climate extremes
ARC centre of excellence

ANNUAL REPORT 2021

© Australian Research Council Centre of Excellence for Climate Extremes

ARC Centre of Excellence for Climate Extremes 2021 Annual Report

The ARC Centre of Excellence for Climate Extremes (CLEX) is financially supported via a Major Investment Grant (CE170100023) from the Australian Research Council. The Centre is financed and hosed by the University of New South Wales. Collaborating partners are Monash University, the University of Melbourne, the Australian National University and the University of Tasmania. They provide significant financial and in-kind support. The Centre also receives financial support from the NSW Research Attraction and Acceleration Program, the NSW Department of Planning and Environment and the Bureau of Meteorology.

Photo Credits
Page 4: JB Brown
Page 36: Todd Lane
Page 48: Zetter/iStock
Page 62: Nuture/iStock
Page 68: LKR/iStock
Page 95: JB Brown

Document
Report: Stephen Gray, Claire Carouge, Alvin Stone, Andy Pitman, Melissa Hart, Ian Macadam, Vilia Co, Chief Investigators

Editor
Kathy Murfitt

Design
Allyson Crimp

CONTENTS

1

OUR CENTRE, OUR PEOPLE

VISION

The goal of the ARC Centre of Excellence for Climate Extremes is to transform the understanding and modelling of climate extremes, including their dependence on climate change and variability; to advance scientific understanding; and to assist decision-makers.

CLEX will focus on key processes, mechanisms and phenomena, informed by a two-way dialogue with government and business, to ensure our research has influence and impact.

To achieve this goal, we are building the world's first fully integrated centre to understand and predict climate extremes. We have five Strategic Objectives: focused on world-class research, an outstanding environment for all involved in the Centre, exceptional research infrastructure, strong national and international partnerships, and a focus on impact and engagement beyond academia.

EXECUTIVE SUMMARY

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 updated Strategic Plan:

World-class Research

We 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 Research Infrastructure

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

Transformative Collaboration

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

Engagement and Impact Beyond Academia

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.

Legacy

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.

The following graphic highlights some of our major achievements in 2021 that contributed directly to achieving the objectives set out in our Strategic Plan.

2021 IN REVIEW

WORLD-CLASS RESEARCH

18 postdoctoral research-associate positions advertised

222 papers published

65% of papers in journals with **>4** impact factor

OUTSTANDING ENVIRONMENT

12 PhD COMPLETIONS with alumni moving to jobs at places such as Deloitte; iFremer, France; BoM; and CLEX universities

Remo workshop showcased almost **100** posters over two days

Multiple and ongoing wellbeing initiatives.

EXCEPTIONAL RESEARCH INFRASTRUCTURE

Weekly CMS training and drop-in sessions

Launch of new land-atmosphere model: CABLE-NUWRF

16 datasets published

TRANSFORMING COLLABORATION

OVER **150** Research Program virtual meetings

90% of papers are cross-institutional

CLEX monthly seminar series launched, with speakers from a range of industry and research fields.

STRONG ENGAGEMENT BEYOND ACADEMIA

20 bespoke briefings delivered directly to parliamentarians on COP26

Work commenced on upgrading the CLEX website to enhance appeal to external audiences.

8 BRIEFING NOTES on topics such as limiting warming to 1.5°C and outcomes of The Indian Ocean and climate tipping points

CLEX 2021 PRIZE WINNERS

ECR Prize **Hakase Hayashida** (UTAS)

Student Prize **Josué Martinez Moreno** (ANU)

Engagement Prize **Kim Reid** (University of Melbourne)

Director's Prize **Everyone in Melbourne!**

DIRECTOR'S REPORT

The ARC Centre of Excellence for Climate Extremes (CLEX), like almost all research centres, navigated the challenges thrown up by Covid-19 through 2021 as well as possible. For a Centre that strives for innovation and a strong impact on business, policy and science, the inability to meet, to attend workshops, to share ideas in-person was initially confronting, then inconvenient, and finally, severely limiting. CLEX managed this to the best of our abilities and reading through this 2021 report, the evidence would appear to suggest that the Covid situation was managed such that its impacts were negligible. We report a quite phenomenal number of very high-impact science papers, PhD completions, awards, postdoctoral fellow placements in excellent business, government or academic institutions – and so on.

I think this hides a truth. The impact of Covid-19 is long-term. We lost our annual workshops two years in a row, our research program meetings, our institutional meetings, our ad-hoc chats over a coffee or tea – the kind that triggers an idea that leads to conversation and a collaboration and, ultimately, discovery. There are PhD students who are two years into a PhD without actually having met their supervisor, or attended their host institution, or attended a conference.. There are Chief Investigators who have had to pick up significant new commitments due to institutional redundancies and have lost research time.

The Centre has managed these challenges to the best of our ability but the impact is real. It is not apparent in the 2021 annual report, but it will emerge later on. The Centre's primary goal is to minimise the impact of Covid-19 on our researchers, to re-light the spark of innovation as quickly as possible and to re-engage as a matter of urgency. This is front and centre of our thinking in the first quarter of 2022. In parallel with this are our efforts to establish the Centre of Excellence as a dominant voice in several key areas; to be influential across the area of climate extremes; to have impact on the thinking in business and government; and to engage, deeply, in helping specific sectors manage climate risk effectively. Our strategies to achieve these goals were affected by Covid-19, but re-establishing appropriate links is also front-and-centre of our thinking in the first half of 2022.

I am delighted to welcome eight new research fellows to CLEX. Despite all the institutional challenges of hiring through the Covid-19 era, issues with immigration and so on, we have been able to hire a genuinely first class group of next-generation researchers. We will do all that we can to support them in developing their careers through our outstanding Researcher Development Program.

I hope you find material in this report of interest. Please do not hesitate to contact us or the specific individuals if you want to know more about their science or our research.

Prof Andy Pitman, AO
Director

FROM THE CHAIR OF THE CLEX ADVISORY BOARD

A year ago, as I reflected on the challenges the ARC Centre of Excellence for Climate Extremes (CLEX) successfully navigated in 2020, I wrote that I hoped 2021 would be a year without pandemic-induced stress. Sadly, Delta emerged and, like everyone, staff and students of CLEX had to pivot once again to working remotely and connecting and collaborating via Zoom. Some faced isolation and loneliness while others juggled carer responsibilities and home schooling in crowded houses. Whatever the individual circumstances, no one had an easy year.

Yet, the Centre steadily pressed ahead in its pursuit of excellence. Each individual's contribution led to the collective advancement of our understanding of the physical processes that underpin climate extremes. Over 200 high-quality papers attest to this. In addition, many in CLEX were directly involved in translating these findings for policymakers, business people and parliamentarians. The Centre's regular Briefing Notes were very well received in government and industry, with positive feedback on the impact of these resources noted by the Centre's Advisory Board. Notable topics covered by the Briefing Notes series included: whether net zero by 2050 will limit average global warming to 2°C; a concise summary of the key policy-relevant points of the Intergovernmental Panel on Climate Change 6th Assessment Report; and a primer on climate tipping points.

The Advisory Board welcomed the Australian Research Council's (ARC) report following the mid-term review of the Centre, which took place in late 2020. The report was tabled at our first Advisory Board meeting in 2021. It highlighted the many strengths of CLEX and provided recommendations for ways to capitalise on those strengths to further enhance the Centre's effectiveness and impact. At that meeting and throughout 2021 the Advisory Board provided guidance and feedback to the Centre Executive group on implementing the report's recommendations, and will continue to do so as work progresses. One of the recommendations in the review was to enhance the diversity of the membership of the Advisory Board. This will be a careful and iterative process. In late 2021 we confirmed our first new member: Danielle Francis, Manager Liveable Communities at Water Services Association of Australia. We look forward to working with Danielle in the years ahead.

This report offers a snapshot of just some of the Centre's superb achievements in 2021. Once again, under incredibly challenging circumstances, the leadership team of CLEX has done an exemplary job in maintaining a sense of community, wellbeing and of forward momentum throughout the year – and they are to be commended.

Dr Tony Press
Chair, CLEX Advisory Board

COVID-19 PANDEMIC: IMPACTS AND RESPONSES

It goes without saying that 2021 presented significant challenges to the ARC Centre of Excellence for Climate Extremes (CLEX). Many of those challenges were an unwelcome repeat of those already faced in 2020, particularly for our Melbourne-based colleagues who faced their second prolonged lockdown. Other difficulties emerged, both new and cumulative. The impacts of the pandemic on the wider university sector cannot be overstated. Staff and students in CLEX have faced departmental restructures, redundancy rounds, loss of local professional support staff, institutional policies that impeded the provision of adequate equipment to work from home, plus restrictive rules on staff recruitment, even for externally funded research positions.

QUALITATIVE /EFFECTS OF COVID-19: THE HUMAN EXPERIENCE

We conducted two targeted surveys of our staff and students. One for early career researchers (ECRs) and students and one for our Chief Investigators. Early in the pandemic our primary focus was supporting our junior colleagues, many of whom were attracted to CLEX from overseas and therefore found themselves far from their usual support networks. This support was provided by peers among the student and postdoctoral cohort, as well as a large duty of care being assumed by the Centre leadership team and the Chief Investigators.

Our ECRs reported that they were grateful for the support that CLEX provided them; however, many faced significant personal and professional challenges. A significant proportion of our student and postdoc cohorts are from overseas. Closed borders meant that all of them were cut off from family and friends when they most needed those support networks. We also had commencing students who were offshore and unable to travel to their Australian universities. Many students reported that their living situations – usually in share houses with other students – made it extremely challenging to do scholarly work that usually requires deep focus and concentration. Finally, Zoom meetings were both a lifeline and a drain on energy. The cohort was evenly split when asked if they felt there were too many or too few opportunities to collaborate online in CLEX.

As time went on, it became evident that pandemic-related stress and fatigue was also affecting Chief Investigators.

During the second year of the pandemic, our challenges moved beyond the more immediate impediments of being unable to travel or of missing out on serendipitous meetings in the office or lab. As with most workplaces, a palpable fatigue set in, especially related to efforts that went into planning activities or events that subsequently had to be cancelled. Opposite is a representative list of some of the examples given by Chief Investigators in response to a survey question on the tangible impediments arising from the Covid-19 pandemic.

Led by the Culture and Diversity Committee, CLEX continued to prioritise wellbeing and support. We sought to normalise conversations about mental health; be realistic and flexible in terms of expectations, whilst maintaining high standards; address Zoom fatigue by limiting meetings; encourage on-campus activities where local conditions allowed; strongly encourage people to switch off altogether over the summer break.

This annual report attests to the remarkable resilience and commitment of each and every member of the CLEX community, despite all the difficulties they have faced. It also shows that the Centre was able to produce work that was impressive in volume and calibre. In some ways, we are fortunate that videoconferencing and working across dispersed teams were already well-established practice in CLEX prior to Covid-19. This meant that research program meetings and virtual seminars continued more or less unchanged. We were also able to attract applications from very strong research associate candidates for most of the positions we needed to fill. By the end of 2021 we had just a few appointments still outstanding. Having said that, we have now had to cancel our annual workshop two years in a row, with a question mark still hanging over 2022. This inability to bring the whole Centre together in-person has possibly been one of the most detrimental effects of the pandemic, particularly as we've seen a natural turnover of staff and students at the mid-point of the Centre's seven-year lifecycle.

85%

of Chief Investigators reported a **drop in research productivity** in 2021

69%

of Chief Investigators reported that their **non-CLEX workload had increased** in 2021

ONLY

30%

of Chief Investigators **have a private home office**. The rest work from shared spaces that range from the kitchen table to a desk in the corner.

EXAMPLES OF TASKS AFFECTED BY THE PANDEMIC INCLUDE:

Online teaching requirements resulted in a ~50% increase in teaching workload.

A research program workshop was postponed three times in 2021, another one planned and abandoned once.

MUCH harder to get research published - collaborating is very difficult online, everything moves slower, you can't just have an in-person meeting to get things done efficiently.

My students were also struggling with isolation and being away from their families in other countries, which impacted their productivity.

Recruitment of research associates was also affected. The centre had planned a major recruitment drive in 2021 to fill 18 postdoc positions. Closed borders meant that international recruitment was severely curtailed. Some CLEX nodes also faced institutional hiring freezes as a result of sector-wide financial challenges.

Our professional and technical staff also faced individual and collective challenges relating to home schooling, isolation and mental and physical health and wellbeing.

STRATEGIC PLAN ON A PAGE

Our Vision: CLEX will transform the understanding and modelling of climate extremes, including their dependence on climate change and variability, to advance scientific understanding and assist decision-makers.

Our Research We will be a world-leading research centre contributing a significant advancement of knowledge	**Our Influence and outreach** We will have influence and impact beyond academia to have a lasting legacy	**Our People** We will demonstrate a commitment to diversity, excellence and community

Strategic Objectives	**Success strategy**	**Strategic foci**	
World class research focused on climate extremes	Our research program's success will be measured and reported via the quantity and quality of our publications	1.1	Focus on four key programs: - Weather and Climate interactions - Attribution and Risk - Drought - Ocean Extremes
		1.2	An uncompromising focus on excellence
		1.3	Leadership in national model development and collaboration
		1.4	Fundamental research into climate variability and change
An outstanding environment for all Centre activities	We will measure and report our effectiveness in achieving an exemplar environment for all students and staff	2.1	Enhanced Researcher Development Program to mentor and train the next generation
		2.2	Proactive Equity, Diversity and wellbeing initiatives
		2.3	Ensure early career representation at all levels of Centre activities
		2.4	Foster a culture of community and belonging across the Centre
		2.5	Post-Covid accelerated recovery strategies
Exceptional research infrastructure	We will measure and report our effectiveness at maintaining research infrastructure	3.1	The Computational Modelling Systems Team provides advise on modelling and data systems
		3.2	Secure and collaborative relationships with NCI and the ACCESS NRI
		3.3	Be an exemplar for data delivery
		3.4	Develop tools for research that are sustainable beyond the Centre's lifetime
		3.5	Lead collaboration to build the next generation climate model
Transform collaboration at all scales	We will measure and report the breadth and depth of our collaboration	4.1	Maintain structures that avoid silos
		4.2	Conduct national workshops and training programs
		4.3	Strategic cross-institutional research team
		4.4	Interact with our Advisory Board on key strategic issues
		4.5	Post-Covid accelerated recovery strategies
Research that engages and has impact	We will measure and report our effectiveness in influence and outreach	5.1	Maintain a knowledge brokerage team to facilitate stakeholder engagement
		5.2	Be an influential and dominant voice in key areas of climate extremes
		5.3	Plan and communicate for influence and impact
		5.4	Promote climate science in secondary school STEM subjects
		5.5	Post-Covid accelerated recovery strategies

Identify gaps in our research, training, infrastructure, influence and outreach and seek additional funding to resolve them

ORGANISATIONAL CHART

GOVERNANCE

ADVISORY BOARD
Chair **Dr Tony Press**

EXECUTIVE MANAGEMENT

DIRECTOR
Andy Pitman

DEPUTY DIRECTOR
Todd Lane

GRADUATE DIRECTOR	CHIEF OPERATING OFFICER	CMS LEADER	KBT TEAM LEADER
Melissa Hart	Stephen Gray	Claire Carouge	Ian Macadam

RESEARCH PROGRAMS, WORKGROUPS AND COMITTEES

RESEARCH PROGRAMS
Weather and Climate Interactions; Attribution and Risk; Drought; Ocean Extremes; Modelling

Committees & ECR Representation	Media	Computational Modelling Support	Operations	Knowledge Brokerage Team

GOVERNANCE, MANAGEMENT AND OUR COMMITMENT TO EQUITY, DIVERSITY AND INCLUSION

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 March and November, 2021.

We are very pleased to have Danielle Francis join the Advisory Board in 2022. Danielle is the Manager of Liveable Communities at the Water Services Association of Australia and has extensive experience in water management. She will bring valuable insight to the Advisory Board from the perspective of a key sector that makes long-term infrastructure decisions that are potentially highly exposed to future climate extremes.

