainfall has a direct impact on atmospheric circulation that has suppressed rainfall half a world away, in the tropical Atlantic Ocean. In the extratropical regions, the most pronounced features include a meridional pressure gradient and strengthening of westerlies in the North Atlantic during austral summer and a zonal wave 3 pattern in the Southern Hemisphere during austral winter. These patterns and associated fields are similar in structure to the circulation trends observed in nature over the past 50 years. This finding suggests a need to take the global influence of the Indian Ocean into greater consideration in observations and climate model studies of the past few decades.

While the surface waters of the Indian Ocean have warmed more than other ocean basins, the amount of heat stored in the top 700m between 1960-2000 did not exhibit such strong increases. It is only since 2000 that we have seen a rapid increase in heat storage. Our researchers used ocean model simulations to investigate this unusual behaviour, which revealed how winds can affect the upper-ocean temperature structure in the Indian Ocean, either through the atmosphere or via an oceanic connection from the Pacific. Understanding this process and whether it is likely to occur again gives us insight into long-term changes in the Indian Ocean that directly affect the regional climate in surrounding countries, as well as how the process may respond in the near future to a warming climate. Understanding what causes these marine heatwaves has been a big part of this year's research effort, working in concert with our colleagues in the Heatwaves and Cold Air Outbreaks research program.

Researchers from both programs came together to identify the worst marine heatwaves, then reveal the key processes that triggered them and led to their eventual demise. They found that these record-breaking heatwaves tended to occur in summer but, surprisingly, before the annual peak for warmest ocean temperatures had occurred; and that they were most often associated with El Niño events. The key factor that formed these marine heatwaves was a lack of wind along with clear skies, usually caused by persistent high-pressure systems. This still, warm water at the top of the ocean had profound effects on algal growth, a foundation species for ecosystems. In tropical regions, marine heatwaves caused a decline in algal growth, while closer to the poles there was a rapid growth in algal blooms.

This shows how marine heatwaves impact the foundations of the ocean food chain. Additional research

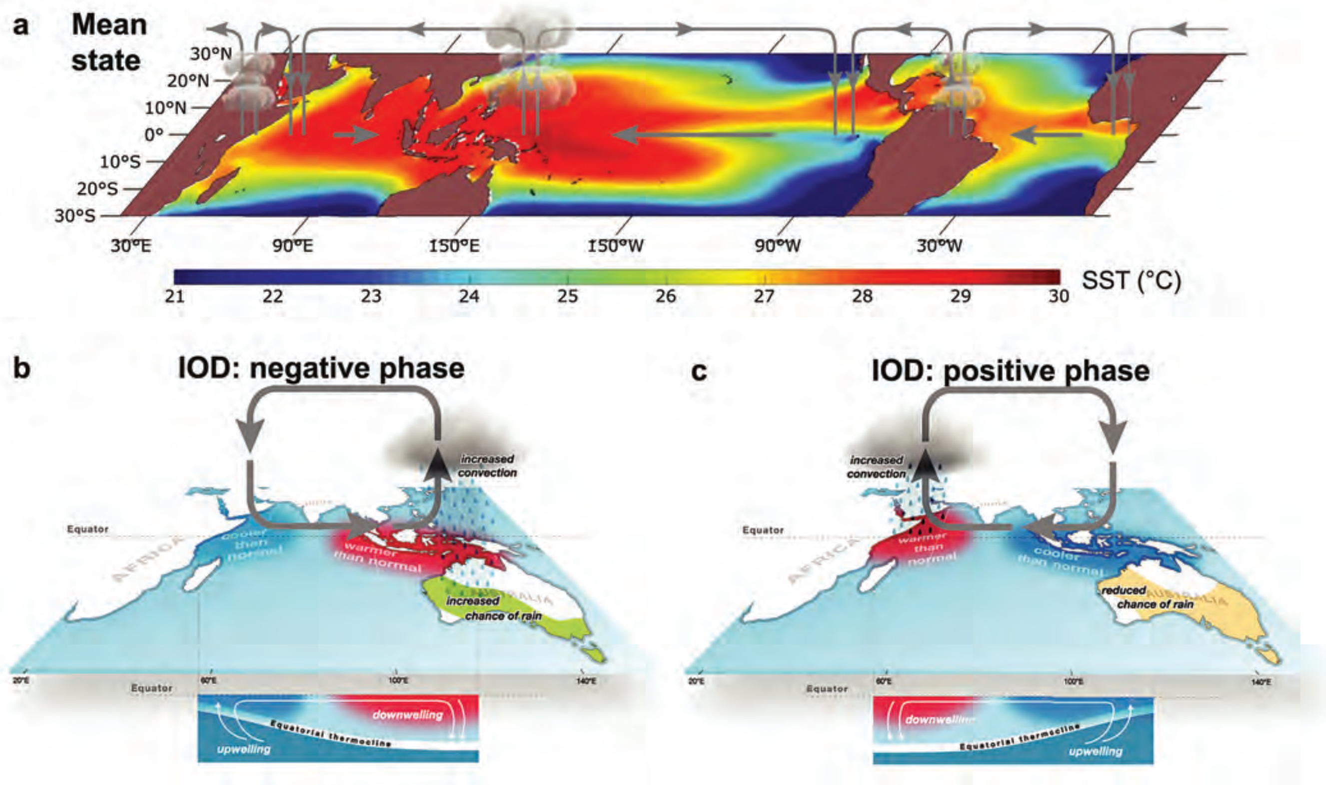


Figure 1: The Indian Ocean Dipole. (a) Background mean state of tropical SST (shading) and Walker circulation (arrows). Image after (Cai et al., 2019). (b–c) Schematic of ocean-atmosphere anomalies associated with negative and positive Indian Ocean Dipole events. Source: Australian Bureau of Meteorology; http://www.bom.gov.au/climate/iod/.

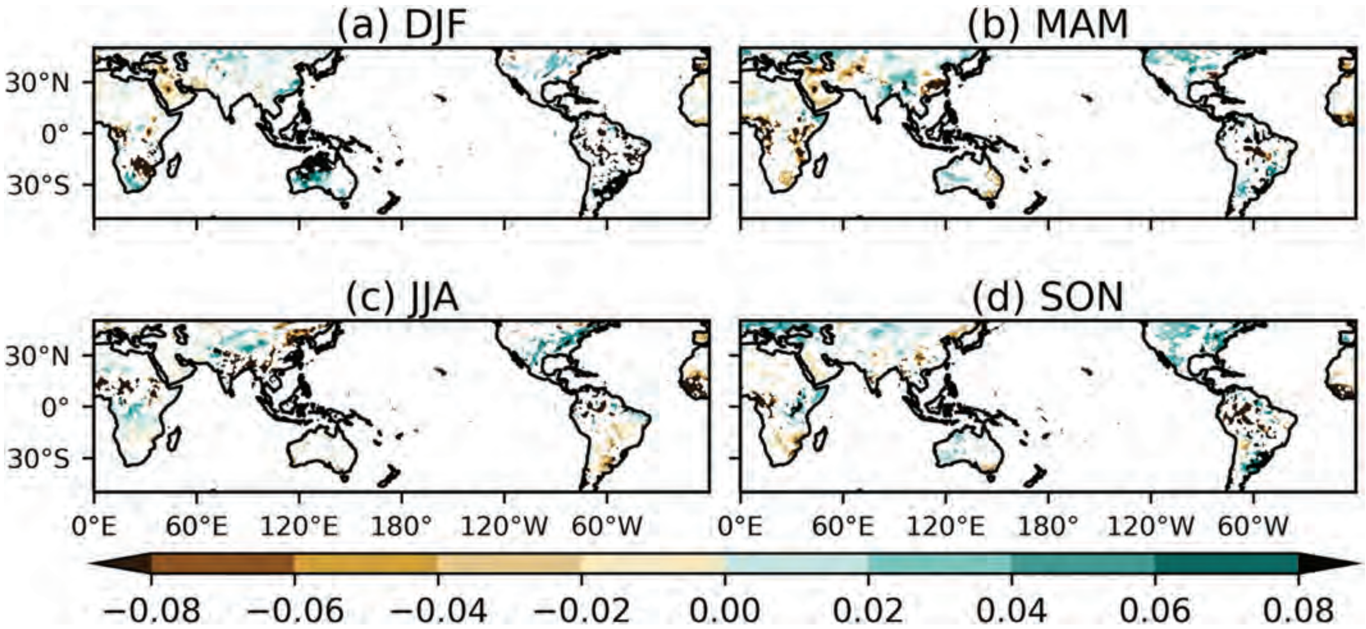


Figure 2: Significant (above 99% confidence interval) seasonal precipitation trends (mm day^{-1} decade^{-1}) in Global Precipitation Climatology Centre (GPCC) rainfall data from 1951 to 2016. Dhame, Taschetto, et al (2020).

showed how nutrient variation, in combination with marine heatwaves, affects ocean productivity. Marine heatwaves are expected to expand and intensify in coming decades due to climate change, while nutrient-poor waters are projected to expand globally. These findings suggest that weaker blooms during marine heatwaves may become more common and widespread. These impacts of marine heatwaves have resulted in call from international researchers, led by our program's investigators, that highlights the need for the development of systems to predict marine heatwaves. The authors called for streamlined and simple information and forecasts that can be widely shared with stakeholders. If this were introduced, marine-resource users and managers of fisheries, aquaculture and conservation would be able to take action to minimise damage – such as harvesting or relocating farmed species, or providing short term protections like cooling or shading.

CLEX researchers are advancing our ability to forecast marine heatwaves. Along with other colleagues they investigated the large-scale drivers that led to the development of marine heatwaves off southeast Australia observed from 1994-2016, including the extreme 2015/16 event. They found about half of marine heatwaves in this region were primarily due to the intensification of the East Australian Current Extension, bringing warmer water with it. The slow-moving waves that generated this can't be seen by the naked eye but the change in wave heights they generate can be detected by satellites. This work means it may be possible to forecast major marine heatwave events around Tasmania up to three years in advance.

These observations are useful but, to truly understand and forecast marine heatwaves, we need to improve how we model these events. The fundamental research carried out on marine heatwaves in 2020 brought together observations of these oceanic heating events compared them to marine heatwaves produced by climate models at low, medium and high resolutions. They found that, regardless of their resolution, all simulations have weaker, longer and less-frequent marine heatwaves, when compared with the real world. Despite these differences, they found that simulations with medium and high resolutions realistically represented global spatial patterns of these heatwaves.

As we noted earlier, ENSO plays a role in these marine heatwaves. But it has always been a major driver in Australia's seasonal weather, as observed in summer 2020/21 as a strong La Niña formed in the Pacific. This powerful ocean-atmosphere connection continues to be a key part of our work, and modelling it accurately is one of the great challenges of climate science.

A shift in El Niño events could be a consequence of global warming. Researchers have already noted changes in the El Niño events, with more occurring in the central Pacific than in the eastern Pacific. The location and intensity of these El Niño events brings differing effects to Australia and many other countries around the world. Using a range of climate models, our researchers found that the general pattern of warming across the Pacific with climate change was likely to have a profound effect on where El Niños formed – and their likely intensity. Another important influence on how future El Niños may manifest was how the models represented Pacific decadal variability, suggesting that natural variability within the climate system may have as much bearing on future El Niños as global warming.

Further work on ENSO processes in the Pacific Ocean is being carried out by CLEX researcher Dietmar Dommenget and colleagues. This work aims to improve how this important phenomenon is accurately represented. In simulating El Niños, our models tend to underestimate the positive (amplifying) zonal surface wind feedback and the negative (damping) surface-heat flux feedback. These are two of the most important atmospheric processes controlling the evolution of El Niño. A new study by CLEX researchers and colleagues shows that Coupled Model Intercomparison Project - Phase 5 (CMIP5) models as a group underestimate the feedbacks by, on average, 54 percent when simulating the sea surface temperatures by themselves. However, if they are forced by observed sea surface temperatures they only underestimate these atmospheric feedbacks on average by 23 percent. This is caused by the Walker circulation being – in most climate models – located too far to the west. By highlighting these biases, this study can help climate modellers improve climate model simulations of natural climate variability and climate change.

Because ENSO is so vital to the Earth's future climate, our researchers came together as part of an international team to produce a textbook that is likely to be of foundational importance in understanding ENSO and its response to climate change. El Niño Southern Oscillation in a Changing Climate, published by Wiley for the American Geophysical Union, is a comprehensive and accessible exploration of ENSO and how it is altering with human-caused climate change. The book tracks the historical development of ideas about ENSO and explores its underlying physical processes. It details how ENSO has varied over decades – and now centuries, thanks to advances in paleo-reconstructions. The book also reveals the latest science on how ENSO responds to external factors. These external influences, coupled with the chaotic nature of the phenomena itself, are examined further in chapters that explain the barriers and potential areas of research that may help us forecast these events. Most importantly, as we look to a future affected by global warming and changes to our climate, the book covers the extensive effects on extreme ocean, weather and climate events; fisheries; marine ecosystems; and the global carbon cycle.

Natural variability within systems can also have an impact on regional climate as was shown when CLEX researchers used climate models to determine how natural variations impacted the overall warming trend caused by climate change. This research found 29%-53% of the variability in sea surface temperatures across each decade were caused by external influences, not internal variability. This external influence was primarily the result of volcanic eruptions, which throw particles high into the atmosphere where they remain for extended periods of time, causing significant cooling by screening the incoming solar radiation. These eruptions add an unpredictable external influence on natural variability that can override the normal processes of our climate system. This means that while we can estimate long-term surface temperature trends into the future, volcanic eruptions can have such a pronounced influence on our climate that decadal estimates might not be predictable.

Natural variability within systems can also affect regional climate. A nice example of this is research that investigated the winds that circle Antarctica and how they contract and expand. In general, these winds have been moving closer to Antarctica and this contraction has been described using a hemispheric index known as the Southern Annular Mode (SAM). Schematics of these general trends essentially show the winds in the form of a doughnut. However, the weather systems that influence the rainfall, temperature and wind conditions that we experience do not look anything like a doughnut. By grouping weather systems by similar patterns rather than averaging conditions over months, seasons or years, CLEX researchers found that between Australia and Antarctica, the "doughnut' structure of SAM is split into multiple "flavours" and is more likely to have "bite marks" out of it than be a perfect ring. These different flavours of SAM mean a hemispheric index often fails to capture the regional variability in surface weather conditions over southern Australia and East Antarctica. This suggests more intricate regional analyses will be required to improve our understanding of how these winds affect Australian climate.

Understanding how these changes to the SAM in a warming world will affect the Southern Ocean is of vital importance because of how this ocean influences Australia's climate and global circulation. Research using global ocean-sea ice models led by Kial Stewart found that when the winds contracted towards Antarctica, they warmed oceans north of the peak wind speed and cooled them to the south. The reverse occurred when the SAM shifted northwards towards Australia. This had a rapid short-term effect on overturning circulation in the Southern Ocean that was exhibited in models of all resolutions. However, the long impacts were very dependent on ocean eddies, adding a level of complexity to understanding how circulation in the Southern Ocean may change over extended periods.

This complexity extends to our basic understanding of the SAM and how it is represented as a pressure shift between Antarctica and Australia. The SAM is often considered to be a smooth measure of the position of storm tracks and the jet stream as they move north and south over the Southern Ocean. Depending on its phases, it has been accepted that the SAM can bring rainfall and storms to Southern Australia or shift them closer to Antarctica. However, research by Clemens Spensberger, Michael Reeder and colleagues has questioned this assumption, showing the SAM cannot be interpreted as a descriptor of midlatitude variability and that it has little imprint on the weather of the storm track. Instead, our researchers argue that SAM is really a measure of how strongly the Antarctic couples with the midlatitudes. The results call for caution in relating midlatitude weather to SAM.

If we are to better understand Australian weather and its connections to Antarctica it is important for us to be able to validate the data that does come from this data-sparse region. A key data point is surface air temperature above Antarctica. This information is usually derived from reanalysis data sets that are best-guess estimates made up from combining observations and models, similar to weather maps. However, multiple reanalysis products have very different surface trends in this region over the past 40 years of satellite observations, so which one should we use? CLEX researchers aimed to bring clarity to these trends through a study based on the well-established fact that sea ice cover is very closely related to surface air temperature. The idea was that researchers could use trends in Antarctic sea ice as an independent validation for the reanalysis trends. This simple approach worked beautifully, showing not only which reanalysis products had the "best" trends overall (at least in terms of their agreement with sea ice), but also highlighting regions where the products are more or less reliable. This will be invaluable information for Antarctic and Southern Ocean researchers who come across the old problem of What data should I use?

We now have a better grasp of surface temperatures in Antarctica, and the warming of waters around the continent is an acknowledged observation. However where the warm water was coming from and what this meant for future climate processes has remained a mystery. Using a high-resolution

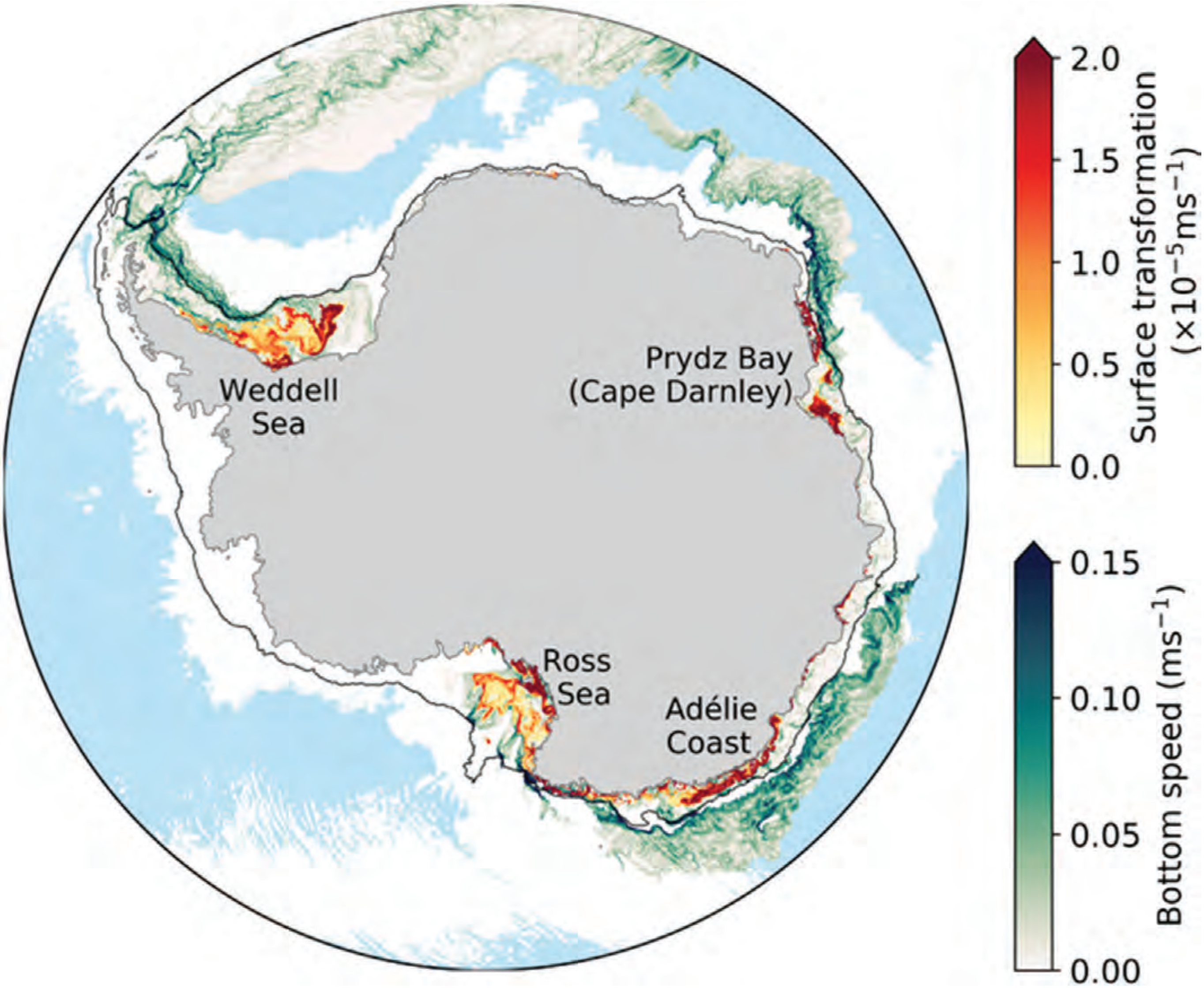


Figure 3: Model simulation of the source locations and descending pathways of dense water. Surface water mass transformation across σ_1 = 32.57 kg/m^3 is shown in red colors. Bottom speed is shown in green colors in the descending pathways of dense water (where bottom density σ_4 >46.105 kg/m^3). Blue background shading shows bathymetry deeper than 4000 m. The black line represents the 1000-m isobath contour. Morrison, Hogg, et al (2020).

ocean model, CLEX researchers unexpectedly found 80 percent of the transport in the warm water layer, known as Circumpolar Deep Water, approached Antarctica in the colder regions. The most surprising result of the study was that warm regions of the Antarctic continental shelf actually have very limited warm water flow onto the shelf, compared with dense water formation sites. Instead, these regions are warm because the waters have been on the shelf for a long time and are subjected to minimal cooling from the atmosphere. These new results are forcing oceanographers to re-examine their understanding of the mechanisms that warm the Antarctic oceans.

The oceans around Antarctica and the sea ice that encompasses the continent also play an important role in deep ocean currents and carbon storage. The storage of carbon in the deep ocean is partly a reflection of the biological activity that occurs when the water is at the surface before it sinks. This is why it is important to evaluate how unexpected and dramatic changes at the surface will change biological and chemical cycles, so that we can understand their effect on a larger scale. In a recent paper, our researchers investigated how a major glacier tongue break in the Mertz polynya in Antarctica impacted phytoplankton blooms. Larger phytoplankton blooms increase the amount of carbon that can be stored in the deep ocean. The researchers found that, following the glacier tongue break the bloom duration and ice-free period decreased, the start of the bloom and the retreat of sea ice were delayed, and the intensity of the bloom and the sea ice concentration increased. These findings show that natural changes can affect the timing of phytoplankton growth that may have consequences for the rest of the ecosystem, from Antarctic krill to baleen whales.

To get a better understanding of phytoplankton growth, PhD student Nic Pittman examined satellite-based chlorophyll observations, which provide the most comprehensive large-scale estimate of phytoplankton abundance in the upper ocean. He evaluated the performance of satellite chlorophyll observations in the tropical Pacific Ocean and consequently suggested algorithm improvements. These reduced errors in chlorophyll estimates will provide essential insights into critical processes like primary productivity and biologically driven carbon dioxide transport.

While phytoplankton may be small creatures with a large impact they are not the only example of how small changes can have a large effect on chaotic systems. This was found to be the case in recent research where we looked at open ocean convection. This convection plays a key role in feeding a series of currents that, together, form a part of the global ocean 'conveyor belt'. This conveyor belt, in turn, transports heat from the equator to the poles and keeps global temperatures relatively mild, which is why open-ocean convection plays an important role in regulating our global climate. However, a large proportion of climate models often make this form of convection too strong. By comparing two models, CLEX researchers found the current generation of convection parameterizations fail to replicate the random, chaotic nature of real-life turbulent convection. Therefore, surface waters sink too far compared to the real ocean. Our researchers have now proposed a convection parameterization that recreates the random nature of turbulent convection, a challenge that will be undertaken in future research.

Our researchers also played a role in a discipline-wide debate around Southern Ocean fronts, as part of a major review. The resulting paper explained how "fronts" - sharp boundaries between water masses - are defined and what their effects might be on the biology of the Southern Ocean. The authors argued that there was no single "correct" definition, only the correct definition for the problem – and data – at hand. To facilitate future research, they included a user guide to help practitioners choose the right definition for their problem. This review will help focus a considerable amount of future research in this region. It also plays a fundamental role in important research on the Southern Ocean and its influences on climate.

Another piece of research by the Variability team led to a profound change to our understanding of one of the most fundamental aspects of the ocean's large-scale circulation: ocean gyres. These are large-scale circulation features that give rise to important ocean currents, such as the Gulf Stream in the North Atlantic and the Kuroshio current off the east coast of Japan. These gyres are critical in transporting heat from the tropics to the poles. Standard oceanographic theory suggests that these gyres are driven by wind stress; however, the simple theory that predicts the strength of these gyres fails in many parts of the ocean. CLEX researchers used coupled models to reveal that ocean gyres (complete with a rich eddy field and strong western boundary current) occur even in the absence of wind forcing. They contend that a significant component of gyre circulation, particularly in the subpolar regions, is due to temperature-driven buoyancy fluxes, a perspective that transforms our understanding of large-scale circulation.

While it is often true that improving models involves a focus on complex interactions, simplifying processes can also have profoundly important results. In one very interesting outcome, CLEX researchers found the the inclusion of upper South Pacific Ocean variability in simple linear inverse models significantly improved predictions of ENSO and Pacific Decadal Oscillation. This result has implications for our capacity to improve forecasts

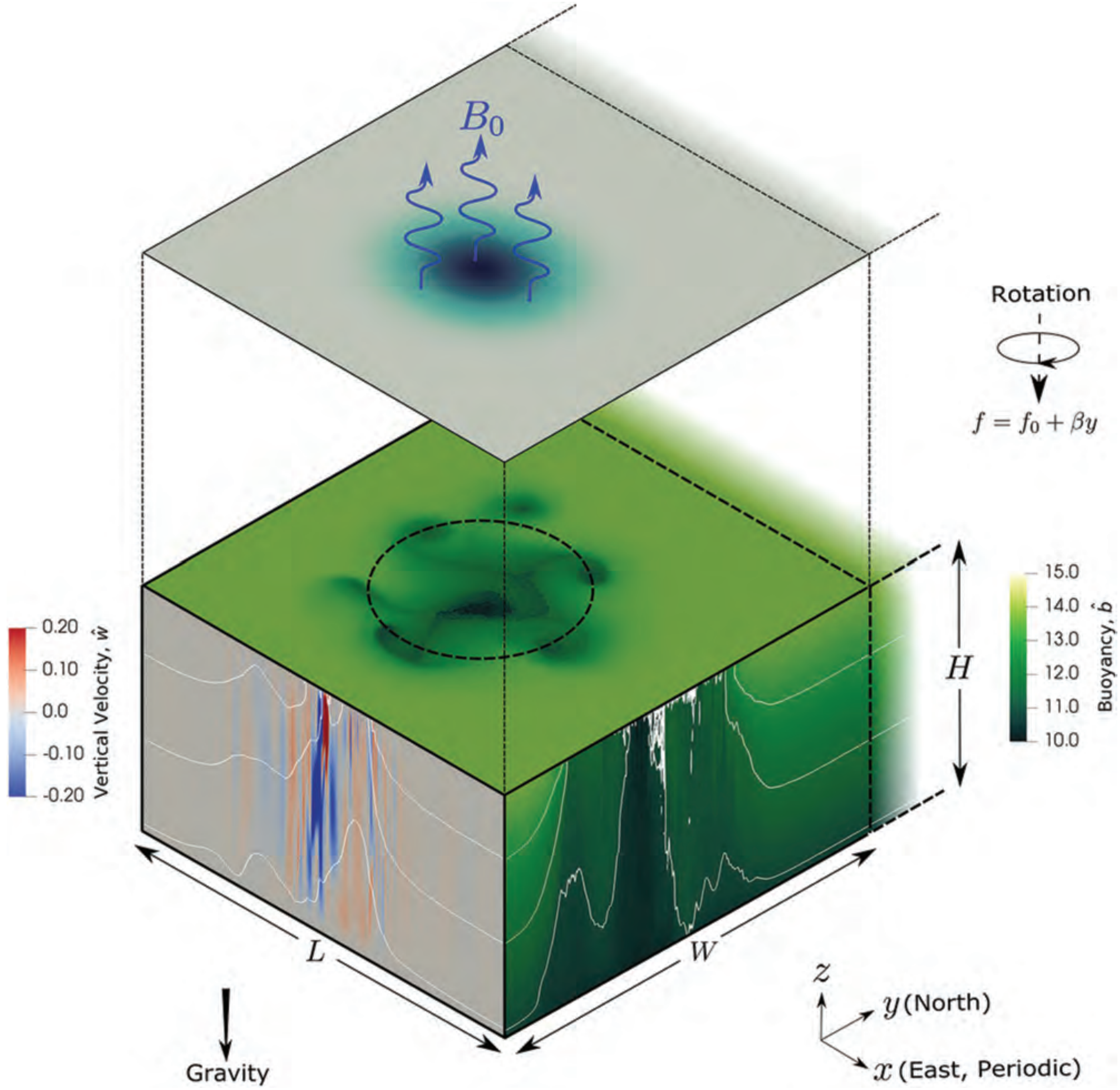


Figure 4: An overview of the model domain, with overlaid flow solutions from the DNS for $Ra_f = 9 \times 10^8$, ^N=4.10, and ^t=355.9. The upper *x–y* plane (in blue-gray) depicts the Gaussian surface heat flux H. The lower *x–y* plane (in green-yellow) shows the normalized buoyancy ^b at *z/H* = 0.98. The dashed black circle indicates the location of the destabilizing buoyancy source at the model surface. The *y–z* plane shows the buoyancy ^b at *x/L* = 0.5. The *z–x* plane depicts the normalized vertical velocity ^w at *y/W* = 0.5. White contours correspond to isopycnals of value ^b=[13,12,11] from top to bottom, respectively. The dashed and dotted lines at *y/W* ≥ 1 indicate the presence of a sponge layer. Buoyancy is defined as $b = g\alpha T$, where *T* is the temperature field. Sohail, et al (2020).

of these events and predict their impacts on Australia further ahead, while using computer models that demand less time and computational expense.

Amid all this oceans work, we also produced two papers that gave us important insights into anthropogenic global warming. At the beginning of the year, in what was a finding that rose out of earlier unconnected research, a paper published in *Environmental Research Letters* led by PhD student Rishav Goyal revealed that the Montreal Protocol, signed in 1987 to stop chlorofluorocarbons, or CFCs, destroying the ozone layer, now appears to be the first international treaty to successfully slow the rate of global warming. The research team found that, thanks to the Montreal Protocol, today's global temperatures are considerably lower than they otherwise would have been. And by mid-century, the Earth will be – on average – at least 1°C cooler than it would have been without the agreement. Mitigation is even greater in regions such as the Arctic, where the avoided warming was found to be as much as 3°C – 4°C. As well as impressive science, it was research that had a message for our policymakers as well.

The second paper focused on a global warming observation that has challenged climate researchers: understanding how, between 2005-2015, the Southern Hemisphere oceans warmed faster than Northern Hemisphere oceans. This asymmetry contributed to a global warming hiatus from 2001 to 2012, and a range of theories have been put forward to explain it – from blaming atmospheric aerosols to the claim that the phenomenon contradicts climate change. PhD student Saurabh Rathore led research combining international datasets and climate models that showed the asymmetry between hemispheres can be explained by natural variability in the climate system superimposed on long-term ocean warming. This finding could help predict sea-level change or future temperature variations on a decadal time scale, something that is not achievable at the moment. It also shows with greater clarity that climate change is detectable in short records, whereas until now we have had to rely on longer trends of 20-50 years.

Finally, in terms of our research we must make a special note of a paper outside the usual selection of research papers in high-impact journals designed for our scientific peers. Amelie Meyer published a paper, The future of the Arctic: what does it mean for sea ice and small creatures?, in the journal *Frontiers for Young Minds*. This is an open-access journal specifically written by scientists and reviewed by children and teens. It's a great outlet for rigorous science articles that the scientists of tomorrow can read.

At the same time Amelie was reaching out to young minds, she was engaging with international collaborators after being appointed to the working group at Analysing Ocean Turbulence Observations to Quantify Mixing, funded by the Scientific Committee on Oceanic Research.

In another useful piece of outreach to our peers, U.Melb student Zebedee Nicholls was part of a team that has developed a CMIP6 visualisation tool of large-scale averaged time series aggregated to global, hemispheric and land and ocean averages. The team is developing examples of how more complex visualisations can be performed and is building a gallery of visualisations, all of which will be available to the scientific community. Another international collaboration has seen Agus Santoso, working with colleagues from the National Center for Atmospheric Research (NCAR), contribute to Asymmetry and diversity in the pattern, amplitude and duration of El Niño and La Niña, as part of the Climate Data Guide.