ADVISORY BOARD MEMBERS IN 2021

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.He was also 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. Dr Brown's research has spanned tropical oceanography, climate projections, fisheries, high-resolution ocean defence tools, and seasonal atmospheric processes in Australia. Her previous role was as a team leader in the Agriculture and Food Business Unit. There, Dr Brown led the Weather and Climate Decisions Team. This team focused on delivering actionable weather and climate knowledge to stakeholders.

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 Ian 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 System Laboratory and the Capacity Center for Climate and Weather Extremes. He has served on a number of committees and review boards for the National Oceanic and Atmospheric Administration, the US National Academies, and NASA – and he chaired the Tropical Meteorological Program of the World Meteorological Organization 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 a highly experience public servant. Prior to his current role, he held positions in the Department of Defence. He currently leads the Climate and Resilience Policy branch in the Department of Agriculture, Water and Environment. The branch leads development of policy on climate, natural resources management and energy, working to ensure issues are appropriately considered as it supports the agricultural sector. The branch draws together capacity and expertise – allowing linkages and inter-related issues to be explored.

Dr Jon Petch, UK Meteorological Office

As Head of the UK Meteorological Office Science Partnerships, Dr Jon Petch is responsible for the UK Met Office's national and international relationships with other science organisations. 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 leads the Global Atmospheric System Studies project.

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

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

Professor Sven Rogge, Pro Vice-Chancellor Research, UNSW

Professor Sven Rogge is Pro Vice-Chancellor (Research) at the University of New South Wales. Prof Rogge's research interest is in condensed-matter physics, in particular quantum electronics, at the School of Physics. He works on quantum computation in silicon at the ARC Centre for Quantum Computation and Communication Technology, as part of a team of enthusiastic researchers. They work on gaining atomistic insight into the interactions of quantum objects, like atoms and qubits, with their environment. This allows the team to manipulate quantum information and minimise decoherence. Before joining UNSW in 2011, Prof Rogge worked at the Kavli Institute for Quantum Nano Science at Delft University and Stanford University.

Dr Bertrand Timbal, Head of Research, Bureau of Meteorology

Dr Bertrand Timbal moved to Australia and the Bureau of Meteorology (BoM) in 1996, soon after completing his PhD at the French National Met Service (Meteo-France) in 1994. After a three-year stint leading the climate branch in the Centre for Climate Research Singapore, Dr Timbal re-joined the Bureau of Meteorology in 2020 as the General Manager for the Research Program, Science and Innovation Group. In this role, Dr Timbal leads a program made up of 130 of scientists, support scientists and science managers delivering along the four objectives of BoM's research and development plan.

CENTRE EXECUTIVE

The Centre Executive is composed of the Centre Director, who carries overall responsibility for day-to-day leadership of the Centre and its research; the Deputy Director; the Chief Operating Officer; the Graduate Director; the Manager of the Computational Modelling Systems team; and the leader of the Knowledge Brokerage Team.

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

CENTRE COMMITTEES

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

Diversity and Culture Committee

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

2021 Members: Hakase Hayashida (UTAS), Christian Jakob (Monash), Stephy Libera (UTAS), Claire Vincent (U. Melb)

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

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 STEM and in higher education generally.

Infrastructure Committee

Chair: Claire Carouge (UNSW),

Members: Gab Abramowitz (UNSW), Dietmar Dommenget (Monash), Jason Evans (UNSW), Andy Hogg (ANU), Neil Holbrook (UTAS)

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 computer and storage resources to CLEX research programs, particularly where there are competing requests, as well as liaise 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.

Engagement and Impact Committee

Chair: Peter Ian Macadam (UNSW)

Members: Nerilie Abram (ANU), Ailie Gallant (Monash), Amelie Meyer (UTas), Alvin Stone (UNSW)

The CLEX Engagement and Impact 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, led by Ian Macadam, and the CLEX communications team, formerly led by Alvin Stone. Our new Media Manager will commence in early 2022. Moving forward, the Outreach Committee looks forward to developing deeper CLEX engagement with government and industry, in areas of emerging climate challenges.

Centre Operations Team

The transformative research that CLEX continues to deliver is supported by a dedicated team of professional staff.

Stephen Gray is the Centre's Chief Operations Officer and brings extensive ARC Centre of Excellence management experience to the role. He is supported by Vilia Co in the role of Finance and Resources Manager. The operations team is further comprised of Project Officers and Executive Assistants Jenny Rislund (UNSW), Sook Chor (Monash), Christine Fury (UTAS), Alina Bryleva (ANU) and Karla Fallon (U.Melb) who was replaced by Simon Parsons in late 2021.

LEADERSHIP DEVELOPMENT

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

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

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

EQUITY, DIVERSITY AND INCLUSION

The ARC 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 work environment. Our equity plan is an ambitious document to guide the Centre's efforts to fulfil our aim of being an exemplar in this space. We are serious about creating a respectful research environment for our diverse population of researchers to ensure our staff and students can reach their full potential, and about making a meaningful contribution to addressing historical prejudices and inequality in Science, Technology, Engineering and Mathematics disciplines.

As noted earlier in this section, the Centre's Diversity and Culture Committee spearheaded a range of initiatives in 2021 by way of implementing the three key objectives of the CLEX Equity Plan. Those objectives cover recruitment, inclusivity, and wellbeing and culture.

RESEARCH ETHICS AND INTELLECTUAL PROPERTY

The ARC Centre of Excellence for Climate Extremes (CLEX) is committed to uncompromisingly high standards of professional conduct and rigour in all activities, including all aspects of our research. Arguably, few disciplines receive as much public scrutiny as climate science. Accordingly, climate scientists have long embraced openness, accountability and an open-source approach to their work. This ensures originality and reproducibility of research, adherence to proven methodological frameworks and rigorous data management practices.

Adherence to FAIR (findability, accessibility, interoperability, reusability) principles is normal practice in our field; indeed, we have been influential in driving this agenda, as was the case with recent Academy of Science reports. All new staff and students at CLEX receive information on the ethical conduct of research as part of their Centre induction, and reminders of this responsibility are periodically circulated. In 2022 we intend to revise and enhance this framework in response to a recommendation in the mid-term review.

Intellectual property customarily relates to inventions as opposed to discoveries. Research in CLEX is driven by our overarching goal to better understand the physical processes in the global climate system that contribute to extremes across scales of time and space. In other words, we are a Centre of Excellence focused entirely on discovery.

Globally, the climate science community has always worked from a foundational premise that all our work is open source and shared, such that others may build on work that has preceded their own, without restriction beyond the norms of attribution. Thus, code, data, models and so on are openly shared, and we benefit from this by having access to data and models that would be impossible for Australia to independently develop.

By returning our contributions into that system, we provide the rationale for the rest of the world maintaining open access to *their* data and models. Accordingly, we place greater emphasis on proper data management – including publishing data and code – than on traditional notions of intellectual property. This approach to open-source development of our models and the tools that assist us in interrogating model output is made explicit in the CLEX inter-institutional agreement. The agreement also offers an intellectual property framework to follow if at any point CLEX were to develop an invention or product that met the standard definitions of intellectual property.

As such, intellectual property is a low priority in climate science: to raise this priority would break our capacity to engage internationally and access data and models developed by the community. However, we recognise that around half of our graduates leave academia and research to take positions in government or industry where intellectual property considerations may be material. We are therefore developing an internal training module on intellectual property that is specific to the uniquely open-source approach taken by researchers in our field.

RESEARCHER DEVELOPMENT PROGRAM

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

In 2021 we welcomed 24 honours and masters students and 24 graduate students to the ARC Centre of Excellence for Climate Extremes (CLEX). All have been actively involved in our graduate activities.

Our Researcher Development Program recognises that climate scientists come from a variety of undergraduate backgrounds and come to us with a varying range of skills and knowledge. Therefore, the program offers important breadth and depth of climate science knowledge, technical and communications training and professional development. Our program produces the next generation of adaptable climate scientist leaders equipped for employment across a range of sectors.

We had **25** students submit this year (**13** PhD and **12** honours/masters) and they have been moving on to positions in a variety of sectors. 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.

Our popular scientific paper writing workshops have gone virtual for now and consist of a three-hour "turbo-charge your writing" virtual workshop, followed by 12 weeks of online coaching. The success of our writing workshops can be seen in our publication numbers, with **66** papers published by Centre students this year (**49** as first author). Included in this impressive publication list was a first-author paper in *Journal of Climate,* by Sonja Neske (Monash University), on the complex relationship between strong winds, the El Niño--Southern Oscillation and ocean temperatures, along with groundbreaking work led by ANU student Josue Martinez-Moreno in *Nature Climate Change* on mesoscale eddies.

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

Our students and early career researchers (ECRs) are represented in the centre via our ECR committee. The ECR committee provides formal and informal communication channels between ECR members and the CLEX Executive Committee. The committee's mission is to facilitate, encourage, and contribute to the development of all CLEX ECR researchers. This year, our ECRs led a wellbeing survey and key findings from that have been implemented into Centre culture. These include meeting-free Fridays and an email protocol that provides guidance on how to use email mindfully and to emphasise that emails received after hours do not require an immediate response.

Climate science students come from a range of quantitative undergraduate degree backgrounds. To ensure undergraduate students are aware of the opportunities within the climate sciences we offer highly competitive undergraduate scholarships. In 2020 we welcomed **18** undergraduate students from **6** universities to the Centre, to work with us on research projects. These scholarships provide the students with an introduction to cutting-edge climate science research at one of our five member universities or one of our national Partner Organisations. Undergraduate students are supervised by our ECRs, giving them vital supervisory experience. Two examples of the success of this program include Julia Potgieter, whohad a first-author paper published resulting from her undergraduate project, and Steven Thomas, who presented his undergraduate project at both the Australian Meteorological and Oceanographic Society conference and at the Bureau of Meteorology.

Finally, we celebrate the success of our students in winning a wide range of prizes and awards. The 2021 recipients included:

- Stephy Libera (UTAS) was awarded Best Student Poster in the Australian Antarctic Program Partnership Symposium
- Nathan Eizenberg (U.Melb) received the Bureau of Meteorology graduate student top-up scholarship of $10,000/year for the duration of his PhD
- Kimberley Reid (U.Melb) won the Outstanding Student Presentation Award for her talk on Atmospheric River Identification Sensitivity at the American Geophysical Union meeting, as well as the Royal Society of Victoria Young Scientist Research Prize in the Earth Sciences category
- Danielle Udy (UTAS) was awarded the Student Presentation Prize at the Australasian Quaternary Association e-conference.

'AS AN ECR, being a CLEX postdoc is the best opportunity you can get to start a research career in Australia, I really appreciate it.'
Dr Chen Li, former CLEX postdoctoral researcher now working at the Bureau of Meteorology

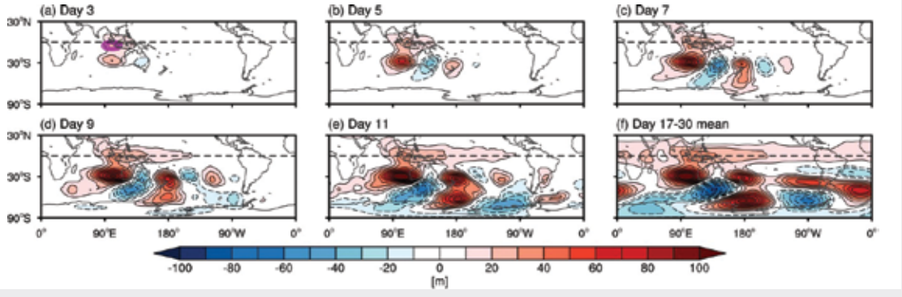
STATEMENT OF INTENT RESEARCHER DEVELOPMENT PROGRAM

Breadth of Knowledge	- An in-person student focused winter school with a focus on atmosphere and ocean dynamics - A series of online science fundamental masterclasses - Implement 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
Impact and influence	- Ongoing engagement between students and industry to build understanding of non-academic career paths - Encourage industry placements, or industry mentoring opportunities - Regular communication training across mediums and sectors
Collegiate and supportive environment	- Support leadership training and mentoring opportunities for ECRs, and offer in-Centre opportunities for ECRs to lead projects and initiatives

ECR PROFILE **DR ZOE GILLET**

I completed a Bachelor of Science at Monash University, majoring in atmospheric science. During this time, I did a summer undergraduate scholarship at the University of Melbourne with the previous CoE (ARCCSS). This experience helped to confirm my interest in pursuing a research career, and I went on to do honours and a PhD at Monash. I am now a CLEX postdoctoral research associate at UNSW. My research combines reanalysis products and idealised climate model experiments to better understand atmospheric variability and teleconnections in the Southern Hemisphere. In my current project, I am exploring the role of ocean variability for multi-year droughts in Australia.

My PhD research was supported by a combined CLEX/Bureau of Meteorology top-up scholarship, which gave me the opportunity to have a BoM supervisor and be part of the Climate Processes team. Thanks to CLEX, I have attended many CLEX winter schools and annual workshops, AMOS conferences, a paper writing workshop, and a conference on stratosphere-troposphere processes in Kyoto, Japan. Covid-19 restrictions unfortunately prevented a two-month visit to NCAR, USA, but I hope to have a few international visits during my postdoc to enhance my international collaborations. After my current position, I would like to do a postdoc overseas.



Daily evolution of the anomalous upper-tropospheric geopotential height response to imposed atmospheric heating over the eastern Indian Ocean (100°E, 5°S; pink contours).

CHIEF INVESTIGATORS

Director Prof Andy Pitman AO

Professor Andy Pitman was born in Bristol, UK, 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 (CLEX).

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 awarding 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.*

Prof 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.

Deputy Director Prof Todd Lane

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 Centre 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 and Head of the School of Geography, Earth and Atmospheric Sciences. Between 2010-2014 he was an ARC Future Fellow.

Prof Lane's primary research focus is on atmospheric processes. He is internationally recognised as an expert on tropical thunderstorms, atmospheric waves and turbulence. He has made important contributions to many aspects of mesoscale meteorology, convective cloud dynamics, and high-resolution atmospheric modelling. His research at the ARC Centre of Excellence for Climate Extremes is within the Weather and Climate Interactions research program, where he works on extreme rainfall and fronts. He uses high-resolution regional atmospheric models to determine the mesoscale processes controlling extremes, in order to better understand and predict them.

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.

Graduate Director A/Prof Melissa Hart

Associate Professor Melissa Hart has led and developed 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 180 graduate students with the skills, knowledge and experience fundamental to developing the next generation of adaptable climate science leaders equipped for employment across a range of sectors.

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

Melissa's research looks at the impact of cities on climate and climate on cities, along with the meteorological controls on air pollution. Melissa is a strong advocate for gender equity in science and is a past chair of the Australian Meteorological and Oceanographic Society's Equity and Diversity Committee, and a proud participant of the 2018 Homeward Bound Women in STEM leadership initiative.

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 studies how this affects Australia's rainfall patterns. Her work also involves proxy-model comparisons to assess the forcing mechanisms behind both natural and anthropogenic climate changes, and to help test climate model performance in historical and last-millennium experiments.

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

A/Prof Gab Abramowitz

Associate Professor Gab Abramowitz's primary research interest is in evaluating computational models in climate science, ecology and hydrology. Currently his research focuses on two main areas: defining and accounting for 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. This raises questions for A/Prof Abramowitz to explore, such as: To what extent, then, do different climate models constitute independent estimates of a climate prediction problem? What is the most appropriate statistical framework with which to define model independence? What are the implications of ignoring model dependence for future climate projection?

A/Prof Abramowitz is also leading the development of modelevaluation.org, a web application that provides automated land surface, hydrological and ecological model-evaluation tools as well as observational data sets. He is a member of the Global Energy and Water Cycle Experiment Global Land-Atmosphere System Study Panel.