Despite all the challenges of this year, we still have an extraordinary array of individual successes to acknowledge within our program.

We were delighted to see two members of the Variability team feature in the 2020 Australian Meteorological and Oceanographic Society (AMOS) awards presentation, with Ariaan Purich receiving the AMOS Uwe Radok Medal for her thesis, "Understanding the drivers of recent Southern Ocean sea ice and surface temperature trends" and Nerilie Abram receiving the AMOS Priestley Medal. Nerilie had quite a run of wins, receiving a Vice-Chancellor's Award from ANU and also being promoted to full professor.

Matthew England was awarded the Royal Society of NSW's 2019 James Cook Medal, one of the Royal Society's most prestigious awards. It was established in 1947 and is awarded periodically for outstanding contributions to science and human welfare in and for the Southern Hemisphere. Matthew was recognised for his sustained track record of outstanding research that has led to improved predictions of rainfall and climate variability, discoveries of the oceanic drivers of severe drought and flooding rains, and quantification of the effects of climate change and the fate of ocean pollution. Matthew, along with Alex Sen Gupta, also appeared in this year's Clarivate Analytics most-cited researchers.

Jan Zika was awarded the Anton Hales Medal by the Australian Academy of Science. The impact that Jan's work has had was outlined in a video that features Jan playing with Lego blocks, which may be the best way to explain complex science to the next generation.

Adele Morrison was one of five winners of a prestigious $25,000 2020 L'Oreal-UNESCO Women in Science Fellowship.

At our recent CLEX Annual

Workshop, Giovanni Liguori was awarded best paper for an ECR, for [A joint role for forced and internally-driven variability in the decadal modulation of global warming.]

Agus Santoso was recognised internationally, stopping off at an American Meteorological Society meeting in Boston (when travel was still possible) to pick up an Editor's Award 2020 for reviews in the *Journal of Climate*. Agus also gave two talks at the meeting.

Congratulations also go to Catia Domnigues who is part of the editing team that produced a special issue for Springer journal, *Surveys in Geophysics*: Relationships between coastal sea level and large-scale ocean circulation, that has been turned into a hardcover book.

We also had a run of impressive grants awarded to our researchers this year. Navid Constantinou and Ryan Holmes won Discover Early Career Researcher Awards (DECRA) in this year's round, continuing CLEX's fine record of talented young researchers who have received this grant.

In addition, Andrew Hogg, Matthew England, Adele Morrison, Paul Spence, Ryan Holmes, William Hobbs, Callum Shakespeare, Ben Evans, Simon Marsland and Stephen Griffies were all part of a large grant to build Australia's next-generation ocean-sea ice model.

Meanwhile, Variability team members received three Australian Research Council Discovery grants this year. Nathan Bindoff and Richard Matear were part of a Discovery Project that aims to quantify how the ocean's biological pump responds to environmental change. Another Discovery Project grant was awarded to Helen Phillips, Maxim Nikurashin, Bernadette Sloyan and Susan Wijffels, for research that expects to develop new knowledge of ocean-atmosphere interactions along the path of the Indonesian Throughflow from the Pacific to the Indian Ocean. And then there was a team from Monash that includes Shayne McGregor, Dietmar Dommenget, Alex Sen Gupta (UNSW) and Scott Power, which was awarded a Discovery grant to focus on improving the credibility of regional sea-level rise projections.

We were also pleased to see Bishak Gayen (University of Melbourne) and Shane Keating (UNSW) receive a Universitas 21 Global Education Fund award to develop online teaching resources in ocean, weather and climate science.

Finally, we have seen some well-deserved promotions, with Peter Strutton promoted to full professor at the University of Tasmania and Associate Investigator Callum Shakespeare promoted to Senior Lecturer at ANU. Callum is a true product of the Centre of Excellence system. He was initially an ARC Centre of Excellence for Climate System Science (ARCCSS) honours student who, after his PhD in Cambridge, returned to ARCCSS as a postdoctoral researcher. He is currently mid-way through his DECRA and is a CLEX Associate Investigator.

These are all amazing efforts in what was an incredibly challenging year for research and academia. It says a great deal about the quality of the Climate Variability and Teleconnections team and gives us hope that 2021 will see more outstanding work to come.

IAN MACADAM STORM OVER EASTERN SUBURBS SYDNEY

2021 Research Statements of Intent

In 2021 the ARC Centre of Excellence for Climate Extremes will undergo some internal reorganisation in order to better achieve our long-term goal of transformational research to better understand the processes that cause climate extremes. Our researchers will continue to work in cross-node project-level teams to answer the underlying questions the Centre set out to achieve. However, to further enhance inter-disciplinarity and fresh thinking we will restructure the centre internally into the following five research programs:

- Weather and Climate Interactions (led by Michael Reeder and Todd Lane)
- Attribution and Risk (Led by Lisa Alexander and Julie Arblaster)
- Drought (led by Nerilie Abram and Jason Evans)
- Ocean Extremes (led by Neil Holbrook and Pete Strutton)
- Modelling (jointly led by Andy Hogg, Christian Jakob and Gab Abramowitz)

In each case, we will pay increased attention to how the research connects with external stakeholders in order to strengthen pathways-to-impact.

The following tables outline indicative work planned for each research program in 2021. Some of these plans are dependent on a new set of research fellows being advertised in early 2021. At the time of writing CLEX was in the process of evolving the way we report on research progress to adopt a more granular project-based approach. This will be reflected in the 2021 Annual Report.

Weather and Climate Interactions

Project	Priority	Intent
WACI1 Fronts	1	Install diagnostic codes for front-tracking and wave-breaking at NCI. and apply them to identify fronts, including extreme dry and wet fronts, and wave breaking in ERA-5.
	1	As part of the ACCESS regional modelling team commence regional 2.2 km (Aus2200) simulations of the 2019/2020 season with an initial emphasis on key 2019/20 frontal events.
	2	Identify fronts and their extremes as well as wave breaking in models including ACCESS global and regional model and global model simulations.
	2	Conduct simulations and analysis to determine the key drying mechanisms during frontal passages starting with the recent 2019/2020 fire season.
	3	As part of the ACCESS regional modelling team complete 12 months of the 2.2 km (Aus2200) simulations.
	3	Identify fronts and their extremes as well as wave breaking in models in CMIP6 models.
	3	Evaluate drying events in global models in collaboration with the Attribution and Risk program Examine future projections of drying events in collaboration with the Attribution and Risk program.
	3	Determine the impact of land surface processes on drying events in the ACCESS regional model.
WACI2 Tropical Depressions	1	Develop an improved version of a tropical/subtropical low identification and tracking algorithm and apply it to ERA5 to examine the relationship of monsoon lows to rainfall and its extremes.
	1	Create publicly available dataset of high-resolution wet-season satellite data to support research into Weather and Climate variability.
	1	Apply indices for the detection of ENSO, IOD and the MJO to gridded reanalysis data and quantify their variability and co-variability in the ERA5, ERA20C and 20CR records.
	2	Construct rainfall composites over Tropical Australia and the Maritime Continent under different modes of variability and co-variability, for mean and extreme rainfall indices on daily and sub-daily timescales. Use AWAP, TRMM/GPM for the recent period and other gridded products as required.
	2	Begin investigation on dynamical characteristics that differentiate lows with extreme rainfall from those without.
	3	Determine how the large-scale and local mechanisms leading to extreme rainfall change for different modes of variability and assess the influence of co-variability, using ERA5 and other gridded datasets as required.
	3	Plan and execute experiments of canonical examples from the historical record using the ACCESS model, to examine interaction of modes of variability and impact on rainfall extremes.

Priority levels: 1 = to be achieved in 2021. 2 = substantial progress in 2021. 3 = progress towards in 2021.

Drought

Project	Priority	Intent
D.1	1	Compare drought metrics in existing last millennium models with historical drought metrics
	1	Identify multi-year droughts in observations and examine their characteristics (e.g. duration, severity, etc) using large ensemble reanalysis (e.g. ERA20C or CAFE).
	1	Assess internal atmosphere versus oceanic forced droughts using CMIP simulations without ocean variability (e.g. piClimControl using multi-model ensemble).
	2	Identify multi-year droughts in historical record and examine links to Pacific (ENSO), Indian (IOD), and Southern Ocean (SAM) variability.
	2	Calculate compound modes of variability in last millennium, and the context this gives to changing likelihood in future scenarios, using PMIP3/4 and CMIP5/6 data
	2	Determine whether ACCESS ESM 1.5 simulates drought-breaking processes and their relationship to high rainfall events.
	2	Explore the sensitivity of Australian vegetation to drought
	2	Evaluate the skill of ACCESS-S in simulating drought
	3	Compare the statistics (e.g. frequency) of ENSO and IOD for different stages of multi-year droughts (i.e. onset, peak and termination) between present climate and future warming scenario in climate simulations (e.g. CESM2LE or CMIP)
	3	Assess the impacts of compound modes (co-occurring and consecutive) on wind-fields, rainfall, soil moisture and fire weather using long/large simulations to build up enough examples for robust statistics
	3	Determine the effect of changes in magnitude of tropical variability on drought length and drought-breaking rain, including expected impacts of future variability change
	3	Examine large-scale dynamics of climate drivers and modulation of synoptics using observations, reanalysis, and climate models, aligned with WCI program.
	3	Use pacemaker-style experiments to examine the role of local and remote SST forcing on the large-scale atmospheric environment, and perhaps subsequently the synoptic processes that lead to drought-breaking rain
D.2	1	Undertake a thorough analysis of observations (rain, streamflow, satellite vegetation and soil moisture etc.) to build a complete picture of what happened during the drought and how vegetation responded
	1	Use observations of past Australian droughts to examine the characteristics of drought termination to provide an overview of what drought termination events “look like”
	1	To what extent can rising CO^2 ameliorate plant drought stress?
	1	On which timescales do optimal adjustments to vegetation function confer resilience? A case study in South-Eastern Australia
	2	Examining the vulnerability of Australian Eucalypts to future drought-induced tree mortality
	2	Understanding stomatal conductance model responses to drought
	2	Australian droughts & HW and the role of groundwater
	2	Determine which synoptic-scale processes are mostly responsible for drought termination and show connections to heavy rainfall
	2	Examine the changes to the regional mean atmospheric state during drought termination and relate these back to the synoptic-scale processes through the dynamics
	2	Implement parameterisations into CABLE that help alleviate known biases during drying and extended dry periods. These may include hydrological processes, soil physics, vegetation processes
	2	Development of the representation of key processes in CABLE to represent dry (drought) processes
	3	Use coupled simulations for the drought to examine the role of the land (including land-atmosphere feedbacks) in the recent drought and quantify the extent to which land surface processes contributed to the drought each year
	3	Explore upstream and downstream impacts of drought using coupled models
	3	Perform and evaluate CABLE simulations of the drought to quantify the impacts on moisture and carbon stores and fluxes and the key processes leading to these changes

Project	Priority	Intent
All of RP	1	Perform CMIP6 last millennium simulation with ACCESS ESM1.5
	2	Support evaluation efforts of land surface component in the high resolution atmospheric simulation (M1) and the coupled high resolution ocean simulations (M2)
	2	Contribute to CM2 long control simulations, and ensemble of historical/future simulations, coordinated across WCI, D and AR programs
	2	Run pacemaker experiments with and without SST variability in individual tropical ocean basins to examine how severity, duration, etc, of multi-year droughts varies.
	3	Run modulated magnitude of tropical variability pacemaker experiments, informed by palaeoclimate data
	3	Perform targeted partially-coupled experiments in ACCESS-CM2 to understand how the frequency of climate drivers can affect the duration and termination of multi-year droughts
	3	Advances towards the development of a regional version of ACCESS incorporating CABLE

Attribution and Risk

Project	Priority	Intent
AR.1	1	Examine the role of the subtropical jet in Indian Ocean teleconnections to south-east Australia
	1	Document an initialized attribution method for extreme events
	2	Determine sources of moisture and pathways to major southeast Australian droughts and connections with modes of variability *[link with D.1]*
	3	Design model experiments to establish the role of internal atmosphere variability versus ocean drivers onto droughts for Australia *[link with D.1]*
	3	Evaluate the simulation of key drying mechanisms during front passages in global models *[link with WCI.1]*
AR.2	1	Set up and begin running twin ACCESS simulations for analysing scale interaction.; Application of methods to existing coarse-scale model ensembles
	1	Survey existing weighting / sub-selection approaches for optimising ensemble representation of intensity-frequency-duration of extremes and begin out-of-sample testbed construction
	2	Research and initial testing of machine learning methods
	2	Evaluation/comparison of the proposed new methods to existing dynamically and/or statistically downscaled extremes and observations
	3	Survey and discuss with end users and partners which extremes variables/metrics should be targeted for ensemble optimisation
	3	Analysis of how statistical methods improve the simulation of, and reduce the uncertainty in climate extremes across existing model ensembles, while understanding how the statistical methods change projections in the risk of climate extremes, across the coarser and finer scaled model simulations
	3	Extending the statistical analyses to attribution assessments, by quantifying changes in the uncertainty of attribution assessments from climate simulations pre- and post-fitting of new methodologies
All of RP	1	Review of event attribution for Australia
	1	Create bespoke ACCESS-CM2 model simulations, both coarse- and fine-scale, run simultaneously
	1	Determine which types of extremes to focus on, consulting with CIs and stakeholders via Ian Macadam, based on ability of the high resolution model simulations to capture relevant extremes

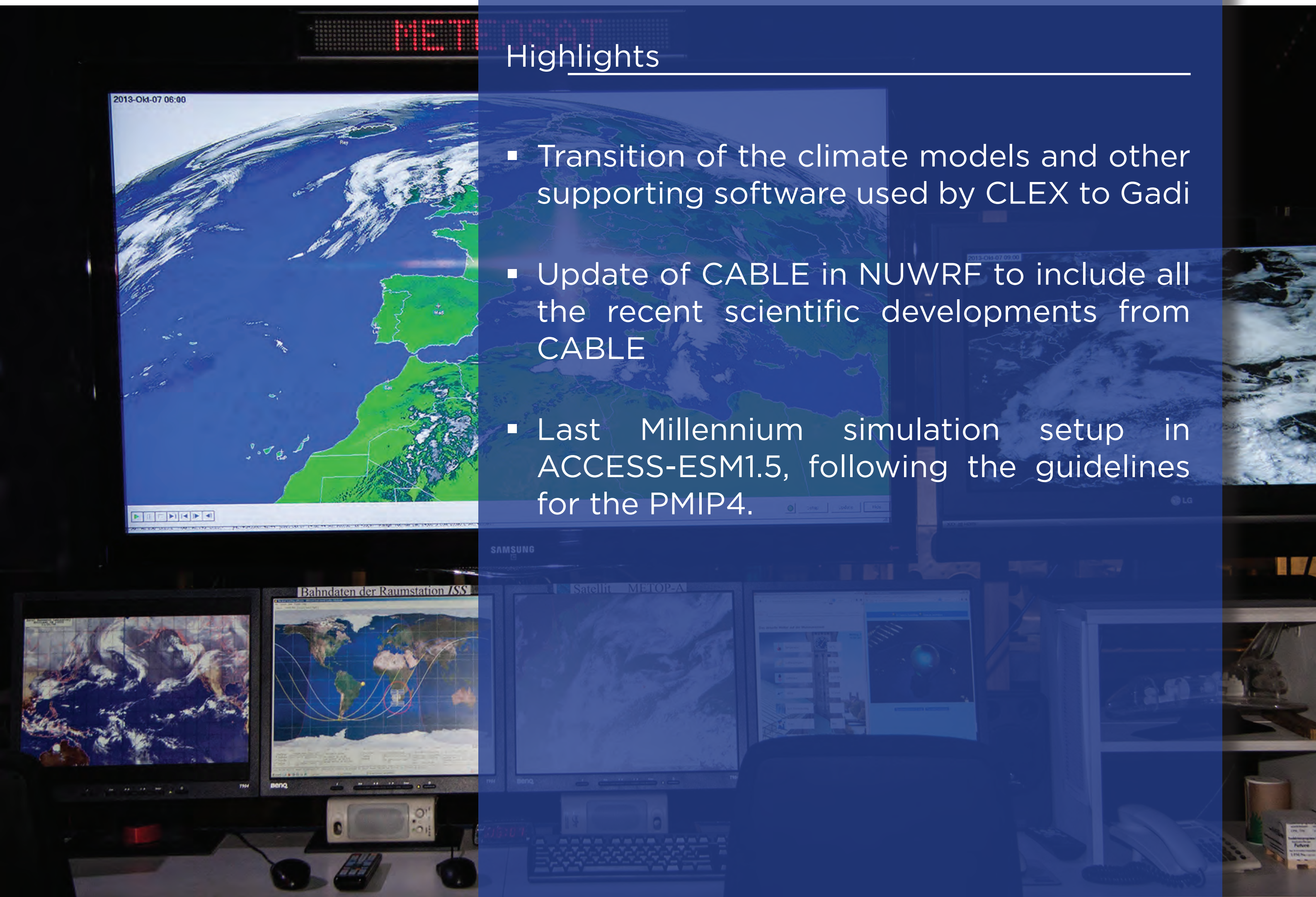
Priority levels: 1 = to be achieved in 2021. 2 = substantial progress in 2021. 3 = progress towards in 2021.

Ocean Extremes

Project	Priority	Intent
[RP OE].1	1	Commence analysis of the representation of marine heatwaves in 0.1° ACCESS-OM2 interannual forced (IAF) simulation for selected case study regions around Australia *[link with M.2]*.
	2	Develop frameworks (e.g. Lagrangian vs Eulerian) to assess processes and marine heatwave predictability around Australia *[link with M.2]*.
	3	Begin to examine marine heatwave predictability using linear approaches (e.g. linear inverse model and/or adjoint model techniques), and possibly nonlinear approaches.
[RP OE].2	1	Identify existing and emerging observational and reanalysis data sets that can be used to quantify biogeochemical characteristics in ocean mesoscale structures.
	2	Develop techniques to quantify biogeochemical structures in mesoscale ocean features such as fronts and eddies using observational and reanalysis data sets *[link with RP AR]*.
	3	Begin analysis of biogeochemical Argo data and existing model outputs such as OFAM and B-SOSE *[link with RP AR]*.
All of RP	1	Implement biogeochemistry in 0.1° resolution ACCESS ocean model: ACCESS-OM2-01-BGC *[link with M.2]*.
	2	Evaluate the representation of mesoscale features in ACCESS-OM2-01-BGC *[link with M.2]*.
	3	Investigate the role of mesoscale features as sources of ocean extremes.

Priority levels: 1 = to be achieved in 2021. 2 = substantial progress in 2021. 3 = progress towards in 2021.

Computational Modelling Support



Highlights

- Transition of the climate models and other supporting software used by CLEX to Gadi
- Update of CABLE in NUWRF to include all the recent scientific developments from CABLE
- Last Millennium simulation setup in ACCESS-ESM1.5, following the guidelines for the PMIP4.

Gadi

With the National Computational Infrastructure's (NCI) new supercomputer, Gadi, coming online at the end of 2019, a significant amount of time was spent porting models and updating tools. The Computational Modelling Support (CMS) team ported nine versions of Weather Research Forecasting (WRF) and four versions of the Unified Model (UM) to the new supercomputer. We also helped significantly in porting NASA-Unified Weather Research and Forecasting (NU-WRF) model, Modular Ocean Module - 5 (MOM5), the Australian Community Climate and Earth System Simulator - (ACCESS-OM2) model suite and ACCESS-ESM1.5. We appreciate the help we received from NCI in this effort. We have also completed performance analyses of some of the models (WRF, UM), while NCI completed the performance analysis for ACCESS-OM2. After some adaptations to the compilation options and processor layouts, all models are running between 25 percent and 100 percent faster on Gadi compared to Raijin.

With the transition to Gadi, NCI reduced the information provided to users, along with significant changes to the tools that NCI provides for reporting computer and disk usage. Coupled with changes to disk layout and mount points, this required a major update by Aidan Heerdegen to the tools for gathering storage and service unit (SU) usage for the ARC Centre of Excellence for Climate Extremes (CLEX).

We continued the development of our analytics dashboards under Grafana. As well as updating to accommodate the transition to Gadi we have now organised the information over three levels of interest: Centre-wide analytics, project analytics, user analytics. This allows us to monitor the resource usage across the Centre and refer to a specific project if there is a need for additional resources for this project. Individual users can also get information on their footprint at NCI across all the projects we monitor.

In addition to this reorganisation we have added the following information:

- Age of the stored data to prepare for the automatic deletion on the /scratch file system at NCI. This data is available at all three levels
- Information on the compute queues and jobs; namely, jobs running on each queue, running jobs for each project of the Centre, jobs with long waiting times, jobs with low CPU efficiency or low memory usage. This enabled us to add automatic alerts to Slack for inefficient jobs wasting SU.

Scott Wales has written a custom version of the Gadi's job status command line, uqstat. This command allows users to have easy access to the status of their jobs or the jobs from the same project. It also informs them of their job efficiency in both CPU and memory usage. Scott also developed another tool so researchers can now easily start Jupyter Notebooks on Gadi compute nodes to interactively analyse their data. This was required to cater for the needs of researchers with particularly large datasets and data workflows which do not fit within the Virtual Desktop Infrastructure offered by NCI.

All of the automated testing we host on our Jenkins server needed to be reconfigured with the upgrade to Gadi. As part of this process, Aidan has also updated all the automated ACCESS-OM2 continuous integration testing to passing status, as well as adding continuous integration build testing to many of the individual components of the ACCESS-OM2 model.

ACCESS-ESM1.5

We continued our cooperative effort with CSIRO around ACCESS-ESM1.5. Holger Wolff has helped to port ACCESS-ESM1.5 to Gadi. He also built a more user-friendly build system. This will enable users to easily recompile the model if they need to modify any of the codes.

Holger and Scott have continued porting and developing additional configurations for ACCESS-ESM1.5 within the payu workflow management tool: the CMIP6 historical configuration and the Last Millennium simulation for the Paleoclimate Modelling Intercomparison Project - Phase 4 (PMIP4). The Last Millennium simulation required a significant amount of work. This simulation requires the orbital parameters to change along with the simulation, but the UM version used in ACCESS-ESM1.5 does not allow the orbital parameters as input parameters. This required some clever changes in the source code to program those modifications of the orbital parameters depending on the simulated time. Several other inputs needed to be updated as well. Additionally, the simulation has to be designed to allow reading of the same input forcing file repeatedly during the spin-up period, which isn't a standard way to run ACCESS-ESM1.5. Holger explained how to manage an ACCESS-ESM1.5 simulation in the CSIRO-led webinar, Getting Started with ACCESS-CM2 and ACCESS-ESM1.5. All users of ACCESS-ESM1.5 are now using the payu tool to manage their simulations.

CABLE

Progress porting Community Atmosphere-Biosphere Land Exchange (CABLE) into the Joint UK Land Environment Simulator (JULES) repository (JaC) has stalled for most of the year because of the preparation of a closed release by the UK Meteorological Office. This release was part of the UK Met Office preparations of the next generation of models (NGM) for the future supercomputers. As such, this release has introduced significant structural changes to JULES. The team working on JaC, Danny Eisenberg, Jhan Srbinovsky and Ian Harman from CSIRO, is actively working to catch up with JULES changes for CABLE. We expect the first version of CABLE working within JULES for a specific configuration to be released in the first half of 2021.

Significant work has been done during the past year on matters relating to the coupling of CABLE to WRF. The major body of work was to update the CABLE version used in ACCESS-CM2 with some additional bug fixes. The update is almost completed. The Land Information Systems code used to couple CABLE to WRF was also updated to allow use of the ERA5 data set as forcing data for CABLE.

ERA5

A successful ARC Linkage Infrastructure Equipment and Facilities (LIEF) grant has enabled some researchers of CLEX to secure storage for the ERA5 collection. This collection will be managed by NCI's data management team. However, the fulfilment of the grant has been delayed because of the COVID-19 pandemic. As such, Paola Petrelli continued to update and manage the temporary ERA5 collection during the year. She kept the already downloaded variables current but also added a significant amount of data: ERA5-Land data set; fire danger indices CEMS-Fire, derived from ERA5; and near-surface meteorological variables from 1979 to 2018, derived from bias-corrected ERA5 reanalysis. The new collection came on line in November and we are now in the transition period between the two collections.

Other datasets

Paola Petrelli has put significant work into organising a new collection for precipitation datasets. Those datasets can be tricky to organise together as they come from very different tools: models, satellites, radar, etc. This means they are distributed using different formats from one another. Paola consulted with Centre researchers interested in those datasets to standardise their formats as much as possible, while keeping the datasets in a useful organisational grouping for the researchers. The collection includes the following :

- CMAP
- CMORPH
- FROGs
- GHCN
- GPCC
- GPCP
- GPM / IMERG
- GSDR
- GSMaP
- TRMM

Paola also downloaded the following datasets at NCI, for CLEX researchers to use:

- HADDIST
- C20C v3
- OISST v2.1
- JRA55, 6-hourly

Aidan Heerdegen created a data-publishing pipeline in python for the ACCESS-OM2 data, which is now a collection in the NCI data catalogue. This pipeline allowed researchers to quickly reformat the ACCESS-OM2 data to ensure a better quality of the data being shared (for example, through following the Climate and Forecast Metadata (CF conventions)).

Data Analysis

XMHW

At the start of the year, we noticed a few oceanographers having issues calculating marine heatwaves statistics with the current tool available: MHW. MHW was written by Eric Oliver. It identifies the heatwave days and calculates a slew of statistics for each heatwave. The tool worked very well when created but would not scale appropriately when using model outputs at higher spatial resolution. Paola has worked during the year to rewrite the code using xarray and dask to speed up the calculations by parallelising the code. Although not all heatwave statistics have been rewritten yet, the XMHW tool has been successfully used by several researchers to identify marine heatwaves in their datasets.

CleF

Paola Petrelli continued updating and maintaining CleF, a tool we developed in collaboration with NCI to facilitate discovery and access of CMIP5 and CMIP6 data at NCI. We had a major reorganisation of the tool, moved the database to a new production server and added new features. In particular, a new citations option and more complex queries were implemented. Documentation was regularly updated and two new blogs have been published to help with the tool uptake.

Climtas

A large part of the analysis of climate datasets now involves using the xarray and dask libraries, to allow easier analysis and parallelisation. Scott has developed several functions to help with these operations, providing improved optimisation for the specific-use case of analysing high-resolution climate datasets. This helps with operations like calculating climatologies and resampling time series to convert hourly data to daily data, for example, as well as controlling the memory use of large calculations. The Climtas library is publicly published on Github and available at NCI as part of the CLEX Conda environment maintained by CMS.

COSIMA data collection GUI

The Consortium for Ocean Sea Ice Modelling in Australia (COSIMA) collection is a complicated collection designed for navigating with simulations spanning different spatial and temporal resolutions as well as temporal periods. There are also several perturbation runs in this collection. Plus, the list of output variables varies depending on the simulation. Additionally, the latest runs need to be available to researchers, with the data being spread among several locations at NCI. This means it can be difficult for a new user to find which simulations include the variables they need for their analysis. To alleviate this problem, Aidan Heerdegen has built a GUI interface to this dataset. The GUI allows users to filter experiments on criteria such as resolution, time period, the model used, etc. It also allows searching for variables using their long name rather than cryptic variable names as well as filtering of the datasets based on a given variable availability. The GUI also includes a dialogue to load a chosen dataset, showing all available variables, the temporal frequencies and time periods available, with controls to select the desired time period and frequency. Aidan has also automated the generation of the COSIMA shared database to keep it constantly updated when new data is added to nominated locations on disk.

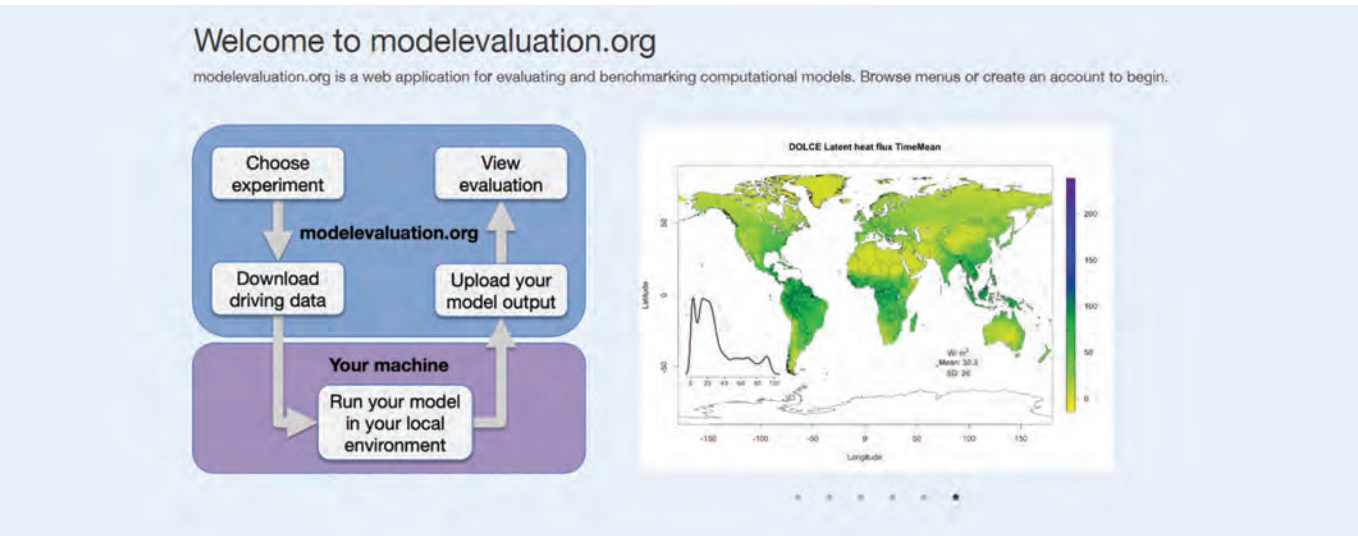
CLEX Conda Environment

The Conda environment maintained at NCI continues to be supported and is widely used both within the Centre and by other NCI users. The Conda environment provides a supported Python installation with a wide variety of libraries focused around climate and weather data analysis. Currently, 330 users have access to the environment through the 'hh5' NCI project. The environment is updated quarterly, alongside NCI's normal maintenance, with three supported environments (old, stable, unstable), which allows for continuous updates but also maintains some stability for existing scientific code. There are more than 600 packages currently installed. Over the year, 20 packages, among them xesmf, earthpy, cupy and ants, were added to the environment.

ModelEvaluation.org

Danny Eisenberg continued developing ModelEvaluation.org a web application designed to evaluate model performance by comparing model simulation results to observational data. This year, the application user base expanded to nearly 100 users internationally, allowing for something equivalent to beta-testing. This led to greater user feedback, resulting in the system being made far more robust and user friendly.

Additionally, the expansion in users required significant rescaling of the system to cater for both the larger number of concurrent users as well as the significantly larger volumes of data being used in the latest model-evaluation experiments. It has also led to an exploration of new directions in functionality that are now in the pipeline, such as the development of an API that could be used to automatically integrate model evaluation into the workflow of model development itself. Finally, modelevaluation.org has been migrated to the NCI cloud with the help of NCI's staff.



CMS Team - Statement of Intent for 2021

Level	Intent
1	Finish upgrade to CABLE in NUWRF version v9p2. Update the simulation workflow system for NUWRF. Develop benchmarking suite with modelevaluation.org
1	Collaborate with CSIRO on ACCESS-CM2-025
1	Link with the CABLE group to review the organisation of the data sets needed by the land surface modelling and data analysis
1	Publishing of new data sets
1	Continue reorganisation of data sets at NCI. Continue linking with NCI, BoM and CSIRO to ensure CLEX needs are considered and help communicate the changes to users
1	Provide support to Centre researchers and ACCESS users via the CWS helpdesk
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
2	Continue integration of CABLE in JULES in compliance with the UM and LFRIC requirements
2	Continue work on high-resolution atmospheric model for the Centre
2	Work on model updates and maintenance at NCI for WRF, MOM and ACCESS
2	Continue collaborating with outreach and admin on CLEX data legacy
2	Pursue more active participation in research programs, establishing relationships at the relevant level and identifying possible improvements to workflows
2	Support MOM5 to MOM6. Transition ocean model configs
3	Improve data workflows
3	Start a new diagnostic toolbox for the Centre in collaboration with post-doctoral fellows

Priority levels: 1 = to be achieved in 2021. 2 = substantial progress in 2021. 3 = progress towards in 2021.