Prof Lisa Alexander

Professor Lisa Alexander holds a BSc (Hons) and MSc in Applied Mathematics from Queens University, Belfast, and a PhD in Climate Science from Monash University. She previously worked as a research scientist at the UK Meteorological Office – Hadley Centre, including a year on secondment at the 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.

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 IPCC assessments in 2001, 2007 and 2021 and to its 2012 Special Report on Extremes, and she was a Lead Author of the IPCC's 5th Assessment Report. She 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 at the National Center for Atmospheric Research (NCAR), USA, before that.

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. Her 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 data sets and sensitivity experiments with a single model. Her strong collaboration with NCAR and participation in various international committees and reports enhances her engagement with the latest advances in climate research internationally.

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 served as a Lead Author of the Intergovernmental Panel on Climate Change 5th Assessment Report and is currently on the Scientific Steering Committee for the 2022 World Meteorological Organization/United Nations Environment Programme Scientific Assessment of Ozone Depletion. She is also a member of the World Climate Research Programme Coupled Model Intercomparison Project Panel and a member of the Australian Academy of Science's National Committee on Earth System Science.

Prof Craig Bishop

Professor Craig Bishop completed his PhD in Applied Mathematics at Monash University. His innovative ensemble-based data assimilation and ensemble-forecasting techniques are now widely used by leading environmental forecasting agencies in several countries. Prof Bishop has held positions at the University of Reading, the NASA Goddard Space Flight Center, Pennsylvania State University's prestigious Department of Meteorology and the Marine Meteorology Division of the Naval Research Laboratory (NRL) in Monterey, California. There he was awarded six outstanding contribution awards, three NRL Alan Berman publication awards, and one NRL Edison Patent Award. He returned to Australia in June 2018 as Professor of Weather Prediction at the University of Melbourne.

Prof Bishop has held numerous notable leadership positions, including founding co-chair of the World Meteorological Organization's Working Group on Predictability, Dynamics and Ensemble Forecasting; associate editor of the *Quarterly Journal of the Royal Meteorological Society*; and 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. He was elected to the International Commission on Dynamical Meteorology in 2010 and as a fellow of the American Meteorological Society in 2012.

A/Prof Dietmar Dommenget

Associate Professor Dietmar Dommenget completed his Diploma (MSc) in Physics at the University of Hamburg. He was awarded a PhD by the Max Planck Institute for Meteorology in 2000. He joined the ECCO (Estimating the Circulation and Climate of the Ocean) project in a postdoctoral position at the Scripps Institution of Oceanography in La Jolla, California, to study the predictability of El Niño--Southern Oscillation 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 in Kiel. Since 2010 A/Prof Dommenget 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. Most of his work centres on the development, conducting and analysis of coupled general-circulation models, but he has also developed simple conceptual models of natural climate variability. Most of his work focuses on sea surface temperature variability in the tropical and extratropical oceans. He is most widely known for his work on the interpretation of patterns and modes of climate variability. A/Prof Dommenget's most recent projects focus on El Niño, climate model developments and climate change. He 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 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 and then research fellow at Yale University in the USA. In 2007 he returned to Australia to take up a position in the Climate Change Research Centre at UNSW, where he remains today.

Prof Evans' expertise is in the area of regional climate, land-atmosphere interactions, the water cycle and climate change. His focus is on regional climate change and its impacts. His research program brings together advanced modelling tools with extensive observational data sets, with an emphasis on satellite-based, remotely sensed earth observations.

Prof Evans was a Lead Author on the Intergovernmental Panel on Climate Change (IPCC) Special Report on climate change, desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial ecosystems. He has also been editor of the *Journal of Climate* since 2016. In 2020 Prof Evans was elected a fellow of the Modelling and Simulation Society of Australia and New Zealand and in 2021 he received their Biennial Medal for outstanding contributions to modelling and simulation over a sustained period of time. He was also elected a fellow of the Royal Society of New South Wales in 2021.

Dr Ailie Gallant

Dr Ailie Gallant completed her PhD at Monash University in 2009 in the School of Mathematical Sciences. She is currently an ARC Discover Early Career Researcher Award Fellow in the School of Earth, Atmosphere and Environment in the Faculty of Science, Monash University.

Dr Gallant's work seeks to characterise and understand climate variability and change on multiple time and spatial scales, primarily for the Australasian and Antarctic regions. Most of her research relates to examining climate extremes, particularly extremes of the hydroclimate such as drought. Her current research interests include identifying and understanding variations and trends in Australian climate extremes; investigating the role of multi-decadal-scale climate variability in the Australian region; and characterising pre-instrumental climate variations in Australia and Antarctica, using paleoclimate data. Dr Gallant has published 28 journal articles, has over 800 citations and an h-index of 13.

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

Prof Neil Holbrook

Professor Neil Holbrook completed his undergraduate degree in applied mathematics and physical oceanography at the University of Sydney with a Bachelor of Science (Honours), in 1990. He was awarded his PhD in applied mathematics/physical oceanography, also at the University of Sydney, in 1995, and 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, he was appointed as a lecturer in atmospheric science in 1996 at Macquarie University. He left Macquarie University as a senior lecturer in 2007 and commenced at the University of Tasmania in 2008 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 a fellow of the Australian Meteorological and Oceanographic Society and an associate editor of the *Journal of Southern Hemisphere Earth Systems Science*. He 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) and as an associate editor of the Journal of Climate (2006-2008). He also 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 from the Ludwig Maximilians University, Munich, in 2001. As a research then senior research scientist for the European Centre for Medium-Range Weather Forecasts from 1993 to 2001, he worked on the development and evaluation of the model representation of clouds, convection and precipitation. From 2002 to 2007 he was senior and principal research scientist at the Bureau of Meteorology and since 2007 he has been a professor at Monash University. He currently is the Chair of Climate Modelling at Monash University's School of Earth, Atmosphere and Environment.

Prof Jakob's 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 Modelling and Prediction Panel from 2007 to 2010.

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

Dr Amelie Meyer

Dr Amelie Meyer completed her PhD in 2014 at the University of Tasmania. Collaborating with CSIRO, her thesis focused on circulation, mixing and internal waves in the Southern Ocean. She worked as a postdoctoral fellow at the Norwegian Polar Institute in Tromsø (Norway) between 2014 and 2018, focusing ocean-ice interactions in the changing Arctic. She is currently a research fellow at UTAS, where she has been awarded an ARC Discovery Early Career Researcher Award Fellowship.

Dr Meyer is passionate about climate variability, polar science and ocean circulation. Her work looks at how and why polar regions are influenced by and influence climate. To understand polar oceans, she collects scientific observations in the Arctic and Antarctic. This work has taken her personally to these remote places, where she has spent over 180 days working both on research ships and on the ice.

Dr Meyer is a strong advocate for science communication and outreach. In 2019 she was awarded the Tasmanian Young Tall Poppy Science Award and the Centre of Excellence for Climate Extremes Director's Prize. She has published 25 journal articles, has over 700 citations and an h-index of 14.

Dr Sarah Perkins- Kirkpatrick

Dr Sarah Perkins-Kirkpatrick completed her PhD at the University of New South Wales in 2010. She is currently an ARC Future Fellowship awardee and a senior lecturer at the Climate Change Research Centre, UNSW.

Her work investigates trends in heatwaves globally and in Australia, as well as exploring the role of human activity behind such trends. She is currently focusing on comprehensive methods of attributing heatwaves to climate change, and how we might be able in attribute the health impacts of heatwaves to climate change.

Dr Perkins-Kirkpatrick was the recipient of the 2013 Young Tall Poppy Award, the 2014 Director's Prize from the ARC Centre of Excellence for Climate System Science and the Australian Meteorological and Oceanographic Society Early Career Researcher Award, 2016. In 2016 she was named one of 'UNSW's 20 rising stars who will change the world'. She has published 82 journal articles, has over 5000 citations and an h-index of 30.

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's research is focused principally on the dynamics of weather-producing systems. He has published on a wide variety of topics, including fronts, tropopause folding, extratropical cyclones, Rossby waves, heat waves, tropical cyclones, gravity waves, solitary waves, convection, boundary layers, the Hadley and Walker circulations, the Madden-Julian Oscillation and bushfires. He has been the principal supervisor for more than 50 graduate students.

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

Prof Steven Sherwood

Professor Steven Sherwood was awarded his 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, later rising to the rank of professor. At the beginning of 2009 he moved to Australia, where he is a professor at and former director of the Climate Change Research Centre at UNSW.

Prof Sherwood 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.

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 currently serves on the review board of the journal *Science,* and co-chairs the World Climate Research Programme's Lighthouse Activity on Safe Landing Climates. Prof Sherwood has co-authored approximately 150 papers published in peer-reviewed journals. He led an international assessment of climate sensitivity published in 2020 that was listed by *Science* magazine as one of the top ten scientific advances of the year.

Prof Peter Strutton

Professor Peter Strutton received his bachelor's degree with honours in marine science from Flinders University, South Australia, in 1993. He went on to complete his PhD in marine science in 1998. He then left Australia to take up a postdoctoral position with the Monterey Bay Aquarium Research Institute in California, which he held until 2002. From 2002-2004 he was assistant professor with the State University of New York's Marine Sciences Research Centre and from 2004-2010 he was assistant, then associate professor at Oregon State University's College of Oceanic and Atmospheric Sciences. In 2010 he returned to Australia on an ARC Future Fellowship and since then has been associate professor then 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 on how modes of variability, such as El Niño--Southern Oscillation, and internal ocean waves affect nutrients in the ocean, biological productivity and carbon cycling. In the ARC Centre of Excellence for Climate Extremes he contributes to the Ocean Extremes research program and he is also contributing to projects in the area of ocean physical, biological and chemical variability. He 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 work on Antarctica through to the tropical Pacific and the Labrador Sea. Prof Strutton 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 has also served on the Scientific Steering Committee and Biogeochemistry Task Team for the redesign of the Tropical Pacific Observing System (tpos2020.org).

A/Prof Andrea Taschetto

Andrea Taschetto completed her PhD in Physical Oceanography at the University of São Paulo, Brazil, in 2006. She is currently an Associate Professor at the Climate Change Research Centre, the University of New South Wales.

A/Prof Taschetto investigates the mechanisms by which the oceans affect global and regional climate, using observations and numerical models. She is interested in climate variability, tropical inter-basin interactions and atmospheric teleconnection patterns. Her work looks at the impact of global sea surface temperature variability on precipitation and droughts over Australia and elsewhere. She is particularly interested in the mechanisms of the El Niño-Southern Oscillation diversity and how this influences atmospheric circulation and interacts with other oceanic basins.

In 2016 A/Prof Taschetto was awarded the Australian Academy of Science Dorothy Hill Award for excellence in earth sciences research. She was awarded an ARC Postdoctoral Fellowship in 2010 and an ARC Future Fellowship in 2016. A/Prof Taschetto has published 58 journal articles, has over 2900 citations and an h-index of 27.

Dr Claire Vincent

Dr Claire Vincent completed her PhD in mesoscale wind variability at the Technical University of Denmark in 2010. Prior to this, she worked at the Bureau of Meteorology, first as a forecaster and then on a project to verify near-surface winds from mesoscale modelling. Presently, she is a lecturer in atmospheric science at the School of Earth Sciences, the University of Melbourne.

Dr Vincent's research interests include tropical variability, clouds and precipitation, and mesoscale meteorology and modelling. She is particularly interested in the interaction between different scales of variability in the atmosphere and how these interactions influence regional weather and climate. Dr Vincent has published 24 journal articles, has nearly 400 citations and an h-index of 10.

OUR STAFF AND STUDENTS

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 Craig Bishop
University of Melbourne

A/Professor Dietmar Dommenget
Monash University

Professor Jason Evans
University of New South Wales

Professor Andy Hogg
Australian National University

Professor Neil Holbrook
University of Tasmania

Dr Ailie Gallant
Monash University

Professor Christian Jakob
Monash University

Dr Amelie Meyer
University of Tasmania

Dr Sarah Perkins-Kirkpatrick
UNSW Canberra

Professor Michael Reeder
Monash University

Professor Steven Sherwood
University of New South Wales

Professor Peter Strutton
University of Tasmania

Dr Andrea Taschetto
University of New South Wales

Dr Claire Vincent
University of Melbourne

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 Cathy Hohenegger
Max Plank Institute for Meteorology (Germany)

Dr Reto Knutti
ETH Zurich (Switzerland)

Dr Rachel Law
CSIRO

Dr Andrew Marshall
BoM

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)

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 Ghyslaine Boschat
BoM

Dr Josephine Brown
U.Melb

Dr Jennifer Catto
Exeter University (UK)

Dr Christine Chung
BoM

Dr Navid Constantinou
ANU

Dr Randall Donohue
CSIRO

Dr Stephanie Downes
NSW DPIE

Dr Nick Earl
UTAS

Professor Graham Farquhar
ANU

Dr Sonya Fiddes
UTAS

Dr Bishakhdatta Gayen
ANU

Dr Joëlle Gergis
U.Melb

A/Professor Donna Green
UNSW

Dr Harry Hendon
Monash University

Dr Benjamin Henley
U.Melb

Dr Will Hobbs
UTAS

Dr Ryan Holmes
University of Sydney

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

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 Acacia Pepler
BoM

Dr Helen Phillips
UTAS

Dr Scott Power
BoM

Dr Tim Raupach
UNSW

Professor Peter Rayner
U.Melb

Professor Moninya Roughan
UNSW

Dr Agus Santoso
UNSW

A/ Professor Robyn Schofield
U.Melb

Dr Alexander Sen Gupta
UNSW

Dr Callum Shakespeare
ANU

Professor Jason Sharples
UNSW

A/Professor Steven Siems
Monash University

Dr Martin Singh
Monash University

Professor Scott Sisson
UNSW

Dr Andrea Taschetto
UNSW

Dr Anna Ukkola
UNSW

Dr Caroline Ummenhofer
WHOI (USA)