Grand Challenge Simulation: Aus400

In early 2020, CLEX completed its first Grand Challenge simulation, Aus400 – a 400 metre grid spacing atmospheric simulation covering the entire Australian continent for a period of 60 hours. At the time Aus400 was the largest grid size ever performed using the Unified Model, the atmospheric component of ACCESS.

A simulation of this size with 400m resolution was needed to directly capture and resolve many atmospheric processes using model equations. With larger conventional grid spacing many kilometres across, these processes are simplified over large areas using parametrisations. This means that processes that produce phenomena like thunderstorms, mountain waves, frontal circulations and cloud fields – many of which are associated with extremes – can not be captured in detail.

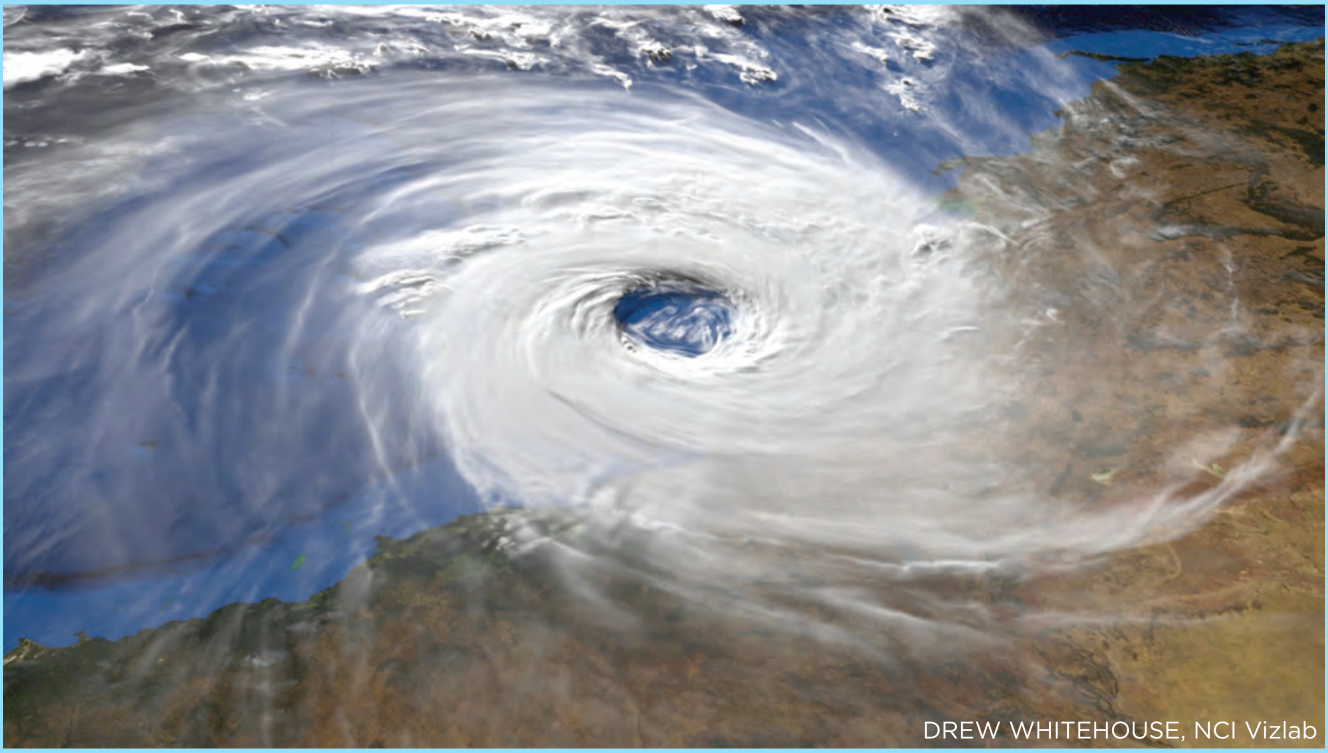
This Grand Challenge Aus400 simulation effectively puts a microscope in the hands of atmospheric scientists enabling them to study the direct influence of small-scale phenomena on the larger weather systems that are the target of weather and climate prediction.

The model run was performed by Scott Wales of Computational Modelling Support (CMS) team, with support from Centre of Excellence researchers, the Bureau of Meteorology (BoM), the UK Met Office and NCI, as part of NCI's STRESS2020 project to stress-test the new Gadi supercomputer.

The full domain of the Australia-wide simulation consisted of 13,000 x 10,000 grid points, with 85 vertical layers. As the model had not previously been run at such large scales, several new techniques and fixes were also used to run the simulation. The ancillary data, which includes information such as the land use and orography for each grid cell, needed to be generated in sections to reduce memory-use during their creation. These were then stitched back together to cover the full domain with the assistance of BoM's Dr Chun-Hsu Su.

The model's initial and boundary conditions used as the starting point for the simulation were derived from a lower resolution 2.2 km grid spacing run. This in turn got its boundary conditions from BARRA, the Bureau's regional reanalysis project. These initial conditions were interpolated from lower resolution into the higher resolution simulation.

This general interpolation process produced the first of many challenges. For the simulation to run successfully the entre grid area for a particular point in time had to be stored on one



of Gadi's huge memory nodes. The problem was that the interpolation procedure becomes far more complex around Australia's coastline at high resolution, with many more small inlets and peninsulas showing up in the higher resolution. The upshot was that the process to resolve coastal points was extremely slow, as there weren't enough CPUs to resolve these regions simultaneously with the land-only grid spaces. This meant it became impossible to store the entire grid in memory at the same time.

To solve this, the setup was split into multiple steps. First the inputs required to run the coast point calculation were exported. Then these were calculated offline using the general Gadi queue that access to many more processes. Finally, the resolved coast points were imported back to finalise the initial conditions setup.

Another challenge was that the huge size of the model grid caused problems with saving the data. Each model hour of the run produced 2.4 TB of data, which took around 30 minutes to save to disk. This required heavy use of the model's IO server support and even this had to be modified to support the size of the domain. Support from NCI was also invaluable in optimising the Lustre file system settings for maximum efficiency.

The full output of the Aus400 experiment is 50 TB of NetCDF data after post-processing. The data has been published by NCI and is available for researchers with NCI accounts to work with locally as well as remote access through NCI's Thredds server. The output variables mirror those produced by the Bureau's BARRA reanalysis. In addition to the primary 400m grid spacing simulation, the outputs of the 2.2 km simulation used as an intermediate between BARRA and 400m are available, with multiple realisations providing a small ensemble.

Finally, to help analyse the output of the Aus400 run the CLEX CMS team has developed a Python 'cookbook' of useful functions for working with the data efficiently, providing tools for interpolating horizontally and vertically as well as for visualisation of the full domain. ■

Researcher Development Program

Highlights

- Actively and effectively shifted RDP online due to COVID-19
- A wide range of initiatives and support networks put in place to support all Centre research during the pandemic
- A successful winter school delivered virtually
- Regular technical training delivered virtually by the CMS team
- A professional development day organised by and for our early career researchers
- Two successful science paper writing workshops
- 14 students submitted PhD theses in 2020
- Our students were authors on 63 journal articles this year, 46 as first author
- 20 undergraduate students were introduced to climate science research via our undergraduate research scholarship initiative.

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

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

This year was particularly challenging due to COVID. However, the support provided via our researcher development programming; the fact the Centre has long used video conferencing for meetings, seminars and training; and our Centre-wide initiatives around health and wellbeing, all meant that we were well placed to tackle the difficulties of 2020.

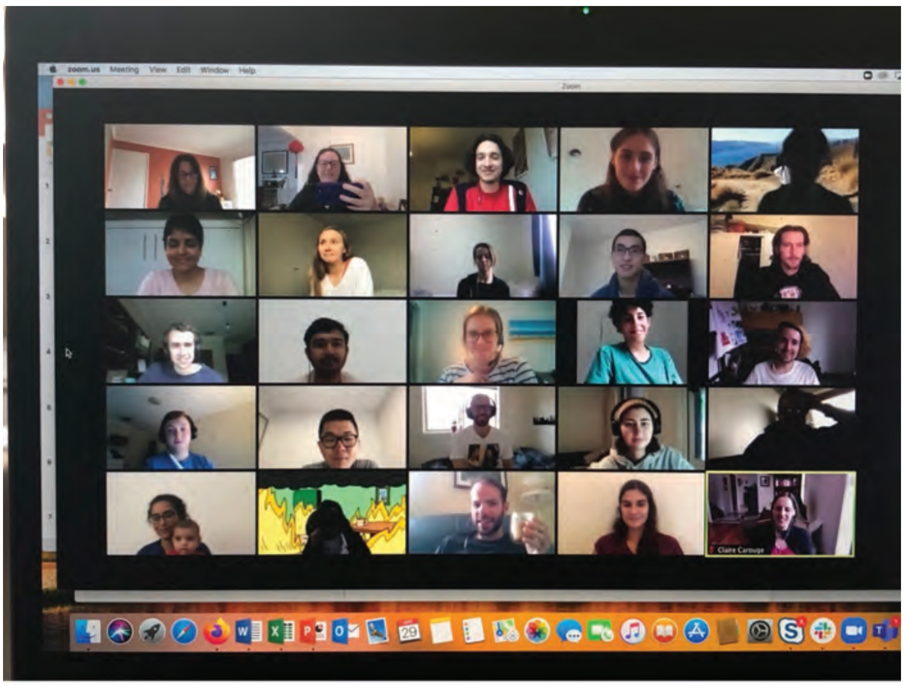
In 2020 we welcomed 13 honours students and 27 graduate students to the Centre. All have been actively involved in our graduate activities. Due to border closures, seven students have started their degrees offshore. These students are being supported via our student buddy system, new research inductions, regular meetings with our graduate director and time-zone sensitive meetings with supervisors.

We had 22 students submit theses this year (14 PhD and 8 honours/masters), and they have been moving on to positions in a variety of sectors. In 2020, recognising that students close to submission may be faced with their scholarships ending at a time of employment uncertainty – often with no access to government support – and closed borders that prevented them returning home, we offered post-submission scholarships to provide bridging funds. These scholarships were offered once individual university support was exhausted, and they required a tangible outcome at the end; for example, writing up a thesis chapter for submission to a journal. Of our graduating PhD students, half have moved on to positions in universities, 30 percent have taken up positions in research institutions, and the remainder are split between government and industry, including data sciences, insurance companies and environmental consultancies.

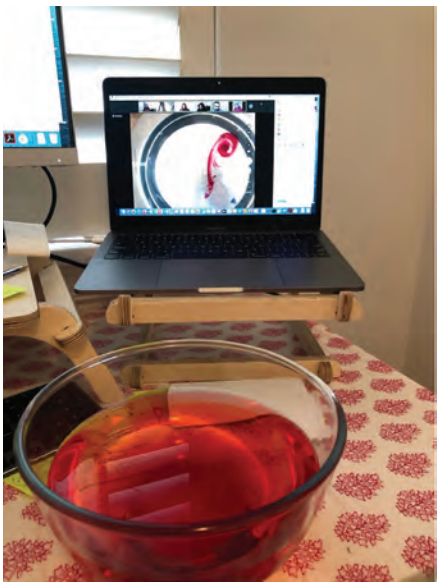
The RDP recognises that climate scientists come from a variety of undergraduate backgrounds and come to us with a varying range of skills and knowledge. Therefore, the program offers important breadth and depth of climate science knowledge, technical and communications training and professional development, including detailed career advice.

Our popular scientific paper writing workshops went virtual this year and introduced an interactive method to develop the outline of a paper using a story-boarding technique. Thirty-three participants joined the session, which included instructional lectures followed by participants developing an electronic storyboard of their paper with feedback from a buddy and CLEX researcher mentor. These sessions are open to all Centre students and ECRs. The success of our writing workshops can be seen in our publication successes, with 63 papers published by Centre students this year (46 as first author). Included in this impressive publication list were three first-author papers in the *Journal of Geophysical Research: Atmospheres*, by Kim Reid (Uni. Melb), Pavan Raavi (Uni. Melb) and Sonny Truong (Monash), along with papers in the *Journal of Climate*, by Jiale Lou (UTAS), Maurice Huguenin (UNSW), Dawn Yang (Monash) and Fabio Dias (UTAS). The full list of publications can be found on page 106

CLEX new researcher induction



In June, the cornerstone of our program, our annual winter school, went online. The virtual event touched on all three pillars of the RDP: science fundamentals, communications and professional development. The science fundamentals lectures covered atmospheric and ocean dynamics and involved participants comparing non-rotating fluids in bowls on their desks at home to the rotating fluids in Navid Constantinou's lounge room. Our communications pillar involved Media and Communications Manager, Alvin Stone and knowledge broker James Goldie presenting sessions on writing for a public audience and data visualisation respectively. Despite this being a time of such employment uncertainty, we held an inspiring and interactive session where three of our Centre alumni shared their advice and strategy on life post-CLEX. Steph Downes joined us from Hobart to discuss her roles in academia, government and now – with her role as a Specialist Master at Deloitte – industry. Steph Jacobs joined us from Melbourne to talk about her role as a consultant at Mosaic Insights. And Peter Gibson joined us from San Diego to talk about his roles at NASA JPL and now, the Scripps Institution of Oceanography, where he has recently started as a senior researcher.



Rotating vs non-rotating fluids- CLEX winter school 2020

Professional development of our students continued via an Early Career Researcher Day developed by our ECRs, for our ECRs. This year the event ran virtually and included a panel discussion on the future of academia and advice on planning your research career. The panel was made up of speakers with a wide range of academic experience: Nathan Bindoff (CLEX Chief Investigator, UTAS), Amelie Meyer (CLEX Associate Investigator, UTAS), Matthew England (CLEX Chief Investigator, UNSW), Ailie Gallant (CLEX Associate Investigator, Monash) and Terry Bailey (Executive Director of the Institute for Marine and Antarctic Studies, UTAS).

In collaboration with our CMS team, technical training opportunities this year have included weekly technical training sessions delivered via our videoconferencing system. This was expanded to also include regular drop-in sessions to replace lost in-person interactions due to COVID-19.

Undergraduate Scholarships

Climate science students come from a range of quantitative undergraduate degrees. To ensure undergraduate students are aware of the opportunities within the climate sciences, we offer highly competitive 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 universities or our Australian Partner Organisations, including CSIRO and the Bureau of Meteorology. In addition, the Department of Environment and Energy has supported a scholarship focused on ozone science. Undergraduate students are supervised by our ECRs, giving them vital supervisory experience. Scholarships are offered throughout the year and can be undertaken either full time during semester breaks or part-time during the academic year. In 2020 we welcomed 20 undergraduate students from five universities to the Centre, to work with us on research projects.

Prizes

Our students were extremely successful in winning both national and international prizes this year, including: Jiawei Bay who the Chinese Government Award for Outstanding Self-Financed Students Abroad; Sopia Lestari, recipient of Hadi Soesastro Prize 2020 and Ariaan Purich who was awarded the AMOS Uwe Radok Award for best thesis. The full list of prize recipients can be found on page 118.

Researcher Development Program Statement of Intent 2021

Priority	Intent
1	Run a student focused winter school with a focus on atmosphere and ocean dynamics
1	Work in collaboration with CMS team to deliver regular virtual training sessions
1	Offer regular researcher development virtual seminars
1	Expand undergraduate scholarship program into additional national partner organisations
1	Support leadership training and mentoring opportunities for ECRs, and offer in-Centre opportunities for ECRs to lead projects and initiatives
1	Expand the library of virtual resources available via the Centre's website
1	Develop researcher development opportunities purely for centre postdocs that identify priority areas for development based on individual needs and career objectives
1	Increase engagement between students and industry to build understanding of non-academic career paths
1	Encourage industry placements, or industry mentoring opportunities, for students and ECRs via existing networks such as IMNIS (Industry Mentoring Network in STEM) and APR.Intern (Australian Postgraduate Research Intern)
1	Implement regular surveys to seek feedback on the researcher Development Program. Results from the survey will be used to inform future development of the researcher development program.
2	Develop individualized training plans for the professional development of PhD students and assess this plan annually to create a culture of continuous learning and professional development.
2	Develop a formal alumni network, including exit surveys, and opportunities for alumni to be involved in centre mentoring and events

Priority levels: 1 = to be achieved in 2021. 2 = substantial progress in 2021. 3 = progress towards in 2021.

Student profiles

Charuni Pathmeswaran

Who in CLEX are you working with?

I am working with Sarah Perkins-Kirkpatrick, Alex Sen Gupta and Melissa Hart

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

I did my bachelor's in environmental science at the University of Colombo, Sri Lanka, after which I pursued a master's in climate change science and policy at the University of Bristol, UK. For my master's dissertation I looked at sub-daily variability in temperature and relative humidity and their impact on heat stress. Towards the end of my master's I started looking at PhD opportunities and that's when I came across a project on heatwaves advertised by Sarah. It helped that I had met her in Bristol when she delivered a guest seminar there on heatwaves. This made me less anxious about moving to Sydney, as I had already met – albeit briefly – one of my supervisors.

Tell us a little about your project

Although numerous studies have been carried out on terrestrial and marine heatwaves separately, little work has been done investigating any potential association between the two. For my PhD I am investigating co-occurring terrestrial and marine heatwaves, specifically looking at the possibility of common drivers and how these events may interact with each other through local land-sea inte ractions. Such interactions could potentially alter heatwave characteristics such as severity and duration.

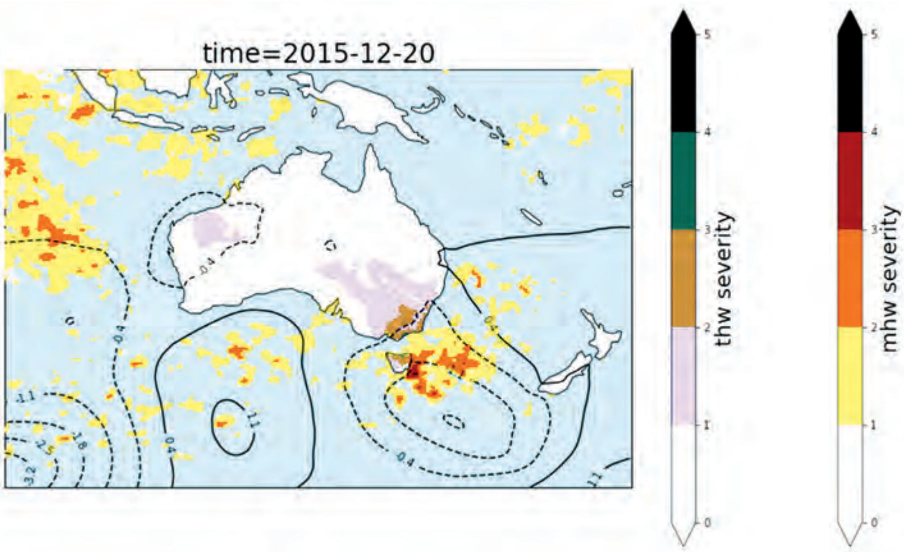
What opportunities has the Centre of Excellence offered you?

During the past one-and-a-half years I have had the opportunity to attend a winter school in Melbourne, the annual workshop in Hobart and the AMOS conference in Fremantle. This has not just opened up avenues for me to discuss my research with other scientists, but I've also had the chance to see different parts of Australia! Other researcher development programs, such as writing workshops, CMS training sessions and seminars have also been invaluable.

What are your hopes/plans for after you graduate?

Besides research, my interests are in science communication, education and public engagement. Ideally, I would like to find work that enables me to pursue these interests. ■

Figure: Terrestrial and marine heatwave severity during the 2015/16 Tasman Sea event. The Hobday et al (2018) framework has been used to define the different categories of heatwave severity.



David Hoffmann

Who in CLEX are you working with?

I was working with Ailie Gallant and Julie Arblaster at Monash University during my PhD.

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

I studied geography in Germany – with a focus on physical geography during my bachelor's and on climate and environmental change during my master's. I'm generally interested in all kinds of climate extremes and their impacts on the environment and society. My supervisor during my master's had a contact at Monash and after a few emails and forwarding I got in touch with Ailie.

Tell us a little about your project

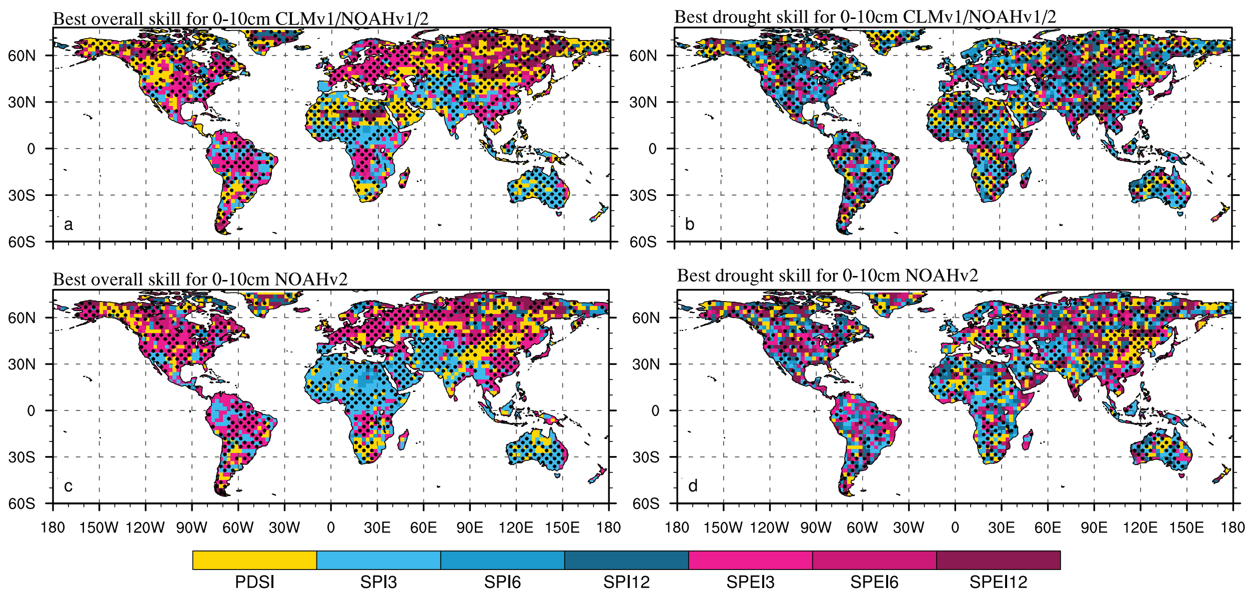
My project focused on drought and how it is represented in observations and climate models, particularly on the inclusion of evaporation. Effective monitoring of drought is crucial, and drought indices have been developed to do this by tracking variables such as precipitation, evaporation and soil moisture. But indices are often affected by uncertainties from measurements in observations and parametrizations in climate models. My project estimated the uncertainties in measurements and I found that precipitation alone is often sufficient for drought detection. By doing so, I also found that the behaviour of the indices in climate models reveal systematic limitations in the representation of drought processes.

What opportunities has the Centre of Excellence offered you?

The CoE has offered me excellent opportunities to connect, network and collaborate with other like-minded scientists across Australia. The Centre has also supported me in extending my international network by (partly) financing trips to workshops and conferences, for example a workshop on flash drought in Aspen/CO and the AGU Fall Meeting in San Francisco/CA in the United States. I'm still in touch with many scientists I met which resulted in a collaborative papers and co-hosting a session on flash drought next year at the EGU 2021.

What are your hopes/plans for after you graduate?

I have very recently graduated and found a job at the World Meteorological Organisation through my co-supervisor's connections with the Bureau of Meteorology. I hope that many of my contacts within the CoE will sustain and that we will reunite in the future.. ■



Sramana Neogi

Who in CLEX are you working with?

I'm a PhD student at Monash University, working with Martin Singh and Michael Reeder.

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

I am originally from India. I did my bachelor's at Calcutta University with an honours in physics and got my master's in atmospheric sciences from the National Institute of Technology, Rourkela, India. I have always been fascinated by clouds, and wanting to learn more about them served as my motivation to enter into this field. As part of my master's dissertation I studied fog and its predictions, which are a major cause of concern, especially in northern India in the winter months.

Tell us a little about your project

For my PhD, I'm studying how the tropical circulations driven by sea-surface temperature gradients change in a future warmer climate and how these changes impact precipitation projections. We simulate the interaction between largescale circulations and convection in a cloud-resolving model using two parameterization schemes, the weak-temperature gradient and damped-gravity wave approximations. We examine the changes in the large-scale vertical velocity with varying surface temperatures. The domain mean vertical velocity appears to be very top-heavy, with the maximum vertical velocity becoming stronger at warmer surface temperatures. The results are understood using a simple model for the thermodynamic structure of a convecting atmosphere based on an entraining plume, providing a stepping stone to understanding the factors driving changes to the large-scale tropical circulation in a future, warmer climate. The ultimate aim of the project is to find a simple framework which could explain some of the model biases we see in precipitation projections in climate models.

What opportunities has the Centre of Excellence offered you?

The Centre has provided me with a hoard of opportunities, not least of which is a chance to be mentored by and network with some of the leading minds in the field. The range of workshops and meetings held regularly, like the writing workshop have also provided a lot of guidance.

What are your hopes/plans for after you graduate?

I am planning to pursue an academic career after I graduate, hopefully within CLEX itself. ■

Sarah Jackson

Who in CLEX are you working with?

I am working with Prof Nerilie Abram, at the ANU.

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

I have always been interested in the outdoors, so I decided to do an undergraduate degree in geology at Victoria University in Wellington. After finishing the BSc, I continued with the Victoria theme and moved to the University of Victoria, in Canada, for my MSc. My MSc project looked at the distribution of dissolved cadmium in the Canadian Arctic Ocean and sparked a firm interest in the polar regions. I graduated from the University of Victoria in 2017 and moved to Cambridge to work in the ice core group at the British Antarctic Survey. I quickly fell in love with ice core research and decided to move to Canberra in 2019 to begin a PhD with Nerilie – with a quick detour to New Zealand first, to spend the summer walking the length of my country.

Tell us a little about your project?

Ice cores are invaluable tools in climate reconstructions, providing continuous records of temperature and greenhouse gas concentration. My project is focused on the water isotopic record from the Mount Brown South ice core, in East Antarctica. In ice cores, variations in water isotopic ratios can be used to reconstruct both temperature changes at the drilling site and broader environmental changes in the evaporative region. This region of Antarctica has been poorly studied, and the core will provide us with an annually resolved record of climate in the Indian Ocean sector of Antarctica for the past 1000 years.

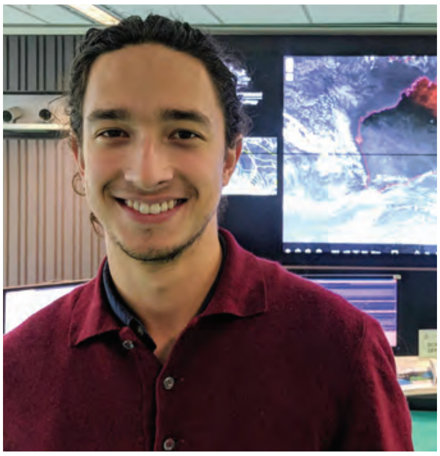
What opportunities has the Centre of Excellence offered you?

As well as providing opportunities to connect with researchers all over Australia, CLEX helped support my attendance at the Ice Core Analysis Techniques PhD summer school in Copenhagen. Attendance at the summer school was invaluable; the Australian ice core community is isolated, and the summer school provided the opportunity to connect with and learn from ice core scientists from all over the world, as well as learning fundamental skills required in my field.

What are your hopes/plans after you graduate?

Having never been to Antarctica to drill an ice core, I constantly feel like a slightly fraudulent ice core scientist – so I would love the opportunity to travel to Antarctica to assist with a drilling project and to then continue research as a post-doc. However, I am also realistic about career prospects – so I'm pretty open to whatever opportunities will come my way! ■

Nathan Eizenberg



Who in CLEX are you working with?

I work with Prof Craig Bishop at the School of Earth Sciences at the University of Melbourne. Well, at least on paper I do. My first day was the day after campus closed in Melbourne! I'm finishing up an honours year researching ensemble-based linear model techniques for atmospheric data assimilation.

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

I have a deep passion for applied mathematics that has taken me to atmospheric modelling and data assimilation. I have a BSc from Monash University and MSc in mathematical modelling and scientific computing from the University of Oxford. I also worked at the Bureau of Meteorology in Melbourne for the last four years as a research scientist on the atmospheric reanalysis project, BARRA. I decided to specialise in data assimilation, and so I've come back to school.

Tell us a little about your project.

The largest improvements in weather forecast skill over the last two decades are due to the implementation of 4D variational data assimilation (4D-Var). In meteorology, 4D-Var involves finding an analysis which minimises the weighted difference between the prior model state (often called the background) and all the observations throughout a time window. A key component of 4D-Var minimisation is the linearised model or adjoint, which encodes the model output sensitivity to initial conditions. Traditionally, these linearised models are written by hand – I'm told it's painful.

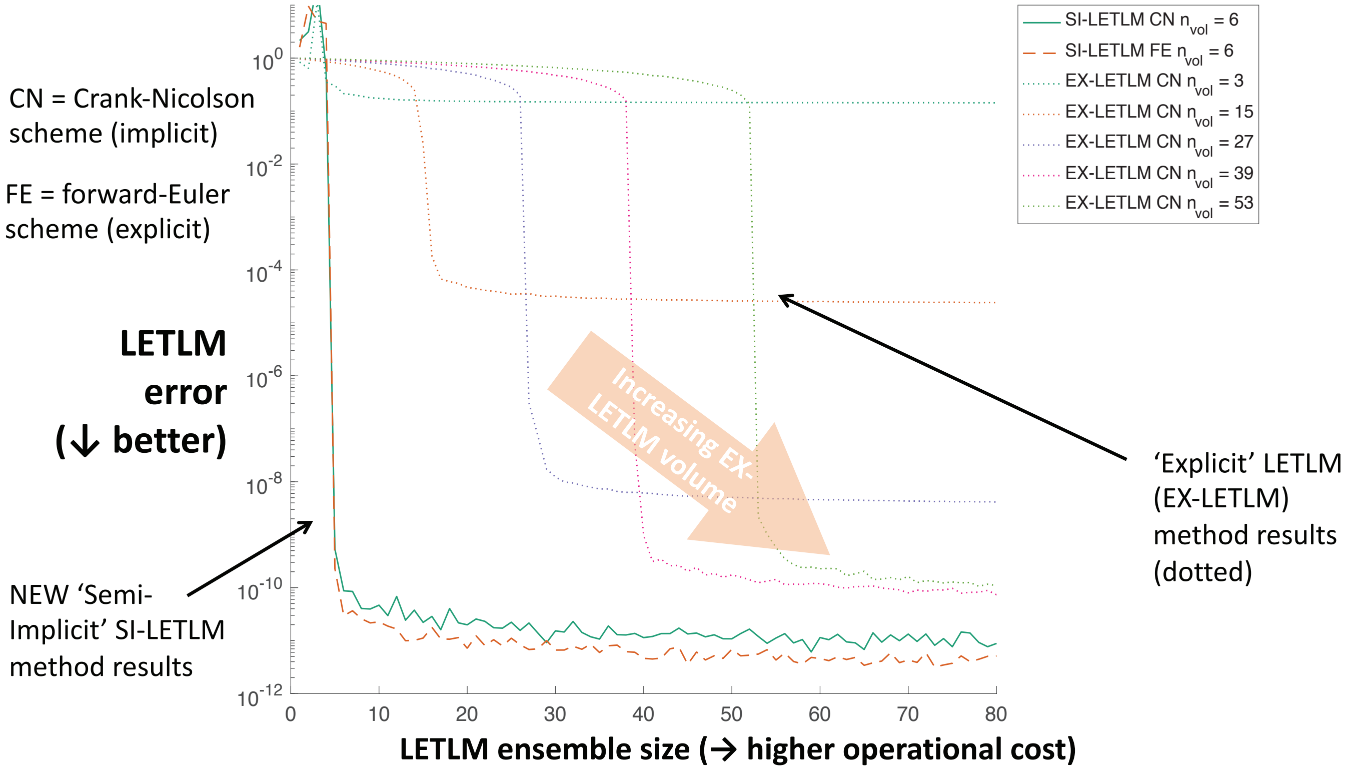
We're working on a new technique which uses an ensemble of nonlinear models to produce these adjoints and linear models – so-called Local Ensemble Tangent Linear Model (LETLM). Specifically, I've looked at the role semi-implicit time-stepping schemes have on the ensemble-based technique. We proposed a new LETLM method which correctly handles models which use semi-implicit/implicit time-stepping schemes (see figure below). Improving the LETLM may drastically reduce the cost of maintaining 4D-Var for operational weather forecasting and unlock this valuable technique for other modelling communities.