Professor Kevin Walsh
U.Melb

Dr Bethan White
Monash University

Dr Jan Zika
UNSW

Research Associates

Dr Margot Bador
UNSW

Dr Diego Saúl Carrió Carrió
U.Melb

Dr Navid Constantinou
ANU

Dr Martin De Kauwe
UNSW

Dr Anjana Devanand
UNSW

Dr Georgina Falster
ANU

Dr Zoe Gillett
UNSW

Dr Hakase Hayashida
UTAS

Dr Stacey Hitchcock
U.Melb

Dr Sanaa Hobeichi
UNSW

Dr Ryan Holmes
UNSW

Dr Yi-Ling Hwong
UNSW

Dr Jules Kajtar
UTAS

Dr Malcolm King
Monash University

Dr Chen Li
Monash University

Dr Ramkrushnbai Patel
UTAS

Dr Ariaan Purich
UNSW

Dr Nina Ridder
UNSW

Dr Shao Yawen
U.Melb

Dr Christopher Thomas
UNSW

Dr Nicky Wright
ANU

Dr DongXia Yang
U.Melb

Computational Modelling Systems and Technical Programmers

Dr Claire Carouge, Team Leader
UNSW

Dr Aidan Heerdegen
ANU

Dr Annette Hirsch
UNSW

Dr Paola Petrelli
UTAS

Dr Scott Wales
U.Melb

Dr Holger Wolff
Monash University

Professional Staff, Media and KBT

Aline Bryleva
ANU

Sook Chor
Monash University

Vilia Co
UNSW

Allyson Crimp
Monash University

Karla Fallon
U.Melb

Christine Fury
UTAS

Dr Ian Macadam – KBT Leader
UNSW

Jenny Rislund
UNSW

Alvin Stone – Media Manager
UNSW

PhD Students

*Indicates thesis submission in 2021

Luis Ackermann
Monash University

Mustapha Adamu
Monash University

Tahare Alinejadtabrizi
Monash University

Hooman Ayat
UNSW

Ashley Barnes
ANU

Shannon Bengtson*
UNSW

Ankit Bhadouriya
U.Melb

Dhruv Bhagtani
ANU

Ce Bian
UTAS

Christopher Bladwell
UNSW

Alexander Borowiak
U.Melb

Annabel Bowden
U.Melb

Andrew Brown
U.Melb

Camilla Crockart
UTAS

Thi Lan Dao
U.Melb

Hannah Dawson
UNSW

Xu Deng
UNSW Canberra

Shreya Dhame*
UNSW

Deepashree Dutta
UNSW

Nathan Eizenberg
U.Melb

Emilio Echevarria*
UTAS

Elizabeth Elwell
U.Melb

Chen-shuo Fan
Monash University

Xinyang Fan
U.Melb

Denisse Fiero Arcos
UTAS

Pia Freisen
Monash University

Maheshinderjeet Garg
U.Melb

Bahman Ghasemi
U.Melb

Zoe Gillett*
Monash University

Rishav Goyal*
UNSW

Jessica Hargreaves
ANU

Qinuo Huang
Monash University

Maurice Huguenin-Virchaux
UNSW

Alejandra Isaza
UNSW

Rachael Isphording
UNSW

Sarah Jackson
ANU

Maya Jakes
UTAS

Chenhui Jin
Monash University

Tom Lemaitre
Monash University

Sopia Lestari
U.Melb

Zeya Li
UTAS

Zhi Li
UNSW

Stephy Libera
UTAS

Ruby Lieber
U.Melb

Guillaume Liniger
UTAS

Sijie Liu
UNSW

Clemente Lopez-Bravo
U.Melb

Jiachen Lu
UNSW

Davide Marchegiani
Monash University

Maxime Marin
UTAS/CSIRO

Josue Martinez Moreno*
ANU

Jennifer McCrindle-Fuchs
UNSW

Roseanna McKay*
Monash University

Sebastian McKenna
UNSW

Jan Jaap Meijer
UTAS

Sarthak Mohanty
Monash University

Estefania Montoya Duque
U.Melb

Mengyuan Mu
UNSW

Rajashree Naha
Monash University

Marzie Naserikia
UNSW

Julia Neme
UNSW

Sramana Neogi
Monash

Phuong Loan Nguyen
UNSW

Zebedee Nicholls*
U.Melb

Qing Yee Ellie Ong
UNSW

Luis Bryam Orihuela Pinto
UNSW

Valentina Guzman Ortiz
UNSW

Jon Page
UNSW

Jyoteesh Papari
UNSW Canberra

Charuni Pathmeswaran
UNSW

Preethi Paul
UNSW

Kishor Kumar Paul
UNSW

Nicholas Pittman
UTAS

Shukla Poddar
UNSW

Katie Quail
UNSW

Clara R. Vives
UTAS

Pavan Harika Raavi*
U.Melb

Tony Rafter
U.Melb

Jemima Rama
ANU

Kimberley Reid
U.Melb

Matthias Retsch
Monash University

Elona Rey-Costa
UNSW

Daniel Robbins
Monash University

Fiona Robinson
UNSW

Manon Sabot
UNSW

Himadri Saini
UNSW

Emmanuel Sarbeng
Monash University

Francesco Sardelli
U.Melb

Abhishek Savita*
UTAS

Christina Schmidt
UNSW

Nasimeh Shahrokhi
University of Melbourne

Ewan Short
U.Melb

Felipe Silva
UTAS

Tanya Singh
UNSW

Annette Stellema
UNSW

Jiaoyang Su
UTAS

Arnold Sullivan
Monash University

Jim Sweetman
ANU

Isaac Tan
Monash University

Lina Teckentrup
UNSW

Thao Lin Tran
UNSW Canberra

Son (Sonny) Truong
Monash University

Danielle Udy
UTAS

Nick Velzeboer
ANU

Robert Vicari
U.Melb

Yohanna Lesly Villalobos Cortes*
U.Melb

Yu Wang
UTAS

Yuxin Wang
UTAS

Charlotte Waudby
UNSW

Jakob Weis
UTAS

Zhiang Xie
Monash University

DongXia Yang*
Monash University

Xiang Yang
UTAS

Kai Yang
UTAS

Nicholas Yeung
UNSW

Shujing Zhang
UTAS

Xihan Zhang
UTAS

Wenhui Zhao
Monash University

Zijie Zhao
U.Melb

Masters Students

*Indicates thesis submission in 2021

Kate Bongiovanni
U.Melb

Alexander Borowiak*
U.Melb

Michael Eabry*
UNSW

Ruby Lieber
U.Melb

Hangyu Meng
ANU

Fadhlil Rizki Muhammad
U.Melb

Nicholas Thorne
U.Melb

Genevieve Tolhurst*
U.Melb

Imogen Wadlow*
U.Melb

Jingwei Zhou*
ANU

Honours Students

*Indicates thesis submission in 2021

Maryam Al-Ansari
Monash University

Yanxuan Du
UTAS

Catherine Gregory*
UTAS

Liam Lamprey
UTAS

Seen Yee Leanne Lee*
UNSW

Josh Li*
UNSW

Xinlong Liu
UTAS

Jordan Loranzetto
UNSW

Yuxuan Lyu*
UTAS

Han Meng
UTAS

Anthea Michalopolous
UNSW

William Palm
ANU

Zhangcheng Pei
UTAS

Matthew Pudig*
UNSW

John Reilly
UTAS

Lara Richards
Monash University

Claire Roucet*
UNSW

Jiaxin Shi
UTAS

Ellie Traill
Monash University

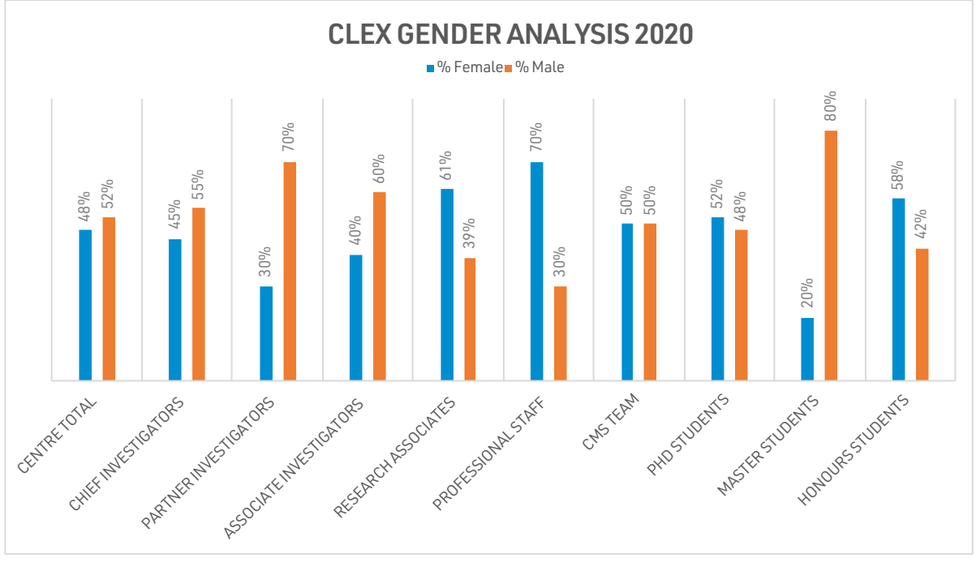
Fengmin Xin
UTAS

Xiang Yang
UTAS

Xin Ye
UTAS

Xiang Yang
UTAS

Claire Yung
ANU



2 OUR RESEARCH AND TECHNOLOGY

INTRODUCTION

As part of our strategy leading into and through the mid-term review of the ARC Centre of Excellence for Climate Extremes (CLEX), we assessed and revised the focus of our research programs to help refresh and reinvigorate them. This was not a change in the scope of CLEX, of course, but it was a refresh of some internal processes and research project organisation. Our objective was to re-energise person-to-person connections, avoid discipline silos, provide leadership opportunities for some mid-career researchers and enhance some integration strategies.

CLEX is now organised around four research programs, plus an enabling program focused on the Centre's models and modelling infrastructure.

Our Weather and Climate Interactions program integrates some of the previous research program in extreme rainfall, along with drought, and other extremes across scales. This integration is designed to bring together several strands of research to enable more ambitious questions to be answered. As will be discovered below, a great deal of the research being undertaken in this theme has direct relevance to business, policy and climate risk.

Our Attribution and Risk research program integrates work on heatwaves, extreme rainfall, drought and other climate extremes building on earlier work conducted in climate variability and teleconnections. Again, a great deal of the research being undertaken in the Attribution and Risk area has direct relevance to business, policy and climate risk.

It would be hard to have a climate extremes research centre in Australia without a Drought research program, and the second half of CLEX retains this program. Noteworthy below is the strong engagement of industry and government in the first year of this revised program.

We are also investing in a new research program, Ocean Extremes, which integrates elements of climate variability, teleconnections and ocean biogeochemistry that were examined in the first half of the Centre's life. Links to fisheries, in particular in Tasmania, are under development.

Virtually all our research depends on our modelling and modelling infrastructure. Building cutting-edge tools, access to data, sharing of data, and so on, enables our research, but also enhances efficiency that allows us to complete research quickly and to a high standard. CLEX has a long and active engagement with the National Computational Infrastructure, and in 2022 and beyond we will add strong engagement with the Australian Community Climate and Earth System Simulator--National Research Infrastructure (ACCESS-NRI) initiative, in the hope of developing even more ambitious modelling systems.

In the reports that follow, each research program describes some achievements both in terms of outreach and impact, as well as in more traditional metrics such as publications, PhD completions, prizes and so on. Our goal in 2022 is to create opportunities to integrate these research programs even more, to find synergies and to create a renewed environment of innovation -- something severely impacted by Covid-19.

RP1: WEATHER AND CLIMATE INTERACTIONS

RESEARCH PROGRAM SUMMARY

The Weather and Climate Interaction Research Program (WaCI RP) is new to the second half of CLEX. This research program explicitly recognises that the climate is defined by the strength and frequency of weather systems, or in other words, weather systems are the building blocks of the climate.

Understanding how these building blocks change as the world warms is the key to understanding how climate change affects people, the economy and the environment. For these reasons, CLEX has created this new research program to investigate the physical mechanisms responsible for weather extremes in the tropics and extra-tropics and the effect of a warming world on these mechanisms.

Our RP focuses mainly, but not exclusively, on two weather systems of particular importance to Australian weather extremes: fronts and tropical lows. Nonetheless, some of the important extreme-weather-related research from earlier research programs, such as heatwaves and convection, now falls under the WaCI RP. Although it has certainly been a challenge to spin up a new research program during the pandemic, WaCI is poised to rapidly accelerate in 2022.

PROJECT 1

What controls the strength, frequency and path of fronts in the Australian extra-tropics, and how do these factors affect extremes?

Fronts are perhaps the only weather systems implicated in heat, wind *and* precipitation extremes. To illustrate this point, consider the following: the most catastrophic fires in recent history in southern Australia have been associated with extreme but shallow, dry, cold fronts that form along the southern coastline; Melbourne's record maximum temperature preceded the passage of the extreme cold front on Black Saturday; and frontal systems commonly provide the uplift needed to produce extreme precipitation. In 2021 the main technical achievement was that we developed code for diagnosing and tracking fronts in gridded data sets and models, which we applied using the ERA-5. In Project 1, we appointed one postdoctoral researcher in mid 2021 and another is due to begin in February, 2022.

PROJECT 2

What causes the long-lived, heavy rains in tropical and subtropical Australia?

Tropical lows are among the most important rain-bearing weather systems in the northern half of the continent. For example, in north-western Australia around half of all summertime rainfall is associated with them. Moreover, tropical lows are commonly implicated in rainfall extremes. One recent and particularly important example is the north Queensland flood of January and February 2019. In 2021 one of the main technical achievements was the development of a code to identify tropical lows in models and data. One postdoctoral researcher started on Project 2 in September, 2021, and another is set to begin in February, 2022.

Outreach and Engagement

Despite the pandemic and lockdowns, it was still a relatively active year for outreach and engagement. Here's a taster of the activities associated with the Interactions program: podcasts on the "Interaction between weather and climate" and on "Known unknowns of climate change"; and a *Conversation* article on "The North American heatwave shows we need to know how climate change will change our weather".

RESEARCH SNAPSHOTS

Urban Heat Island Effect Amplifies Sydney Heatwaves

Urban areas are often hotter than their rural surroundings, which is a phenomenon known as the urban heat island effect. Our work investigated how Sydney's heat island is affected by coastal breezes, air flows coming from further inland or weather phenomena like heatwaves, and the interaction between these different processes. The research was conducted using a new configuration of the Weather and Research Forecasting model run at a very high resolution of 800 metres with a new urban classification scheme that describes the complexity of Sydney's built environment. We found that heatwaves often start with a hot continental flow over the Blue Mountains descending into the Greater Sydney region and that it gets stuck, leading to temperature difference across the city exceeding 15°C. The urban environment, on average, adds about 1°C of heat in the lower atmosphere, but over heatwave periods this can exceed 10°C and can also affect the Blue Mountains areas when sea breezes act to push the heat further inland.

Hirsch, Annette L., Jason P. Evans, Christopher Thomas, Brooke Conroy, Melissa A. Hart, Mathew Lipson, and William Ertler. Resolving the Influence of Local Flows on Urban Heat Amplification during Heatwaves. *Environmental Research Letters* 16, no. 6 (June 2021): 064066. https://doi.org/10.1088/1748-9326/ac0377

How Cumulus Convection Changes with Extreme Rainfall

Convection that produces cumulus clouds is typically thought of as being made up of long continuous plumes of warm rising air, rather than shorter, incoherent plumes of around only one kilometre in vertical extent. Global climate models tend to parameterize cumulus convection in the first form, but detailed numerical simulations and aircraft observations tend to support the latter for typical warm-season convection. CLEX researchers used data from a wind profiler radar pair at Darwin, Australia, to determine the characteristics of individual up- and downdrafts observed at the site. Most drafts were found to be less than two kilometres km in vertical extent. They also identified that the updraft length increased with rain rates. With extreme rain rates, the average updraft lengths were around five kilometres. These results are broadly consistent with other numerical modelling studies but are in contrast to the common view that deep convection is dominated by continuous, deep drafts.

Yeung, Nicholas K. H., Steven C. Sherwood, Alain Protat, Todd P. Lane, and Christopher Williams. "A Doppler radar study of convective draft lengths over Darwin, Australia", *Monthly Weather Review* (published online ahead of print 2021). https://doi.org/10.1175/MWR-D-20-0390.1

What Drives Extreme Heat Events in Spring?

Maximum temperatures in Australia during spring have exceeded historical records on multiple occasions in recent years. Understanding what drives these high temperatures may lead to better forecasts of extreme heat in the future. In this study, we looked at three extreme heat events, September 2013, October-November 2014, and October 2015, in reanalysis and in a seasonal prediction model. We compared the atmospheric circulation during each of the events to find circulation features that could help us understand how the heat formed. Cyclonic circulation southwest of Australia and an atmospheric wave train with anticyclonic circulation over southern Australia were important features in these events. While the Indian Ocean Dipole was not active, the wave train appeared to come from the tropical Indian Ocean and was particularly important in the second two events.

McKay, R.C., Arblaster, J.M., Hope, P. et al. Exploring atmospheric circulation leading to three anomalous Australian spring heat events. *Climate Dynamics* (2021). https://doi.org/10.1007/s00382-020-05580-0

Ring-like Structure in Cyclone Leads to Rapid Intensification of Surface Winds

The most intense and destructive tropical cyclones generally go through a period of rapid intensification, where "rapid" means that the near-surface winds increase by more than 15 m/s (54km/hr) in 24 hours. Because of the close connection between rapid intensification and the final intensity of the storm, accurately forecasting the timing and magnitude of such periods of intensification is important. However, the physical processes by which storms rapidly intensify are not well understood and there has been little improvement in forecasting rapid intensification over the past three decades. This study uses very high-resolution simulations with the UK Meteorological Office Unified Model of the 2016 north-Pacific super typhoon Nepartak, to explore the processes responsible for its rapid intensification. It found the inner core of Nepartak fluctuated between a structure that was ring-like and one that was monopolar. During the ringlike phase the low-level wind intensified, whereas during the monopole phase the low-level wind remained mostly constant.

Hardy, S., Schwendike, J., Smith, R.K., Short, C.J., Reeder, M.J., Birch, C.E., 2021. Fluctuations in inner-core structure during the rapid intensification of Super Typhoon Nepartak (2016). *Monthly Weather Review* 141, 221–243. https://doi.org/10.1175/MWR-D-19-0415.1

New Zealand's Costliest Floods Caused by Atmospheric Rivers

Atmospheric Rivers are over 2000km long, flow in the first few kilometres of the atmosphere and transport more water than the Amazon and Nile rivers combined. There are about six of these weather systems on the globe at any time. These huge weather highways are responsible for moving 90 percent of atmospheric moisture from the tropics to the poles. Our study showed that nine out of 10 of the most expensive floods in New Zealand (2007-2017) were due to Atmospheric Rivers and seven to all 10 of the top 10 most extreme rainfall events at 11 different locations occurred during Atmospheric Rivers.

Reid, K.J., Rosier, S.M., Harrington, L.J., King, A.D., Lane, T.P., 2021. Extreme rainfall in New Zealand and its association with atmospheric rivers. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/abeae0

Why Melbourne's Worst Storms Come in Lines

It has long been suggested that rainfall in Melbourne often occurs as lines of precipitation. However, this had yet to be quantified. We analysed 15 years of radar data from the Australian Radar Archive to identify and track these so-called linear systems based on their observed characteristics. We then explored heavy and extreme rainfall events from those systems,. "Heavy" events are the top five percent and "extreme" events are the top one percent of average rainfall days. On these heavy or extreme days, those that had linear systems contributed to 70-85 percent of the rainfall. We found that the linear systems on days with heavy rainfall had more north-south orientation, and were larger, slower, and longer-lived than more ordinary linear systems. Those on extreme rainfall days were even larger, slower, and longer-lived, but also had a greater degree of southward movement and were more likely to be associated with taller, more intense storms.

Hitchcock, S.M., Lane, T.P., Warren, R.A., Soderholm, J.S., 2021. Linear rainfall features and their association with rainfall extremes near Melbourne, Australia. Monthly Weather Review 149, 3401–3417. https://doi.org/10.1175/MWR-D-21-0007.1

WEATHER AND CLIMATE INTERACTION RESEARCH PROGRAM STATEMENT OF INTENT 2022

PROJECT 1 **What controls the strength, frequency and path of fronts in the Australian extra-tropics, and how do these factors affect extremes?**	- Create a climatology of extreme summer cold fronts at points across Australia from the local temperature timeseries. - Identify fronts and their (wet and dry) extremes as well as wave breaking in models including ACCESS global and regional model and global model simulations. - 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. - Conduct simulations and analysis to determine the key drying mechanisms during frontal passages starting with the recent 2019/2020 fire season. - 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. - Determine the impact of land surface processes on drying events in the ACCESS regional model
PROJECT 2 **What causes the long-lived, heavy rains in tropical and subtropical Australia?**	- Apply tropical/subtropical low identification and tracking algorithm to reanalyses and study the relationship of monsoon lows to rainfall and its extremes. - Finalise study on QLD mean and extreme rainfall (daily and sub-daily scales) and variability with ENSO / MJO / IOD. - Establish variability/co-variability of ENSO/IOD and MJO in long historical datasets, and examine composite large-scale variability over tropical Australia. - Make progress towards understanding Northern Australian rainfall variability under different climate modes using pacemaker experiments.
Engagement	- Apply CLIMPACT indices to QLD mean and extreme rainfall and variability with ENSO / MJO / IOD (publish paper). - Present CLIMPACT analysis at least two stakeholder-relevant forums.

ECR PROFILE **DR HOOMAN AYAT**

Who in CLEX are you working with? I was a PhD student at CLEX under the supervision of Jason Evans and Steven Sherwood. I have also started a new position at the University of Melbourne as a postdoc researcher, working with Todd Lane.

Tell us a little about your background, how did you get here? I have always loved programming and the potential that it can offer to understand physics and explore its unknown areas. This passion has led me to experience different fields in my life. I am originally from Iran, and I did my bachelor's and two master's degrees in civil engineering there. In my latest masters thesis, I was interested in the applicability of remotely sensed data in estimating the precipitation over the northern part of my country, which led me to start a PhD in climate science and employ these data sets to understand storm characteristics and their changes in different parts of the world.

Tell us a little about your project The overarching goal of my thesis project was to quantify various storm characteristics, including their changes, using radar and satellite observations. Storms have often been studied using point-based (Eulerian) approaches. In these approaches, storm characteristics are derived from a fixed point, observing the storms as they are passing over. Thus, studied characteristics are often limited to intensity and frequency. In my PhD project, I employed an object-based (Lagrangian) approach, by which storms are considered as moving objects on a precipitation map, and a wide range of characteristics such as size, shape, speed, direction, lifetime, track length, ... can be investigated. One of the most important findings in my PhD was that sub-hourly rainfall extremes are intensifying 20 percent per decade near Sydney, Australia, and are changing faster than those on longer time scales. This trend is seen consistently across multiple independent ground radars and rain gauges, and does not appear to be associated with known natural variations.

What opportunities has the Centre of Excellence offered you? CLEX has been the right choice for me to learn how to do research. At CLEX, I have had the chance to be mentored by, and network with, some of the leading minds in my field. The annual workshops and winter schools were great opportunities to connect with and learn from other researchers. The regular rainfall extremes meetings have been very inspiring for me to find new directions in my PhD and also have resulted in collaborative papers.

What are your hopes/plans for after you graduate? I have just started a new position at CLEX and will continue as a postdoc researcher at the University of Melbourne for another three years. It's hard to predict the future, but according to my interests I am planning to continue as a researcher in academia or industry.

RP2 ATTRIBUTION AND RISK

RESEARCH PROGRAM SUMMARY

The Attribution and Risk research program at the ARC Centre of Excellence for Climate Extremes (CLEX) was established at the beginning of this year. The program seeks to understand how climate extremes are changing, as well as the cause of these changes. We have held regular monthly meetings to discuss the latest research on this topic and to bring the climate attribution and risk community together. Despite Covid-19-19 limiting our plans to gather in person, we have had vibrant virtual discussions and heard from both junior and senior researchers in Australia and overseas. Four out of five research fellow positions have now been filled: We are excited that Yawen Shao, Zoe Gillett, Sanaa Hobeichi and Kim Reid are joining us and will build momentum as we go into 2022.

The Attribution and Risk program team was active in its engagement over 2021, giving well-received briefings on the Intergovernmental Panel on Climate Change Working Group I 6th Assessment Report , to federal Members of Parliament Dave Sharma and Matt Thistlethwaite, in NSW, and to Senator Janet Rice, in Victoria. Chief Investigator Sarah Perkins-Kirkpatrick and others in CLEX were also very active, providing background information around the need for strong climate action in the lead-up to the United Nations Framework Convention on Climate Change - Conference of the Parties 26 (UNFCCC COP26) meeting in Glasgow, in November. In addition, Sarah was recognised for her research excellence as a world-leading expert in heatwaves, by the award to her of the 2021 Australian Academy of Science Dorothy Hill Medal. The Attribution and Risk program team participated in many briefings to industry and in outreach activities – including taking part in an episode describing attribution and risk on Cimpatico TV's Climate Australia program, hosted by Lee Constable. Another highlight was the series of presentations by Chief Investigator Andrea Taschetto and Associate Investigator Tim Raupach in the Forewarned is Forearmed Community of Practice seminar series, which brings together climate scientists and agricultural practitioners.

Despite extensive Covid-19 restrictions, this year has seen good progress against our research goals and also saw our research forge into the new territory of machine learning. A whole of Research Program goal of the Attribution and Risk team this year was to identify user-relevant metrics and indices of climate extremes. A small team led by postdoctoral researcher Yawen Shao has developed a database of currently used indices which will help identify gaps and coordinate metric development activities going forward. We outline progress against our two main goals, below.

PROJECT 1

How do the relative roles of large-scale, regional and local-scale processes and their interactions shape Australian extremes and govern their changes?

Significant progress has been made over this year in understanding changes in extremes as well as in evaluating these extremes in the latest Coupled Model Intercomparison Project - Phase 6 (CMIP6) simulations. A number of studies have focused on the relative importance and/or interaction between internal variability (e.g cut-off lows, jets, Rossby waves, El Niño--Southern Oscillation (ENSO), decadal variability) as well as anthropogenic climate change, helping to elucidate mechanisms through which the largest extremes can occur. We also found that Interdecadal Pacific Oscillation and ENSO phases, and the interaction between them, play significant roles in both determining the timing of extreme rainfall in Australia and constraining interannual variability. Several papers examined event attribution, including a collaboration with the Bureau of Meteorology describing an initialised attribution method for understanding recent extreme events.

PROJECT 2

Can machine learning/statistical approaches be used to improve the representation of scale interactions, processes and projection of the risk of extremes?

The Attribution and Risk program team has made several advances in the application of advanced statistics and machine learning techniques. Highlights for 2021 include Josh Li's honours thesis, which examines statistical and machine learning techniques for diagnosing errors in global model simulations of rapid ramp up and ramp down of precipitation. In addition, our new postdoctoral researcher Sanaa Hobeichi has developed a machine-learning-based technique for the analysis and prediction of drought impacts, based on the learned association of documented drought impacts and large- and local-scale drought related predictors. Major progress has also been made by postdoctoral researcher Yawen Shao and Chief Investigator Craig Bishop in the implementation of a new, multiplicative method for correcting systematic errors in the temporal variance of time series produced by climate models, without changing the temporal order of events. The technique has been applied to CMIP models for Melbourne, Sydney and Canberra. These time-scale-dependent multiplicative corrections of the variance result in time series that are subjectively more like observed time series, in addition to the corrected climate model time series having correlations from day to day which are much closer to that observed.

RESEARCH SNAPSHOTS

Pathways and Pitfalls in Extreme Attribution

The field of extreme event attribution – namely, the analysis of extreme weather and climate events to estimate the relative influence of different forcings caused by climate change – only began this century. However, the field has grown quickly in recent years and, as more studies have been performed, more lessons have been learnt about how to approach these studies and the traps to avoid.

A 2020 study takes the step-by-step approach to event attribution employed by the World Weather Attribution team. Choices taken at each step may affect the final outcome and its usefulness. Some of these issues include biases in the choice of events to study, characterisation of an event as meteorological-based or impact-based, the choice of observational and model data, evaluation techniques employed and the communication of results.

Overall, the 2020 study suggests that event attribution studies can be most useful when designed carefully to account for the methodological choices that can be made along the way.

van Oldenborgh, G.J., van der Wiel, K., Kew, S., Philip, S., Otto, F., Vautard, R., King, A., Lott, F., Arrighi, J., Singh, R., van Aalst, M., 2021. Pathways and pitfalls in extreme event attribution. *Climatic Change* 166, 13. https://doi.org/10.1007/s10584-021-03071-7

Evapotranspiration Shows an Increasing Trend Since 1980

Climate change is affecting the amount of water evaporating (from soils and surfaces) and transpiring (evaporating through plant leaves) from the land surface. Previous reports of trends in global evapotranspiration (the combination of evaporation and transpiration, ET) are, however, inconsistent, mainly owing to uncertainties in the estimates used to derive these trends.

This paper combines several existing ET products with field measurements of ET from global flux networks and derives two hybrid ET products using a weighting approach. Evaluation using independent field measurements showed that the new ET products, Derived Optimal Linear Combination Evapotranspiration - Version 2 (DOLCE V2) and DOLCE V3, match measurements more closely than any other assessed data set. ET trends show clear increases since 1980 over the majority of the Earth's surface.

Hobeichi, S., Abramowitz, G., Evans, J.P., 2021. Robust historical evapotranspiration trends across climate regimes. *Hydrology and Earth System Sciences* 25, 3855–3874. https://doi.org/10.5194/hess-25-3855-2021

New Global Land-Based Precipitation Data Set

Despite the importance of understanding the global water cycle, high quality long-term global rainfall data sets are hard to find. For this reason, we developed a new global land-based daily precipitation data set called Rainfall Estimates on a Gridded Network (REGEN), aimed at facilitating studies to understand changes and variability in several aspects of daily precipitation distributions, extremes and measures of hydrological intensity.

REGEN utilises multiple archives of in-situ data, including two of the largest archives, the Global Historical Climatology Network – Daily, hosted by the National Centers of Environmental Information, USA, and the archive hosted by the Global Precipitation Climatology Centre operated by Deutscher Wetterdienst.

This resulted in an unprecedented station density compared to existing data sets. The study documents the substantial quality control and the gridding of the data using advanced methods that was performed to cover the globe, while also providing guidelines for best practices for users.

Contractor, S., Donat, M.G., Alexander, L.V., Ziese, M., Meyer-Christoffer, A., Schneider, U., Rustemeier, E., Becker, A., Durre, I., Vose, R.S., 2020. Rainfall Estimates on a Gridded Network (REGEN) – a global land-based gridded dataset of daily precipitation from 1950 to 2016. *Hydrology and Earth System Sciences* 24, 919–943.
https://doi.org/10.5194/hess-24-919-2020

Drought Modulates Interactions between Heatwaves and Bushfire Fuels

Australia's so-called 'Black Summer' in 2019/2020 was characterised by intense heatwaves and deadly bushfires. While considerable effort has gone into trying to understand the physical processes behind these extreme events individually, there has been little on studying both concurrently.

This study considered the relationship between heatwaves and bushfire fuels by considering dead fine-fuel moisture content, a critical factor that regulates the intensity, spread rate and likelihood of profuse spotting of fires. Relationships were explored using statistical correlations between the frequency, duration, magnitude and amplitude of heatwaves and mean dead fine-fuel moisture content over south-east Australia in the peak heat and fire season.

While relationships varied among different heatwave characteristics and regions, the prolonged duration of a heatwave correlated well with fuel dryness around the south-eastern parts of the region, whereas the hotter heatwave season favoured the lower dead fine-fuel moisture content over the north-eastern parts. Results also suggest that dead fine-fuel moisture content is significantly decreased on heatwave days compared to non-heatwave days and that rainfall deficits can modulate the relationship between heatwaves and mean dead fine-fuel moisture content in some regions and seasons.

Jyoteeshkumar reddy, P., Sharples, J.J., Lewis, S.C., Perkins-Kirkpatrick, S.E., 2021. Modulating influence of drought on the synergy between heatwaves and dead fine fuel moisture content of bushfire fuels in the Southeast Australian region. *Weather and Climate Extremes* 31, 100300.
https://doi.org/10.1016/j.wace.2020.100300

ATTRIBUTION AND RISK 2022 STATEMENT OF INTENT

Whole of RP Activities	- A whole of RP workshop in first half of the year - Continue to develop metrics/indices work with the potential for a progress workshop with possible stakeholder engagement later in the year - Develop a strategy for making the best use of the Pacemaker experiments
PROJECT 1 **How do the relative roles of large-scale, regional and local-scale processes and their interactions shape Australian extremes, and govern their changes?**	- Start evaluating tropical to extratropical interactions in state-of-the-art models - Establish characteristics of Australian multi-year droughts and begin pacemaker experiments to identify individual oceanic sources causing multi-year droughts in Australia - Investigate the causes of anomalous long-term trends in observed precipitation extremes
PROJECT 2 **Can machine-learning/ statistical approaches be used to improve the representation of scale interactions, processes and projection of the risk of extremes?**	- Start developing machine-learning based approaches to characterising and predicting local scale extreme events, starting with hail prediction, and apply to model runs including multiscale ACCESS runs as a minimum - Develop machine learning downscaling methods as a benchmark for dynamical downscaling - Develop a machine learning based application to PLUMBER2 MIP - Further refine new multiplicative correction approach to create a set of CMIP-based projections that have much more realistic variances across a range of time scales and apply ensemble weighting to more accurately project and attribute climate extremes
Engagement Activities	- Engage with stakeholders in CLEX priority sectors to identify extreme indices of relevance to them - Open a dialogue with finance sector stakeholders on intended research avenues in machine learning - Contributions to CLEX communication activities around the release of the IPCC A6 Working Group II report - Contributions to a CLEX summary report "The state of weather and climate extremes in Australia in 2021" - Coordinate with the Drought Research Program to identify potential collaborations with relevant stakeholders focussed on the agriculture and water resources sectors. - Release a CLEX briefing note on compound events - Lead a workshop "Compound events in Australia – Strategic Planning for Multivariate Risk" involving researchers, industry and government and identify a selection of compound events of interest to an important sector

ECR PROFILE **DR MARGOT BADOR**

Tell us a little about your background, how did you get here? Like many French researchers, I have an engineering background. I always knew I wanted to do a PhD -- but not in hydrology, the focus of my studies in engineering school. I thus decided to take a break from my three-year engineering course to discover the reality of climate scientists in academia, through a nine-month internship. It confirmed my motivation for working in climate science. I validated my engineering diploma by doing a masters the next year, and continued my path to academia with a PhD on temperature extremes after that. During the course of my candidature, I met Lisa Alexander, who inspired me and is the reason I got here!