What opportunities has the Centre of Excellence offered you?

This has been a tough year for starting a new project. Luckily, I've had great support from Craig to help me through. I have also really appreciated the strong social community that is cultivated through CLEX. I look forward to continuing to get to know everyone properly soon. I was also lucky enough to attend the academic writing workshop last year in Hobart, which was invaluable.

What are your hopes/plans for after you graduate?

I hope to continue onto a PhD in data assimilation next year so that I can be a part of new research. Data assimilation bridges the gap between model projections and reality in a dynamic way. As our ways of observing and recording reality dramatically shift, new assimilation methods will create exciting opportunities in environmental modelling (and beyond!). I also like teaching, so I'm hoping to continue helping out in university meteorology subjects. ■



Semi-Implicit LETLM (SI-LETLM) produces better ensemble-based linear models when the time-stepping is implicit, the traditional 'explicit' method (EX-LETLM) requires a much larger ensemble and LETLM volume

Publications

Book Chapters

Cai, W., Santoso, A., Wang, G., Wu, L., Collins, M., Lengaigne, M., et al. (2020). ENSO Response to Greenhouse Forcing. In *El Niño Southern Oscillation in a Changing Climate* (pp. 289–307). American Geophysical Union (AGU). https://doi.org/10.1002/9781119548164.ch13

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Abram, N. J., Wright, N. M., Ellis, B., Dixon, B. C., Wurtzel, J. B., England, M. H., et al. (2020). Coupling of Indo-Pacific climate variability over the last millennium. *Nature*, *579*(7799), 385–392. https://doi.org/10.1038/s41586-020-2084-4

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Impact, Engagement, Prizes and Outreach

Engagement with Industry, Government and NGOs

Abram, N. Gave presentation on climate change and contributed to roundtable at ANU on emissions strategies attended by state and federal government representatives

Abram, N. Participated in roundtable discussions on the Australian bushfire and climate plan (Emergency leaders for climate action and Climate council)

Abram, N. Provided expert advice to the NSW Bushfire Inquiry

Alexander, L. Contributed to UN Environment Programme Finance Initiative Report

Alexander, L. Presentation on 'Recent developments in climate science: what do insurers need to know' to insurers at Extreme Hazards risk management and modelling summit

Di Luca, A. Lead author of the IPCC Sixth AR6 Chapter "Weather and climate extreme events in a changing climate"

Alexander, L. UNEP-FI presentation for TCFD on WCRP Grand Challenge on Extremes

England, M. Weddell Gyre circulation and variability CSHOR seminar series, CSIRO

Evans, J. Presentation to Parkes Shire Council

Evans, J. Lead author IPCC Special Report on Climate Change and Land - Desertification Chapter

Fan, X. Presentation to the Groundwater Management Team of DELWP, Victoria

Macadam, I. Attended online Natural Environment (biodiversity, soils, coastal, floods) NARCliM2 information session run by NSW DPIE

Macadam, I. Interviewed on development of NARCliM1.5 data portal by Link Digital, acting on behalf of NSW DPIE

Macadam, I. Meeting to describe CLEX to Genevieve Neilsen and colleagues of Australian Business Roundtable

Macadam, I. With CIs, contributed to IAG Severe Weather in a Changing Climate report

Meyer, A. Part of the APECS ECR group review of the IPCC Sixth Assessment Report (AR6) Climate Change 2021: Impacts, Adaptation and Vulnerability from Working Group II (WGII)"

Pitman, A. Advice provided to Aon Reinsurance solutions on climate risk assessment

Pitman, A. Briefed the Australian Climate Roundtable workshops on costs and impacts of climate change

Pitman, A. Briefed the co-chairs of the NSW independent bushfire inquiry on the role of climate change in 2019/20 bushfires

Pitman, A. Coordinated CoE letter to Dept of Education on national HPC infrastructure strategy

Pitman, A. Panel member for the CMSI/ESCC Hub report ' Scenario analysis of climate-related physical risk for buildings and infrastructure: climate science guidance'

Pitman, A. Written comment on Defence "ADF Response to Natural Disaster/Emergency"

Stone, A. Expert panel discussion at the Australian Science Communicators conference

Stone, A. Guest mentor at mentor event for science communicators at Australian Science Communicators conference.

Prizes and Awards

Abram, N. AMOS Priestley Medal

Alexander, L. Nominated a Fellow of AMOS

Alexander, L. 2020 Web of Science highly cited author

Ashcroft, L. 2020 AMOS Outreach Award

Bao, J. Chinese Government Award for Outstanding Self-Financed Students Abroad

England, M. 2020 AMOS Morton medal for leadership in meteorology, oceanography and climate science

England, M. 2020 Web of Science highly cited author

Fury, C. Green Impact award for Sustainability on campus Team IMAS lead by Christine Fury

Gergis, J. AMOS Science Outreach Award

Goyal, R. 2020 CCRC award for best student paper and the prize science communication and outreach

Hart, M. UNSW Vice Chancellors Award for Higher Degree Research Leadership

Hart, M. 2020 CLEX Director's Prize

Henley, B. 2020 Victorian Young Tall Poppy Science Award

Keating, S. Universitas 21 Global Education Fund award to develop online teaching resources in ocean, weather, and climate science.

Lestari, S. 2020 Hadi Soesastro Prize

Liguori, G. CLEX prize for best paper by an Early Career Researcher

Morrison, A. 2020 L'Oréal-UNESCO For Women in Science Fellowship

Pathmeswaran, C. Best talk, AMOS 2020 Conference

Pepler, A. AMOS Meyers Medal

Purich, A. AMOS Uwe Radok Award

Reid, K. First prize, Haiku Thesis Competition

Ridder, N. 2020 CLEX Career Development Award for women and underrepresented groups

Sabot, M. 2020 CLEX prize for best paper by an honours, masters or PhD student

Sabot, M. Evolution & Ecology Research Centre (UNSW) Research Excellence Awards 2019: Outstanding Evolution & Ecology Student Paper

Santoso, A. American Meteorological Society 2020 Editor's Award

Sen Gupta, A. 2020 Web of Science highly cited author

Zika, J. Anton Hales Medal, Australian Academy of Science

Editorships and Committee Memberships

Abram, N. Co-editor in Chief, Climate of the Past

Abramowitz, G. Associate Editor Journal of Hydrometeorology

Abramowitz, G. Member of the GEWEX Global Land/Atmosphere System Study (GLASS) Panel

Alexander, L. AIMES Scientific Steering Group

Alexander, L. Co-chair WMO Expert Team on Climate Information for Decision-making

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

Alexander, L. Member, WCRP Joint Steering Committee

Arblaster, J. Member National Climate Science Advisory Committee

Arblaster, J. Member, Coupled Modelling Intercomparison Project (CMIP) panel

Arblaster, J. National Committee for Earth System Science

Arblaster, J. Scientific Steering Committee of the WMO/UNEP Scientific Assessment of Ozone Depletion: 2022

Brown, J. Appointed Chair of the Australian Meteorological and Oceanographic Society's Expert Group on Climate Variability

England, M. Chair of the Advisory Board for the European Southern Ocean Carbon and Heat Impact on Climate Project (SO-CHIC)

England, M. Chair, Advisory Panel, Securing Multidisciplinary Understanding and Prediction of Hiatus and Surge events Project (UK)

England, M. SCAR Ant-Clim-Now Working Group

Green, D. Executive Editorial Board, Environmental Research Letters

Green, D. Expert advisory for Governing Plastic, Swiss Network of Int. Studies, Institute for Advanced Studies, Switzerland

Hart, M. Board member, International Association of Urban Climate

Hitchcock, S. Founding member of AGU Atmospheric Sciences Early Career Committee

Jakob, C. GEWEX Scientific Steering Group member

Macadam, I. NESP2 data subgroup

Maharaj, A. President of AMOS

Maharaj, A. WCRP Lighthouse Activity Science Plan Development Team

Meissner, K. Executive Editorial Board, Environmental Research Letters

Meyer, A. Member of the International SCOR working group 'Analysing ocean turbulence observations to quantify mixing (ATOMIX)'

Morrison, A. Member of CLIVAR Ocean Model Development Panel

Perkins-Kirkpatrick, S. Vice-Chair of the Early Career Scientist Committee, International Association of Meteorology and Atmospheric Sciences

Pitman, A. International Editorial Board, International J. Climatology

Pitman, A. Member of the AGU International committee for international participation

Pitman, A. Monash Foundation Scholarships

Ridder, N. Executive committee member, Young Earth System Scientists Community

Santoso, A. Associate Editor, Journal of Climate

Sen Gupta, A. Member of the CLIVAR enforced North Pacific Ocean Circulation Experiment (NPOCE) committee

Sen Gupta, A. National Committee for Earth System Science

Sherwood, S. Review Editor, Science

Sherwood, S. Steering Committee member of the WCRP Grand Challenge on Climate Sensitivity

Taschetto, A. CLIVAR Tropical Basin Interactions Working Group

Public Talks, Outreach and School Engagement

Abram, N. Ambassador and judge for the ABC Top5 Science program

Abram, N. Invited plenary lecture: Antarctic Science David Walton Memorial Lecture for online SCAR 2020 OSM."

Abram, N. Public talk on the Indian Ocean Dipole to Farmers for Climate Action members

Ashcroft, L. Panellist on Climate Conversations - an online discussion about a positive future run by Unimelb

Ashcroft, L. Presentation at the Benalla Probus group on climate science: past, present and future

Ashcroft, L. Public talk on climate change in New England hosted by Armidale Historical Society and Australian Garden History Society

England, M. Gateways to the Ocean A Symposium Celebrating Arnold Gordon's Contributions to Physical Oceanography Sponsored by the National Science Foundation

England, M. Lecture for Royal Society of New South Wales "Dispelling climate change myths – how ocean physics can help explain surprises in the modern-day climate record "

England, M. UNSW Climate Reality Leaders present: The Climate Crisis & its Solutions Panel discussion and Q&A

Goyal, R. Contributed to Q&ARC video

Hitchcock, S. Contributed to Q&ARC video

Hobbs, W. Presented at monthly marine science outreach event in Hobart

Hobeichi, S. Published Lesson Plan Power, Energy, Dynamics - Wind Turbines Physics - Year 11-12

Hobeichi, S. Published lesson plan: Formula substitution Mathematics - Year 11-12

Hobeichi, S. Published lesson plans for Geography – Year 10 Energy use, greenhouse gas emissions and sustainability

Hobeichi, S. SciX@UNSW program

Hogg, A. Contributed to Q&ARC video

Jakob, C. General Climate Change Talk to the Bendigo Field Naturalists Club

Lane, T. Public lecture on Fire, rain and storms - how will we predict hazardous weather in the future

Macadam, I. SciX@UNSW program

Meyer, A. Public talk at IMAS (University of Tasmania) to visiting high school students from the Canberra French Telopea School 'An example of research and career in oceanography'

Ridder, N. Contributed to Q&ARC video

Ridder, N. Expert panellist of a high school climate summit in Germany, Bad Oeynhausen

Santoso, A. Guest lecture at Institute Technology Bandung "Air-Sea Interaction", with lecture title: "Understanding El Nino Southern Oscillation".

Sherwood, S. Address to Northside Forum, Sydney

Sherwood, S. Talk (online) on climate science to MIT Alumni Climate Association

Sherwood, S. Talk to COSMOS Club in Washington DC on climate sensitivity and projections

Stellema, A. SciX@UNSW program

Stone, A. Climate change and communications presentation to Waverley Greens

Stone, A. Talk on climate change to Macarthur Sunrise Rotary Club

Strutton, P. Joint UTAS/AMOS event From Sky to Sea: Bushfires, the atmosphere and the marine environment

Vincent, C. STEM talk to Grade 3 class at 'Deutsche Schule Melbourne' about Thunderstorms.

2020 Key Performance Indicators

Performance Measure	Reporting interval	Target 2020	Achieved 2020
Number of research outputs	Annually		
Journal articles		60	226
Book chapters		5	9
Software modules published		2	5
Data sets published,		2	5
Facebook posts		52	131
Centre website updates		25	198
Science explainer videos		2	2
Quality of research outputs	Annually		
Percentage of publications in journals with impact factors greater than 2.0		80	90.7%
Percentage of publications in journals with impact factors greater than 4.0		60	58.4%
Number of papers in journals with impact factors greater than 10		8	21
Number of training courses held/offered by the Centre	Annually		
Professional development training in gender equity and diversity		1	1
Professional training for ECRs in engaging with government and decision makers		1	1
Computational skills workshops/tutorials		3	15
Science fundamentals workshops		1	1
Leadership and professional development workshops		1	1
Communications/writing workshops		1	2
Number of centre-wide virtual lectures/seminars		5	29
Percentage of students/ECRs attending researcher development activities		90%	81%
Number of workshops/conferences held/offered by the Centre	Annually		
National workshop		1	1
International conference/workshop		1	1
Topical/Research Program workshops		3	4
Number of additional researchers working on Centre research	Annually		
Postdoctoral researchers		14	1[a]
Honours students		10	14
HDR students		20	22
Associate Investigators		26	54[b]
Graduate Student Training	Annually		
Number of PhD completions		3	2
Number of Masters by Research completions		4	4
Number of Honours student completions		10	10
Percentage completing PhD students submitting within 4 years (FTE)		100%	100%
Number of mentoring programs offered by the Centre We have an integrated researcher development program for HDR students and early-mid career researchers. It includes 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 2020	Achieved 2020
Number of presentations/briefings	Annually		
To the public		10	26
To government		10	8
To industry/business/end-users		5	7
To non-government organisations		5	2
To professional organisations and bodies		5	6
Number of new organisations collaborating with, or involved in, the Centre	Annually	-	-

Footnotes (blue and red tables)

a. The centre postponed its major mid-term recruitment drive until 2021 due to the COVID-19 pandemic and the delayed timing of the Midterm review

b. This target refers to the total number of AIs attached to the Centre in 2020 as opposed to newly added AIs. Adding 30 new AIs per annum would be unsustainable.

c. A number of changes to senior roles in the centre take effect on 1 Jan 2021 to address this metric

d. In response to a recommendation in the CLEX Midterm review, the Advisory Board is taking measured steps in 2021 to improve its gender balance

e. Travel restrictions in 2020 made this target impossible to meet

Centre-specific Key Performance Indicators for the ARC Centre of Excellence for Climate Extremes	Reporting Frequency	Target 2020	Achieved 2020
Equity and Diversity Initiatives Percentage of female graduate students Percentage of female research fellows Percentage of senior female research fellows Percentage of Centre leaders who are female Percentage of administration team who are female Percentage of board members who are female Percentage of keynote speakers at workshops and conferences who are female	Annually	 50% 50% 50% 50% 50% 50% 50%	 49% 50% 50% 36%[c] 67% 22%[d] 50%
Computational Modelling Support New/refined/enhanced software modules for the climate models developed and served to the community. New/refined/updated software tools for data analysis developed and served to the community. New/refined/updated data sets served to the community. Monthly bulletin to all researchers on CMS-related updates Explainer videos on key CMS issues	Annually	 2 2 2 12 4	 5 5 14 6 12
Percentage of students with cross node and/or partner organisation supervision	Annually	80 %	43%
Percentage of students/ECRs making a research visit to other nodes and/or Australian partner organisations	Annually	65%	3%[e]
Student / ECR internships in industry/government		2	2
Percentage of students/ECRs making a research visit to international partner organisations or organisation with a collaborative relationship	Annually	30%	0%[e]
Number of undergraduate summer scholarships offered	Annually	15	18
Regular Research Program videoconference meetings p/a	Annually	10	214
Media KPIs Media Releases Website – Unique Hits Website – Page Views Stories in media Social Media – Twitter (followers) Social Media – Facebook (followers)	Annually	 15 30000 40000 300 300 200	 33,661 86,772 351 713 91
Knowledge Brokerage Team Establishment of significant partnerships Data sets provided to stakeholders Strategic advice provided to stakeholder	Annually and at mid-term review	 1 1 1	 1 2 3
Demonstrated examples of model improvements available for use in national modelling systems	Annually and at mid-term review	2	4

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 2020, CLEx received $6,173,123 (100%) income compared to the full-year budget of $6,173,123. In terms of the Centre's expenditure, $4,870,785 (97%) was spent compared to the full-year budget of $5,007,010.