Tell us a little about your research. My main interest is in climate extremes (precipitation and temperature extremes, tropical cyclones, etc.), their variability, future changes and underlying physical mechanisms. My research relates to the global and regional climate response to increasing greenhouse gases, the influence of anthropogenic emissions and the role of natural climate variability in future changes. My work includes evaluating climate models and exploring the uncertainties associated with the use of multi-model ensembles and observational data sets. I also design model experiments and run regional atmospheric models to further diagnose the mechanisms responsible for climate extremes.

What opportunities has CLEX offered you? CLEX has given me the opportunity to strengthen my network locally, nationally and internationally. The Centre has offered me the chance to meet, learn and get feedback from specialists from diverse horizons. CLEX has also provided me with great working conditions and has been very supportive during this hard pandemic time.

What is your ideal next position? Or if you have already moved on from CLEX, where are you now? I have now moved into a permanent position as a CNRS researcher in France. I will continue exploring how climate extremes respond to anthropogenic emissions and will enjoy very much being a climate scientist!

RP3: DROUGHT

RESEARCH PROGRAM SUMMARY

Despite the challenges of another Covid-19-affected year, some great research progress has been made, and industry engagements have become a regular part of the Drought research program's work at the ARC Centre of Excellence for Climate Extremes (CLEX). Covid-19 led to the Drought program workshop being postponed three times in 2021. It is now scheduled to occur in 2022. The pandemic also led to some delays in hiring new postdoctoral researchers to the program, though by year's end we were pleased to have made offers to promising candidates.

The establishment of industry talks as part of the regular Drought program meetings meant a series of industry talks was delivered. Participants included Jon Welsh (Principal Climate Analyst & Research Economist at AgEcon), Jennifer Wurtzel (NSW Department of Primary Industries) and Elisabeth Vogel (Bureau of Meteorology). We also gave several talks to the Forewarned is Forearmed agriculture group, sharing various drought-related research findings relevant for agriculture. Further, the Intergovernmental Panel on Climate Change 6th Assessment Report, Working Group 1, was released this year, and it initiated an extended series of presentations on key findings in the report for the water industry. This included briefings given to the Water Services Association of Australia, Sydney Water and South Australia Water.

We also published some fantastic research. Droughts are rare, long-lasting events, and there aren't a lot of droughts in our historical record. So, it is great to see the history of Australian droughts being extended and the 1888 Centennial Drought added to our set of well-observed droughts. Other research examined the role of groundwater in maintaining vegetation function during drought. It demonstrated the key role this can play in lowering temperatures and therefore heat impacts on vegetation during drought.

Progress towards answering our Drought program research questions continues.

PROJECT 1

What determines the onset, persistence and termination of drought?

The role of climate modes such has El Niño-Southern Oscillation (ENSO) has been further examined, demonstrating its role in the onset and persistence of 19th century droughts, as well as demonstrating that the various ENSO types have similar impacts on the terrestrial carbon cycle. Further research has demonstrated that flash drought onset depends strongly on extreme precipitation deficits, while evaporation increases play a secondary role.

PROJECT 2

Why did the 2017 to 2020 drought in eastern Australia develop and what made it so impactful?

Research found some similarities between this recent drought and the 1888 Centennial Drought, demonstrating that the relative shortness of the historical record may overstate the uniqueness of each drought event. Further, groundwater appears to have played a key role in sustaining transpiration and easing plant heat pressure during the heatwaves that occurred during the 2017-2019 severe drought over south-east Australia.

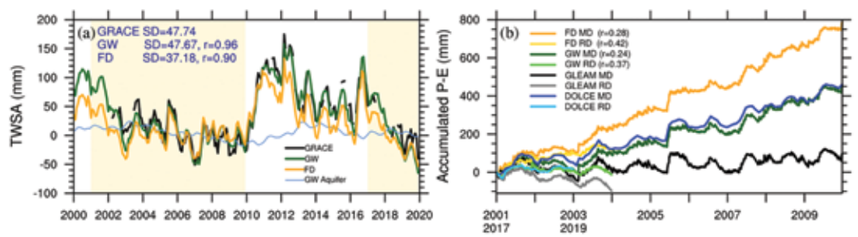


Figure above (a) Total water storage anomaly (TWSA) during 2000–2019 and (b) accumulated P–E for the two droughts over SE Australia. In panel (a), observations from GRACE are shown in black, the GW simulation in green, FD in orange, and the aquifer water storage anomaly in GW in blue. The shading in panel (a) highlights the two drought periods. The left top corner of panel (a) displays the correlation (r) between GRACE and GW/FD, as well as the standard deviation (SD, mm) of GRACE, GW, and FD over the periods when GRACE and the simulations coincide. Panel (b) shows the accumulated P–E for two periods; the dark lines show the 2001–2009 Millennium Drought (MD) and the light lines show the 2017–2019 recent drought (RD). The correlation (r) between the P and E is shown in the legend of panel (b).

RESEARCH SNAPSHOTS

Revisiting The 1888 Centennial Drought

'The earth was brown, the sky was blue,
No moisture fell, no drop of dew. ...
There a grey toad all parched and dead,
Stuck in a crack with blistered head'
Glenmaggie, 1888

Each drought has a different spatial and temporal footprint, so the more we can understand about past droughts, the better prepared we will be for future such events. To shed more light on short droughts of the past, CLEX researchers have taken advantage of a newly released data set from the Bureau of Meteorology to re-examine the infamous Centennial Drought of 1888. They analysed monthly rainfall variability across south-eastern Australia throughout 1888. They found declines occurred throughout the year, but particularly in April and early spring. The most severely affected regions were inland New South Wales and Victoria, as well as eastern Tasmania. The magnitude of the declines was similar to those observed in the recent drought (2017–2019), although not quite as severe as the devastating drought of 1982–83. They found that a strong El Niño event in the equatorial Pacific Ocean likely drove the strong declines seen in the second half of the year, while the precipitation pattern throughout the year was modulated by a positive phase of the Southern Annular Mode in the Southern Ocean. This case study adds the 1888 Centennial Drought to our growing library of key events in Australia's climate history, helping us understand the nature of our droughts and how they will change in a warmer world.

Ritman, M.E.H., Ashcroft, L.C., 2020. Revisiting the 1888 Centennial Drought. *Proceedings of the Royal Society of Victoria*. 132, 49–64. https://doi.org/10.1071/rs20004

Groundwater's Essential Role in Preserving Plant Transpiration During Drought

Groundwater buffers the negative impacts of droughts and heatwaves on ecosystems. However, most climate models do not represent groundwater dynamics and neglect its moderation effects, which undermines our confidence in the predicted impacts of future climate extremes. CLEX Drought Program researchers and colleagues used a land-surface model that considered groundwater dynamics to explain how groundwater sustains transpiration and eases plant heat pressure during the heatwaves that occurred during the Millennium Drought and the 2017-2019 severe drought over south-east Australia. The results show groundwater plays an essential role in helping vegetation maintain transpiration and reduces forest temperatures by up to 5°C during individual heatwaves, particularly where the water table depth is shallow. Nevertheless, the role of groundwater diminishes as the drought lengthens beyond two years and soil-water reserves are depleted. The lack of deep roots or the closure of stomata (tiny pores on leaves used for gas exchange) caused by dry air or high temperatures can also reduce the extra transpiration sustained by groundwater.

Mu, M., De Kauwe, M.G., Ukkola, A.M., Pitman, A.J., Guo, W., Hobeichi, S., Briggs, P.R., 2021. Exploring how groundwater buffers the influence of heatwaves on vegetation function during multi-year droughts. *Earth System Dynamics* 12, 919–938. https://doi.org/10.5194/esd-12-919-2021

Accuracy Of Ground and Satellite Measurements for Precipitation

The absence of ground observations in many parts of the world highlights the importance of satellite products for capturing precipitation. In this study, CLEX researchers evaluated the effect of different sources of data and the uncertainties in satellite data by comparing the data with a ground-based radar product, using both location-based and storm-based approaches. The results showed the satellite data had better agreement in terms of the average precipitation intensity and area. However, the satellite observations tended to show storms with smaller areas compared to the ground-based observations, possibly due to the effect of light precipitation not being detected properly. Satellite sensors are best at capturing observed storm characteristics: the average intensity of precipitation events, and precipitation area. Overall, storm characteristics viewed from satellites are similar enough to ground observations to recommend the use of satellite data more broadly.

Ayat, H., Evans, J.P., Behrangi, A., 2021. How do different sensors impact IMERG precipitation estimates during hurricane days? *Remote Sensing of Environment* 259, 112417. https://doi.org/10.1016/j.rse.2021.112417

El Niño Variations Have Little Impact on Terrestrial Carbon Cycle

The El Niño–Southern Oscillation (ENSO) describes changes in the sea surface temperature patterns of the tropical Pacific Ocean. This influences the global weather, affecting vegetation on land. However, there are two types of El Niño: the central Pacific El Niño and the eastern Pacific El Niño. CLEX researchers explored the long-term effects on the carbon balance on land linked to these two El Niño types. Using a dynamic vegetation model, we simulated what would happen if only either a Central Pacific or Easter Pacific El Niño event occurred. We found that the different expressions of El Niño do affect interannual variability in the terrestrial carbon cycle. However, the effect over longer timescales was small. This means the changing frequency of these two types of El Niño events may be of little importance in terms of robustly simulating the future terrestrial carbon cycle.

Teckentrup, L., De Kauwe, M.G., Pitman, A.J., Smith, B., 2021. Examining the sensitivity of the terrestrial carbon cycle to the expression of El Niño. *Biogeosciences* 18, 2181–2203. https://doi.org/10.5194/bg-18-2181-2021

What Generates Flash Droughts in Climate Models?

Flash drought is a type of drought that is characterised by a rapid onset and intensification and with substantial impacts on agriculture. Direct soil-moisture measurements are rarely employed in drought indices because in-situ soil-moisture observations are sparse in space and time. Instead, proxies that reflect moisture supply and demand, such as precipitation and evaporation, are commonly used. Until now, flash drought research has been on the regional scale and has been limited to observations and reanalyses. CLEX Drought Program researchers have been the first to examine flash drought in climate models. Specifically, we have examined how climate models simulate flash drought and how models represent flash drought processes to allow for assessment in a changing climate. The work compares the skill of drought indices based on precipitation, evaporative demand, and a combination of evaporative demand and actual evaporation for flash drought early detection on a global scale. The results show that all drought indices show a higher frequency of flash drought events, particularly those based on precipitation or evaporative demand alone compared to the models' soil moisture. Precipitation deficits are the main contributor to flash drought in climate models, with evaporation playing a secondary role. However, an overestimation of evaporative demand in some models causes significant inter-model disagreement, reflecting differences in the representation of land-atmosphere interactions.

Hoffmann, D., Gallant, A.J.E., Hobbins, M., 2021. Flash Drought in CMIP5 Models. *Journal of Hydrometeorology* 22, 1439–1454. https://doi.org/10.1175/JHM-D-20-0262.1

CLIMATE CHANGE LEADERSHIP FORUM

In November, Chief Investigators Nerilie Abram and Jason Evans were invited to brief the Sydney Water Climate Change Leadership Forum on the latest findings of the Intergovernmental Panel on Climate Change. The event was attended by more than 300 leaders in the water industry, and their briefing received praise for the clarity and accessibility of the information presented, which was vital to the success of the forum. Sydney Water is an organisation that is building climate change awareness for its workforce - and for its customers, with whom they need to engage about the adaptations that will be necessary for water services in a warming world. This is just one example of the many industry briefings given by Nerilie and Jason to the water services sector in 2021. In 2022 we look forward to building on this engagement, including through having representatives of Sydney Water given an industry talk at one of our upcoming Drought program meetings.

DROUGHT STATEMENT OF INTENT 2022

Whole of RP Activities	- Publish ACCESS-ESM1.5 last millennium simulation to CMIP6 - Design and run pacemaker experiments across the drought program and attribution and risk program
Project 1 Activities **What determines the onset, persistence and termination of drought?**	- Compare characteristics of recent droughts with natural variability over the last millennium - Determine the changing frequency of drought-promoting combinations of compound climate variability - Assess individual roles of ocean and atmosphere variability in causing droughts
Project 2 Activities **Why did the 2017 to 2020 drought in eastern Australia develop and what made it so impactful?**	- Conduct a detailed examination of the 2017-2020 drought, how vegetation responded, and the context compared to droughts in extended historical observations. - Assess changes in the intensity and frequency of fire-weather producing cold fronts over southeast Australia, including during the 2019/20 Black Summer - Improve CABLE model representations of hydrological and vegetations processes during extended dry periods.
Engagement Activities	- Regular industry and government engagement in drought RP meetings and workshop - Communication of drought-related findings around the release of the IPCC WGII assessment report - Identification of collaborations with stakeholders focussed on the agriculture and water resources sectors.

ECR PROFILE **DR ANJANA DEVANAND**

Tell us a little about your background, how did you get here? I am a hydrologist by training and I am interested in understanding changes in the water cycle and water availability on regional scales. I received my PhD from the Indian Institute of Technology, Bombay, India, working on understanding the influence of land processes on the Indian Summer Monsoon rainfall. I have also worked on various projects to understand the climate feedback of land-use land-cover changes, as well as to assess climate risks on water resources systems. At the Centre of Excellence for Climate Extremes, I am part of the Drought program project focusing on improved regional simulations of droughts.

Tell us a little about your project Currently, I am looking at events that break soil-moisture droughts in historical data sets to estimate the probability of such events under ambient local- and large-scale climate conditions. In the future, I'll work on regional simulations of the recent drought event in south-east Australia and work on improving the simulation of droughts in land models.

What opportunities has the Centre of Excellence offered you? The Centre offers me an excellent research environment, computational facilities and the opportunity to collaborate with top researchers in the field. The Centre also provides me the opportunity to attend seminars/training sessions and provides guidance on ways to strengthen my profile for a research career.

What are your longer-term career hopes or plans? I want to pursue a career doing research either in academia or in an organisation like CSIRO/Bureau of Meteorology.

RP4: OCEAN EXTREMES

RESEARCH PROGRAM SUMMARY

The Ocean Extremes research program at the ARC Centre of Excellence for Climate Extremes (CLEX) published a range of groundbreaking research keenly focused on our three research projects and posted a significant increase in our interactions with policymakers and industry in 2021.

We have had a number of striking papers published. Some, like the paper that explored a massive phytoplankton bloom in the South Pacific, generated significant media coverage, while others had smaller media impact but a profound impact on our understanding of ocean processes and the science itself. As an example, research published in *Nature Climate Change* found for the first time that ocean eddies were reorganising in a warmer world, which has significant effects on mixing and transport of heat, carbon, biota and nutrients, with implications for climate and fisheries. While not specifically aligned to one of our three primary goals, this research has an impact on all of them.

On October 19 and 20, 2021, students, researchers and stakeholders of the Ocean Extremes program gathered in Hobart and over Zoom to hold the first Ocean Extremes program workshop. The main objectives of the workshop were to get the Ocean Extremes team together; share current research, and outline where it is going; facilitate collaborations in and around CLEX; and foster dialogue with key marine stakeholders to better understand their concerns and needs. The workshop consisted of four key components: an opening session, science talks, stakeholder panel discussions and a closing discussion. Invited stakeholder representatives were from the Tasmanian Government Department of Premier and Cabinet (Tasmanian Climate Change Office), the insurance sector (Deloitte), industry partners (Shellfish Market Access Program, ShellMAP) and academia (Institute for Marine and Antarctic Studies, UTAS).

PROJECT 1

Marine heatwaves: How can we best model and predict marine heatwaves?

CLEX Ocean Extremes researchers have developed a new catalogue of marine heatwave (MHW) metrics and trends for the Australian region as well as a global multiproduct of coastal MHWs, which will provide valuable data sets against which to test model hindcasts (back predictions). Researchers have also analysed modelled climate change projections of MHWs across the tropical western and central Pacific Islands region to better understand potential impacts on communities in the future. New insights have been gained into the processes that produce shallow MHWs that led to bleaching events over the Great Barrier Reef during cool La Niña periods, which will help forecast these events in the short term. Looking to the longer term, a high-resolution model investigation of MHWs around Australia and New Zealand has revealed how climate change will alter local hotspots, showing warming impacts by the East Australian Current, around Tasmania and the waters close to New Zealand.

PROJECT 2

Mesoscale ocean processes: How do MHWs interact with other climate extremes?

There have been significant advances in this project. Highlights from 2021 include a comprehensive review of Indian Ocean systems and interactions, which is foundational to understanding the processes that generate ocean extremes; a paper highlighting the future impacts of warmer oceans on Antarctica; and another paper examining the processes in a warmer world that lead to amplification effects in certain areas that create marine heatwave hotspots here and around the world.

PROJECT 3

Biogeochemistry: What are the current and future roles of mesoscale physics and biogeochemistry in the climate system?

As noted in the introduction, the Australian bushfires served up a perfect example of the connections between land and ocean extremes. Ash and dust from the fires produced an enormous phytoplankton bloom out-of-season in the Southern Ocean, but two other papers have also explored how changes already occurring in the Northern Hemisphere could be a precursor of what is to come in Antarctica. As ice retreats around the Arctic, primary production has altered, with a range of winners and losers. Some biota are expected to thrive in an environment with less ice and more light, but with that additional growth comes a need for more nutrients, something that requires further exploration for Antarctica.

RESEARCH SNAPSHOTS

Changing Eddies Reorganise Ocean Energy

In a world-first, CLEX researchers revealed that ocean eddies – whirlpools with sizes between 10 and 100 kilometres – are becoming more energetic over large regions of the ocean. These eddies move and mix heat, carbon, salt and nutrients and affect everything from regional processes right up to the global ocean circulation. The researchers used satellite data from 1993 to analyse changes in the strength of the eddies over the whole globe. They found a significant increase in eddy strength over the Southern Ocean, and significant changes in eddy activity over the boundary currents such as the Gulf Stream and the East Australian Current. These findings have far-reaching implications for climate and fisheries.

Martínez-Moreno, J., Hogg, A.M., England, M.H. et al. Global changes in oceanic mesoscale currents over the satellite altimetry record. *Nature Climate Change* 11, 397–403 (2021). https://doi.org/10.1038/s41558-021-01006-9

Australian Bushfires Spawn Massive Phytoplankton Bloom

CLEX researchers and colleagues found that smoke from the 2019-20 bushfires produced a phytoplankton bloom larger in area than all of Australia, thousands of kilometres away in the Southern Ocean. The vast aerosol plumes created by the bushfires reached altitudes of 16 km and changed stratospheric winds, transporting the smoke to the Southern Ocean. The researchers estimate it deposited three times more iron into the ocean than is normally found there. Rapid phytoplankton growth can absorb carbon dioxide as part of the photosynthetic process. This bloom removed significant amounts of CO2, roughly equivalent to that released by the fires. However, it was impossible to determine if the carbon descended into the deep ocean – a necessary condition for it to have a permanent climate impact.

Tang, W., Llort, J., Weis, J. et al. Widespread phytoplankton blooms triggered by 2019–2020 Australian wildfires. *Nature* 597, 370–375 (2021). https://doi.org/10.1038/s41586-021-03805-8

Projected Marine Heatwave Futures for Pacific Island Nations

This paper investigates MHWs in the tropical western and central Pacific Ocean region, focusing on observations, associated impacts, and future projections using Coupled Model Intercomparison Project – Phase 6 (CMIP6) simulations under a low (SP1-2.6) and a high (SSP5-8.5) greenhouse-gas scenario. Documented impacts from "moderate" mean-intensity events in Fiji, Samoa and Palau, which were categorised as "strong" at their peak, included fish and invertebrate mortality and coral bleaching. While "extreme" category events occur less than one day per year in the present climate, they are projected to occur more than 50 days per year under the high-emissions scenario and less than five days per year under the low scenario.

Holbrook, N. J., V. Hernaman, S. Koshiba, J. Lako, J. B. Kajtar, P. Amosa, A. Singh (2021). Impacts of marine heatwaves on tropical western and central Pacific Island nations and their communities. *Global and Planetary Change*, 208, 103680, https://doi.org/10.1016/j.gloplacha.2021.103680.

Changing Currents

Western Boundary Currents are important for the climate system, moving large amounts of heat and marine organisms. CLEX researchers looked at the ability of climate models to simulate these critical currents and how they are projected to change in the future. They found that the East Australian Current, Brazil Current and Agulhas Current extensions are due to intensify, while the Gulf Stream, Indonesian Throughflow and Agulhas Current are projected to weaken. For many, the changes are linked to the winds. The south-east coast of Australia is expected to experience some of the most dramatic changes.

Sen Gupta, A., A. Stellema, G. M. Pontes, A. S. Taschetto, A. Vergés, and V. Rossi, (2021) Future changes to the upper ocean Western Boundary Currents across two generations of climate models. *Scientific Reports*, 11, 9538, https://doi.org/10.1038/s41598-021-88934-w.

Sunny Days Power Shallow Marine Heatwaves

Coral bleaching events have been reported over the Great Barrier Reef during cool La Niña events, when sea-surface temperatures may be cooler than normal. CLEX researchers found the sea-surface temperature anomaly over the Great Barrier Reef is more highly correlated with local cloud cover than with El Niño--Southern Oscillation. This significant relationship can be found over two-thirds of the study area even when the El Niño–Southern Oscillation impact is ignored. This indicates local-scale reduced cloud cover plays an important role in regional shallow water warming over the Great Barrier Reef, regardless of large-scale El Niños.

Zhao, W., Huang, Y., Siems, S., & Manton, M. (2021). The role of clouds in coral bleaching events over the Great Barrier Reef. *Geophysical Research Letters*, 48, e2021GL093936. https://doi.org/10.1029/2021GL093936

Antarctic Ocean Warming Doubles Under High-Emission Scenarios

Ocean warming around the Antarctic coast plays a critical role in melting ice shelves. Understanding changes in this warming is critical to determine future changes in ice shelves and ice sheets. CLEX researchers assessed average ocean temperature and trends around the Antarctic margin using coupled climate models. The projections suggest the ocean around Antarctica will warm under future emission scenarios, with the level of warming under the high-emission scenario almost double that under the medium-low emission scenario. The projected warming around Antarctica is due to wind-driven circulation changes, as well as ocean warming to the north of coastal regions.

Purich, A., & England, M. H. (2021). Historical and future projected warming of Antarctic Shelf Bottom Water in CMIP6 models. *Geophysical Research Letters*, 48, e2021GL092752. https://doi.org/10.1029/2021GL092752

How Internal Waves Drive Mixing in the Southern Ocean

Internal waves, as their name suggests, travel in the ocean interior, sometimes propagating great distances before they break. Major gaps exist in our understanding of the pathways between the generation and the breaking of internal waves in the Southern Ocean. This has important implications for the distribution of internal wave-driven turbulent mixing and the representation of ocean mixing in numerical models. CLEX researchers used observations of internal waves from a turbulent mixing hotspot in the Southern Ocean to identify and characterise internal waves and the background environment. They found the Antarctic Circumpolar Current strongly influences the life cycle of internal waves. This suggests it is important to represent mesoscale flow impacts when parameterizing internal wave-driven mixing in the Southern Ocean.

Waterman, S., Meyer, A., Polzin, K. L., Naveira Garabato, A. C., & Sheen, K. L. (2021). Antarctic circumpolar current impacts on internal wave life cycles. *Geophysical Research Letters*, 48, e2020GL089471. https://doi.org/10.1029/2020GL089471

Warmer Oceans Amplify Length and Frequency of Coastal Marine Heatwaves

There are few marine heatwave studies in coastal areas. In this study, CLEX Ocean Extremes program researchers used four global satellite data sets of sea surface temperature to estimate marine heatwave characteristics and long-term changes to coastal heatwaves over 25 years. Hotspots were concentrated along the Mediterranean Sea, Japan Sea, south-eastern Australia, and the north-eastern United States. The frequency of marine heatwaves and duration globally increased by one to two events per decade and 5–20 days per decade. The main driver was long-term changes in sea-surface temperatures. In some regions, like the south-eastern Pacific coast, long-term changes in marine heatwaves were driven by the local variability of the climate system.

Marin, M., Feng, M., Phillips, H. E., & Bindoff, N. L. (2021). A global, multiproduct analysis of coastal marine heatwaves: Distribution, characteristics and long-term trends. *Journal of Geophysical Research: Oceans*, 126, e2020JC016708. https://doi.org/10.1029/2020JC016708

THE IPCC SIXTH WG1 ASSESSMENT REPORT: WHAT DOES IT MEAN FOR TASMANIA?

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) --Working Group 1 (WG1) report, released this year, gave us a particular moment to share our research and expertise. Members of the Ocean Extremes research program presented special briefings to the Tasmanian Government Premier's Office at Parliament House; Federal Shadow Minister of Environment, Terri Butler; the Tasmanian leader of the Opposition, Rebecca White; Tasmanian Greens MPs Cassy O'Connor and Rosalie Woodruff; the Tasmanian Legislative Council; and University of Tasmania staff and students.
This was in addition to a number of other engagements we have had with industry, particularly fisheries groups.

Figure above: UTAS Cls Holbrook, Meyer and Strutton briefed Tasmanian Premier Peter Gutwein and Environment Minister Roger Jaensch

Based on the IPCC AR6 WG1 report and a review of work undertaken by researchers in Tasmania, CLEX researchers outlined a climate-risk outlook for Tasmania: Tasmania, with its cool temperate climate, is relatively well placed to adapt to the impacts of global warming. Nonetheless, detailed downscaled modelling undertaken by Climate Futures and the Fire Centre Research Hub at the University of Tasmania, as well as other research groups, has identified significant state-level risks, including the ongoing and escalating bushfire risk (see below). These risks are broadly consistent with the global trends as described by the IPCC AR6 WGI report but are mediated by local geographic and social factors.

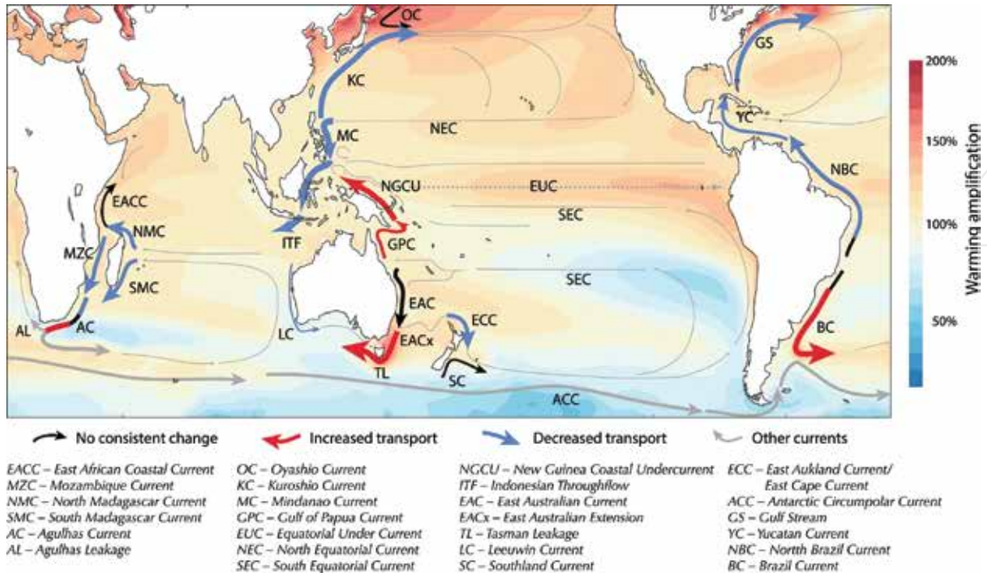


Figure above: Schematic showing projected changes in WBC transport. Background colours show the multi-model mean projected change in sea surface temperature divided by the global mean change, e.g. 150% implies a warming rate 1.5 x the global average.

OCEAN EXTREMES RESEARCH PROGRAM 2022 STATEMENT OF INTENT

Whole of RP Activities	- Run ACCESS 0.1° ocean model with biogeochemistry (ACCESS-OM2-01-BGC) for ~60 years, 1958-present *[link with RP Modelling]*. - Investigate ocean mesoscale features in observations and models *[link with RP Modelling]*. - Investigate marine heatwaves at selected case study regions around Australia based on the ACCESS-OM2 interannual forced (IAF) simulations *[link with RP Modelling]*.
PROJECT 1 ***How can we best model and predict marine heatwaves?***	- Explore Lagrangian frameworks to understand marine heatwave processes and predictability *[link with RP Modelling]*. - Investigate mesoscale features as sources of marine heatwaves and their predictability. - Examine marine heatwave predictability using a linear approach (e.g. linear inverse model).
PROJECT 2 ***What are the current and future roles of mesoscale physics and biogeochemistry in the climate system?***	- Characteristics of Southern Ocean dynamics (processes, eddies, fronts, meanders…) and impacts on associated systems (sea ice predictability and trends, marine ecosystems, marine biodiversity…). - 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]*. - Build on our analysis of satellite and biogeochemical Argo data to incorporate data products such as OFAM, B-SOSE and GO-SHIP, for analysis of seasonal, interannual and mesoscale variability *[link with RP AR]*.
Engagement	- 2022 Annual Ocean Extremes workshop involving key ocean extremes stakeholders. - IPCC AR6 WGII response team to follow up the release of the report. - State of Climate Extremes 2021 Report (to be released in March 2022) – CLEX postdoctoral fellows contributions.

ECR PROFILE **DR JULES KAJTAR, UTAS**

I have had a fairly atypical research career. My passion during my undergraduate years was for astrophysics. I did an honours project on developing a new approach to numerically solving the Einstein field equations for general relativity. This work continued into my PhD, but it was coupled with an almost entirely unrelated topic: the modelling of swimming fish, using a Lagrangian approach to computational fluid dynamics. I therefore ended up with a PhD thesis in two halves. After my first postdoc, continuing in fluid dynamics, I then joined UNSW for my first climate science appointment, studying climate variability. I spent some time in Exeter in the UK, before returning to Australia and joining CLEX.

In my current position with UTAS, my research will focus on developing Lagrangian frameworks for understanding marine heatwave processes and predictability. The three-year appointment will provide a good opportunity for me to solidify my career in climate science. My hope is that it will set me up for an ongoing position, somewhere in Australia or abroad.

My research focuses on the processes that lead to marine heatwaves, such as the event that occurred off north-west Australia in the summer of 2020/21. Understanding the drivers of marine heatwaves can help to improve predictability.