In 2020, personnel accounted for the highest proportion of expenditure of $4,165,145 (86%), followed by scholarship expenditure of $322,371 (7%). Overall, the Centre's cash balance in 2020 is $1,302,338.

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

2020 Income

Cash income totalled $6,173,123 from all sources. The Centre derived its income from the ARC, participating universities, the Bureau of Meteorology (BoM), the NSW Department of Planning, Industry and Environment (DPIE), the NSW Department of Industry Research Attraction and Acceleration Program (RAAP) and the Department of the Environment and Energy. Income is summarised by the source in detail in the tables that follow.

1: Australian Research Council Funding

The Centre received indexed income from the ARC of $4,595,388. This was distributed to the institutions following the inter-institutional agreement and was used for payroll, scholarships, consumables and events, equipment and maintenance and travel.

2: Government Funding

2.1 Bureau of Meteorology

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

2.2 NSW Department of Planning, Industry and Environment

The cash investment from DPIE is specifically intended to support pathways-to-impact by supporting an improved understanding of climate extremes in NSW and by making this knowledge available to the community and decision-makers in the form that they need. The Centre received $165,000 in 2020.

2.3 NSW Department of Industry RAAP

RAAP funding invests in appointing a Research Fellow to focus on high-resolution modelling of processes relating to climate extremes (e.g. hail, drought processes, vegetation-climate extremes, etc.). The Centre received $143,000 in 2020.

2.4 Department of Agriculture, Water and the Environment

Funds were provided to deliver one annual Ozone Science Summer Scholarship per year over 3 years (2019 to 2021).

3: Collaborating Organisation Funding

Cash contributions to the Centre of Excellence from the Administering Organisation and the Collaborating Organisations amounted to $1,236,647, as follows:

$514,408	UNSW
$155,934	ANU
$158,947	University of Melbourne
$156,338	University of Tasmania
$251,020	Monash University

4: In-kind Contributions

In-kind support totalled $8,012,154 in 2020. The Centre is grateful for $5,747,615 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 $2,264,539. Again, this was mainly personnel time.

Organisation	In Kind Budget	In Kind Actual
ANU	814,474	884,833
BOM	145,986	145,986
CSIRO	335,000	333,707
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	852,351	1,042,638
NASA Goddard Space Flight Center	41,737	41,737
NCAR	114,299	114,299
NCI	892,000	892,000
NOAA	30,000	30,000
DPIE	312,785	312,785
Risk Frontiers Grp	45,000	45,000
Swiss Federal Inst of Tech	83,835	83,835
UMEL	874,772	852,155
Uni of Arizona, USA	56,790	56,790
UNSW	1,807,330	2,068,255
UTAS	513,931	899,733
TOTAL	7,128,690	8,012,154

2020 Leverage

The Centre's 2020 cash income of $6,173,123 and in-kind support of $8,012,154 total $14,185,277, with ARC funding accounting for $4,595,388 of the total income. The Centre's leverage of $9,589,889 equates to $2.09 of external funding and in-kind contributions for each $1.00 received from the ARC.

2020 Expenditure

In 2020 the Centre expended $4,870,785, analysed below:

Personnel (including on-costs)	$4,165,145	86%
Scholarships	$322,371	7%
Equipment and Maintenance	$30,088	1%
Consumables and Events	$158,622	3%
Travel	$194,559	3%

2020 Income Vs Expenditure

Income and Expenditure are based on cash and is derived from the institutions' general ledgers. The Collaborating Organisations certify income and expenditure by formally acquitting all grants as of 31 December 2020.

The Centre's cash expenditure of $4,870,785 was below income of $6,173,123 by $1,302,338.

The Centre will carry over a balance of $1,302,338 to 2021. The carry-over by institution is as follows:

University of New South Wales	$662,709	surplus
Australian National University	$57,572	surplus
University of Melbourne	$78,897	surplus
University of Tasmania	$105,8884	surplus
Monash University	$397,276	surplus

In summary, as at 31 December, 2020, the financial position for the life of CLEx after its fourth year of operation is as follows:

Total Cash Income	$6,173,123
Total Expenditure	$4,870,785
Surplus carried forward to 2021	$1,302,338

COECX Cash Income & Expenditure

1. Cash Income	Actual 2017	Actual 2018	Actual 2019	Budget 2020
Australian Research Council- Centre of Excellence	4,350,000	4,250,000	4,250,001	4,300,000
Australian Research Council- Centres of Excellence Indexation	65,250	128,456	211,645	295,388
Bureau of Meteorology	10,000	20,000	30,000	30,000
NSW Department of Planning and Environment	100,000	100,000	100,000	165,000
NSW Department of Industry/ RAAP	143,000	143,000	142,857	143,000
University Node Cash Contributions	1,103,142	1,285,737	1,253,234	1,236,647
Other (Interest Distribution)	0	15,871	19,146	3,087
Department of Agriculture, Water and the Environment	0	0	4,523	0
Sydney Water Corporation	0	200,000	0	0
Total	**5,771,392**	**6,143,064**	**6,011,406**	**6,173,122**

2. ARC Expenditure	2017	2018	2019	2020
Personnel	114,662	1,941,921	3,354,377	3,350,987
Scholarship	6,358	90,723	158,714	191,388
Equipment and Maintenance	0	5,105	33,216	12,814
Consumables and Events	16,369	165,632	160,379	110,198
Travel - Conference, workshops and meetings (Staff, AI)	12,634	133,395	210,647	48,557
Travel - Conference, workshops and meetings (Postdocs and Students)	0	40,497	178,653	49,316
Travel - Visitor travel to the Centre and other	1,336	38,236	31,324	22,335
Travel - New staff relocation expenses	0	0	0	0
Travel - Research Visits (Staff, AI)	0	9,585	34,451	7,153
Travel - Research Visits (Postdocs and Students)	1,341	380	3,484	1,802
Total	**152,701**	**2,425,476**	**4,165,244**	**3,794,550**

3. Nodes Expenditure	2017	2018	2019	2020
Personnel	65	311,556	615,789	475,725
Scholarship	10,706	61,092	132,039	120,983
Equipment and Maintenance	6,182	48,972	46,325	17,274
Consumables and Events	4,575	43,568	53,831	48,424
Travel - Conference, workshops and meetings (Staff, AI)	12,901	49,055	67,758	21,570
Travel - Conference, workshops and meetings (Postdocs and Students)	2,969	60,341	104,294	18,986
Travel - Visitor travel to the Centre and other	0	9,570	41,971	9,881
Travel - New staff relocation expenses	7,354	55,163	22,719	2,193
Travel - Research Visits (Staff, AI)	5,132	8,979	22,952	4,320
Travel - Research Visits (Postdocs and Students)	0	10,981	13,860	8,446
Total	**49,885**	**659,276**	**1,121,538**	**727,802**

Budget Forcast

2021	2022	2023	2024	TOTAL
4,300,000	4,300,000	4,300,000	0	**30,050,000**
378,106	0	0	0	**1,078,845**
30,000	20,000	20,000	0	**160,000**
100,000	100,000	100,000	0	**765,000**
142,857	142,857	142,857	0	**1,000,428**
1,226,708	1,226,593	1,226,495	0	**8,558,556**
3,000	0	0	0	**41,104**
0	0	0	0	**4,523**
0	0	0	0	**200,000**
6,180,671	**5,789,450**	**5,789,352**	**0**	**41,858,456**

2021	2022	2023	2024	TOTAL
4,406,318	4,311,375	4,200,404	2,909,987	**24,590,032**
328,635	377,678	378,592	260,864	**1,792,952**
26,200	26,200	16,200	34,950	**154,685**
269,196	266,962	264,042	287,972	**1,540,750**
256,980	288,943	278,943	235,778	**1,465,877**
73,596	101,463	101,463	70,000	**614,987**
86,576	108,273	113,970	92,118	**494,168**
0	0	0	0	**-**
50,772	70,487	70,487	45,072	**288,007**
25,072	55,787	55,787	43,731	**187,385**
5,523,346	**5,607,168**	**5,479,888**	**3,980,471**	**31,128,843**

2021	2022	2023	2024	TOTAL
627,315	856,274	547,529	288,064	**3,722,317**
415,704	409,870	410,784	335,648	**1,896,826**
46,293	36,853	31,853	31,166	**264,920**
53,295	61,568	63,343	56,637	**385,240**
163,936	163,936	163,809	144,661	**787,625**
186,086	189,768	189,128	145,288	**896,860**
30,000	29,828	29,501	24,236	**174,987**
35,467	19,825	2,000	5,967	**150,688**
27,500	27,500	27,500	12,954	**136,838**
29,700	29,700	29,700	19,868	**142,255**
1,615,296	**1,825,122**	**1,495,147**	**1,064,489**	**8,558,554**

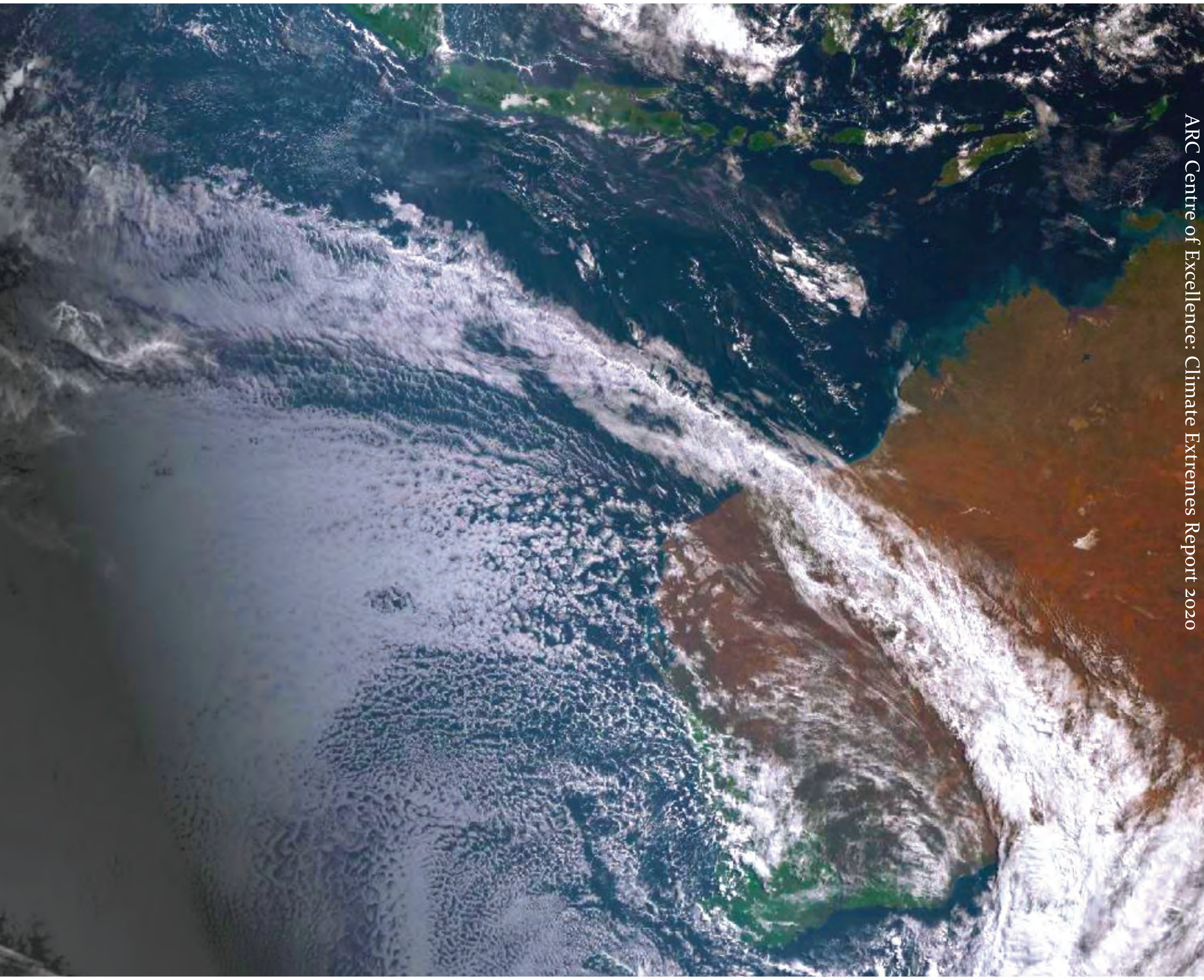
4. Others	Actual 2017	Actual 2018	Actual 2019	Budget 2020
Personnel	61,192	192,341	272,939	338,433
Scholarship	0	10,000	14,000	10,000
Equipment and Maintenance	0	0	0	0
Consumables and Events	0	0	0	0
Travel - Conference, workshops and meetings (Staff, AI)	0	0	0	0
Travel - Conference, workshops and meetings (Postdocs and Students)	0	0	523	0
Travel - Visitor travel to the Centre and other	0	0	0	0
Travel - New staff relocation expenses	0	0	0	0
Travel - Research Visits (Staff, AI)	0	0	0	0
Travel - Research Visits (Postdocs and Students)	0	0	0	0
Total	**61,192**	**202,341**	**287,462**	**348,433**

5. Summary Income Vs. Expenditure / Carry Over	2017	2018	2019	2020
ARC				
Total Income	4,415,250	4,378,456	4,461,646	4,595,388
Total Expenditure	152,701	2,425,476	4,165,244	3,794,550
Income less Expenditure	4,262,549	1,952,980	296,402	800,838
Nodes				
Total Income	1,103,142	1,285,737	1,253,234	1,236,647
Total Expenditure	49,885	659,276	1,121,538	727,802
Income less Expenditure	1,053,257	626,461	131,696	508,845
Other				
Total Income	253,000	478,871	296,526	341,087
Total Expenditure	61,192	202,341	287,462	348,433
Income less Expenditure	191,808	276,530	9,064	-7,346
Carry over surplus / deficit	**5,507,614**	**2,855,971**	**437,162**	**1,302,337**

Budget Forcast

2021	2022	2023	2024	TOTAL
335,127	341,830	348,666	166,003	**2,056,531**
30,000	20,000	20,000	10,000	**114,000**
0	0	0	0	**-**
0	0	0	0	**-**
0	0	0	0	**-**
0	0	0	0	**523**
0	0	0	0	**-**
0	0	0	0	**-**
0	0	0	0	**-**
0	0	0	0	**-**
365,127	**361,830**	**368,666**	**176,003**	**2,171,055**

2021	2022	2023	2024	TOTAL
4,678,106	4,300,000	4,300,000	0	**31,128,845**
5,523,346	5,607,168	5,479,888	3,980,471	**31,128,843**
-845,240	-1,307,168	-1,179,888	-3,980,471	**2**
1,226,708	1,226,593	1,226,495	0	**8,558,556**
1,615,296	1,825,122	1,495,147	1,064,489	**8,558,554**
-388,588	-598,529	-268,652	-1,064,489	**1**
275,857	262,857	262,857	0	**2,171,055**
365,127	361,830	368,666	176,003	**2,171,055**
-89,270	-98,973	-105,809	-176,003	**0**
-1,323,097	**-2,004,670**	**-1,554,349**	**-5,220,963**	**4**



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