UNDERPINNING CAPABILITY: MODELLING

Numerical models of the weather and climate system are our primary means of predicting future states. The Modelling research program aims to develop improved simulations tools and procedures, thereby enabling research in all research programs across the ARC Centre of Excellence for Climate Extremes (CLEX).

PROJECT 1
Global Coupled Modelling
This project is conducted in collaboration with our partners at CSIRO, and involves the preparation and delivery of a higher resolution version of the ACCESS-CM2 climate model. The first steps in this development were taken this year, using a prototype model which upgrades the ocean component of the Australian Community Climate and Earth System Simulator-- Computational Modelling Systems 2 to eddy-permitting (0.25°). A preliminary present-day simulation is in progress, with a view to undertaking new science with the model in 2022.

PROJECT 2
Atmospheric Regional Modelling
Postdoctoral researchers to work on this program are appointed to commence early 2022. In the meantime, there has been ongoing work analysing the AUS400 results to examine small-scale features like storms, fronts and waves -- something that would be unresolved in coarser-resolution models. A a paper on this is planned for 2022.

PROJECT 3
Land-surface Modelling
Work continues towards a merged Community Atmosphere-Biosphere Land Exchange (CABLE) and Joint UK Land Environment Simulator modelling and benchmarking environment, although several personnel changes have slowed progress a little. A replacement for Martin De Kauwe to work on science side development is pending; Nic Hannah recently moved on from his role developing modelevaluation.org (once again, replacement pending); and we welcome Ramzi Kutteh as the Computational Modelling System team's new appointment to focus on CABLE development. Despite the changes, our partners at the UK Met Office, ACCESS R and CLEX CIs remain committed to shared resource development for the land surface modelling community.

RESEARCH SNAPSHOTS

Can The Ocean's Intrinsic Dynamics Feed Back On The Atmosphere?
The atmosphere and ocean are coupled through air-sea interactions. It is well understood that the ocean's circulation is fuelled by the atmosphere, with the winds and storms at the surface of the ocean imparting momentum to the ocean, driving ocean currents and eddies.

To better understand the changing climate we must grasp how the atmosphere and ocean vary at decadal time scales; we refer to variability at those time scales as "low-frequency variability".

The ocean's much larger heat capacity acts as "memory", suppressing the atmosphere's "high-frequency variability" (over time scales of weeks) while producing oceanic motions that vary over longer time scales. This paradigm aims to explain how low-frequency variability emerges in the ocean. But, recently, this paradigm has been challenged.

CLEX Researchers **Navid Constantinou** and **Andy Hogg** set out to ask the following questions:

- Can the ocean's intrinsic dynamics *alone* lead to large-scale patterns of upper-ocean heat flux that vary at decadal time scales?
- And, if so, are these ocean-generated patterns of upper-ocean heat flux large enough to potentially feed back into the atmosphere and affect the climate?

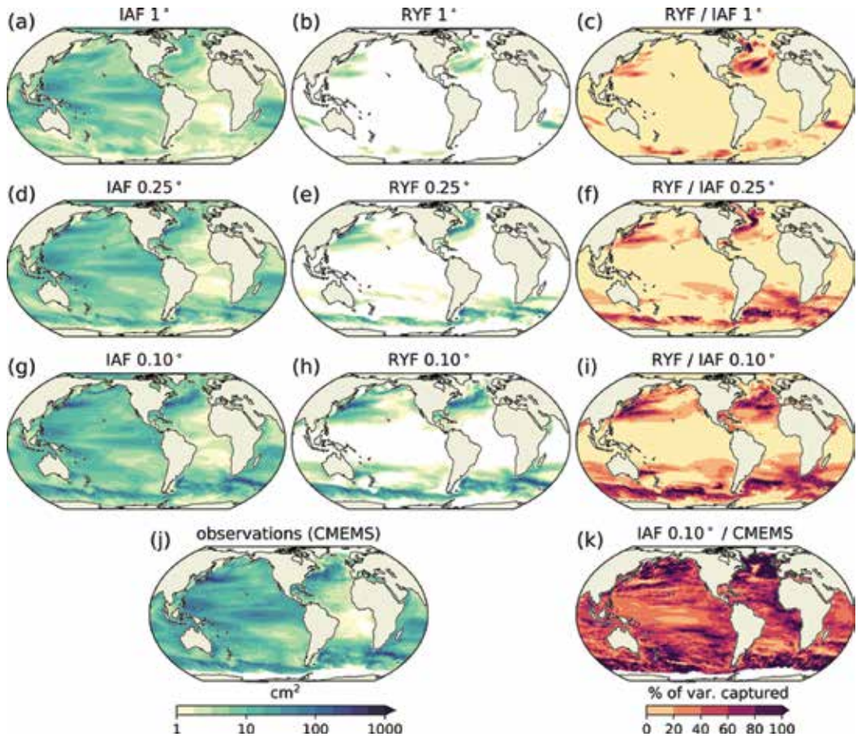


Figure (above): The total and the ocean-intrinsic component of the low-frequency variability of sea-surface height at three different horizontal resolutions. The sea-surface height is a good indicator of the upper-ocean heat content but with the additional advantage that we can compare with satellite altimetry observations.

The researchers used output from a global ocean-sea ice model to answer these questions. They found that models that resolve rather than parameterize eddies produce more variance of upper-ocean heat content at decadal time scales, with very different spatial patterns that vary at longer time scales.

The researchers found through this process that an ocean that resolves eddies shows upper-ocean heat-content patterns that vary at time scales that seem to match those of the various climate modes of variability (El Niño, Interdecadal Pacific Oscillation, North Atlantic Oscillation, etc). This raises the follow-up question: Could ocean eddies somehow be responsible for triggering these climate modes of variability?

Constantinou, N.C., Hogg, A.M., 2021. Intrinsic Oceanic Decadal Variability of Upper-Ocean Heat Content. *Journal of Climate* 34, 6175–6189. https://doi.org/10.1175/JCLI-D-20-0962.1

Extreme Events in South-East Australia To Increase In Frequency By 2100

Results of our research showed an increase in the frequency of extreme conditions across the majority of south-east Australia by the end of the 21st century. This was true for all of the different types of extremes considered but was especially conclusive for heat extremes and for conditions conducive to thunderstorms. South-east Australian capital cities showed increases in the frequency of multiple different types of climate extreme. Several cities were projected to experience some extremes more than six times more frequently at the end of the century than under current climate conditions. We used statistical techniques to investigate changes in extreme climate events that currently occur, on average, only once every 20 years. These techniques are applied to data related to heat, rainfall, drought and conditions conducive to bushfires and thunderstorms. The data were from detailed climate modelling commissioned by the NSW and ACT Governments. The study is an exemplar of the use of detailed climate modelling to assess future changes in potentially damaging climate extremes, providing information relevant to planning for managing future climate risks.

Herold, N., Downes, S.M., Gross, M.H., Ji, F., Nishant, N., Macadam, I., Ridder, N.N., Beyer, K., 2021. Projected changes in the frequency of climate extremes over southeast Australia. *Environmental Research Communications. 3*, 011001. https://doi.org/10.1088/2515-7620/abe6b1

Southern Ocean Overturning Circulation Responds to the Southern Annular Mode

The Southern Ocean has accounted for the vast majority of the global ocean heat uptake since the early 2000s. The atmospheric winds over the Southern Ocean play a leading role in its ability to uptake heat, by way of driving much of the Southern Ocean circulation.

Observations of these winds indicate that they have been steadily changing over the past few decades, and hence, so too is the Southern Ocean heat uptake. However, despite recent research efforts, the details of the Southern Ocean's response to these changing winds remain uncertain.

CLEX researchers introduced a novel methodology to examine the Southern Ocean's response to changing winds. They performed numerical simulations with a global ocean-sea ice model suite that spans a hierarchy of spatial resolutions and is driven by realistic atmospheric forcing conditions.

The initial response of the Southern Ocean circulation to changes in winds is robust across the model suite and insensitive to model resolution; longer-term response, however, depends on the representation of eddies in the model.

Stewart, K.D., Hogg, A.M., England, M.H., Waugh, D.W., 2020. Response of the Southern Ocean Overturning Circulation to Extreme Southern Annular Mode Conditions. *Geophysical Research Letters* 47, e2020GL091103. https://doi.org/10.1029/2020GL091103

NEW JULIA PACKAGE SOLVES GEOPHYSICAL FLUID DYNAMICS PROBLEMS

Often our understanding of physical processes comes from idealised configurations rather than from inspecting the output of realistic (and complicated) general circulation or Earth system models.

In atmospheric and oceanic fluid dynamics, simple conceptual models that capture the essence of certain physics have helped improve our understanding of certain processes and also have helped push the boundaries of the field. In teaching, conceptual models often give students a vivid visual representation of certain phenomena and the concepts the equations are describing. Such simple conceptual models are, for example, two-dimensional turbulence, quasi-geostrophic flow on a beta-plane, Phillips model of baroclinic instability, two-dimensional Rayleigh-Benard convection between parallel plates, and more.

People often code up these simple models to solve them on a computer. Sometimes they publish their codes on their personal websites. However, often these codes come without any form of documentation. Understanding somebody's code without documentation is usually much harder than coding up your own version from scratch. This is one reason why we often see people rewrite code to accomplish something that many others have already established.

With this in mind, CLEX researcher Dr Navid Constantinou and collaborators developed GeophysicalFlows.jl, a Julia package that provides solvers for geophysical fluid dynamics problems in periodic domains. Currently, the package includes solvers for two-dimensional turbulence, barotropic or equivalent barotropic quasi-geostrophic flows, surface quasi-geostrophic flows and multi-layer quasi-geostrophic flows. All modules are well documented and include continuous integration of both simple unit tests and physics-specific tests for each module. The examples in the package's documentation demonstrate how users can easily set up, customise, solve and produce animations for the model of their choice. Some tutorials even demonstrate how users can code up a solver for a partial differential equation of their liking.

GeophysicalFlows.jl is written in Julia, a free, open-source programming language that has been gaining in popularity. Julia is designed with scientific computing in mind – it can be as fast as C but as user-friendly as Python. Julia aims to solve the "two-language problem", i.e., the fact that we often run models in Fortran and analyse output using Python or Matlab. Furthermore, Julia's functionality enables all modules within GeophysicalFlows.jl to run seamlessly on both CPUs and GPUs – something extremely useful, given the recent rise of machine-learning applications in atmospheric and oceanic sciences.

It is said that a picture is worth a thousand words. If an animation is worth a thousand pictures, then animations may be worth around a million words. For scientists, the ability to visualise solutions of particular models with ease while, at the same time, also being able to change parameter values and rerun the simulation is priceless. We can learn so much simply by looking… even before we start quantifying.

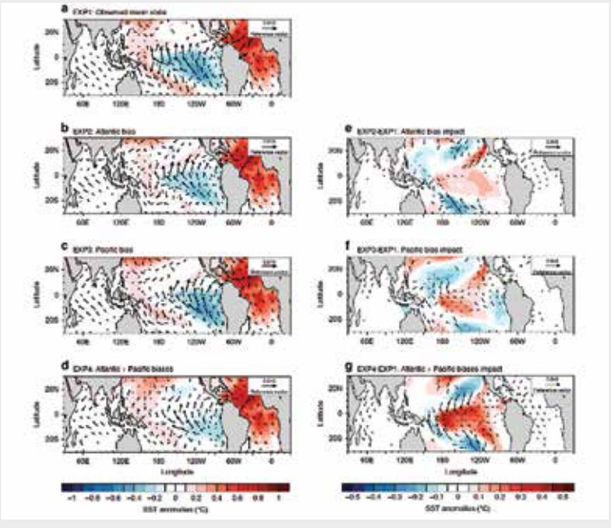
MODELLING CAPABILITY 2022 STATEMENT OF INTENT

Global Coupled Modelling	- Run long present-day control with ACCESS-CM2-025, and investigate effect of ocean resolution on global climate variability. - Run ACCESS 0.1° ocean model with biogeochemistry (ACCESS-OM2-01-BGC) for ~60 years, 1958-present *[link with Ocean Extremes RP]*.
Atmospheric Regional Modelling	- 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.
Land-surface Modelling	- Continued joint development of JULES-and-CABLE (JaC) modelling framework and benchmarking platform (modelevaluation.org) with the UK Met Office
Engagement Activities	- Act as point of liaison between the developing ACCESS-NRI initiative and CLEX.

ECR PROFILE **DR CHEN LI, MONASH UNIVERSITY**

Tell us a little about your background, how did you get here? I finished my PhD at Chinese Academy of Sciences in 2017. During my PhD, I received a scholarship to support me to study at the Bureau of Meteorology for one year. I greatly enjoyed the Australian climate research environment and aimed to start my research career in Australia. Luckily, CLEX released a few postdoc positions in 2017. I applied for the one that matched my research interest, which is focused on climate model development.

Tell us a little about your research. My postdoc project is focused on introducing corrections schemes into the ACCESS model to control the model mean state, then using the model simulations to understand the role of the simulated mean state in representing the climate variability (See Figure). During this project, I successfully modified the UM code to correct the land surface temperature through flux adjustment. I also introduced a new subroutine into the atmospheric model to adjust the air temperature. Furthermore, I contributed to the development of the computing-efficient ACCESS-CM2 N48 global coupled model.



What opportunities has CLEX offered you? CLEX has provided me the best possibilities to meet and discuss with climate researchers across Australia. The Centre also encourages and supports its researchers to attend various domestic/international conferences, meetings and seminars.

What is your ideal next position? Or if you have already moved on from CLEX, where are you now? I will start a new position at the Bureau of Meteorology in early 2022, working in the coupled-modelling team. My postdoctoral experience at CLEX has provided me a strong competitiveness in applying for this new position.

Figure: The important role of the simulated SST mean state in representing the observed Atlantic-Pacific teleconnection. From Li et al. 2020, Nature Communications

COMPUTATIONAL MODELLING SYSTEMS

The year 2021 was punctuated by staff changes. First, Danny Eisenberg left to pursue other interests and was replaced by Annette Hirsch, who then found an ongoing position and left the ARC Centre of Excellence for Climate Extremes (CLEX) in July. Annette is now replaced by Ramzi Kutteh, who will start in February 2022.

As everyone had to, we wove our way through Covid-19-related complications, such as home schooling, lack of socialisation, inability to travel for our annual Computational Modelling Systems (CMS) meeting and to visit nodes. Despite all of this, we achieved significant goals in climate model development, strengthening our data management practices and delivery of data analysis tools and data sets to the climate science community. We also started a collaborative process across climate-focused institutions to tackle sector-wide issues around climate data.

A major achievement of the year was the release of the Community Atmosphere-Biosphere Land Exchange--Weather Research Forecasting (CABLE-WRF) model, a regional land-atmosphere model that enables regional simulations at high spatial resolution with representation of the land carbon cycle. We have also continued to participate in the Joint UK Land Environment Simulator (JULES)-and-CABLE (JAC) project and have updated the CABLE benchmarking system based on the PLUMBER2 data set and modelevaluation.org.

In other climate model developments, we have worked on several aspects of the Australian Community Climate and Earth System Simulator (ACCESS) climate model. We continue to support the Modular Ocean Model - 5 (MOM5) community ocean model. Holger Wolff and Scott Wales delivered three new ACCESS-ESM 1.5 model configurations to our researchers. We also contributed to developing higher-resolution models. Aidan Heerdegen collaborated on the development of ACCESS-CM2-025: a model based on ACCESS-CM2 with a higher resolution eddy-permitting configuration of the ocean model. Scott did some preliminary work towards using the ACCESS atmospheric model, at much higher resolution, focusing on identifying simpler schemes for some computationally expensive atmospheric processes. Some climate research does not require detailed schemes for these atmospheric processes. This work would then benefit such research by allowing longer or more simulations to be performed.

We have continued to strengthen our data management practices for CLEX's data and software. In particular, in collaboration with Denisse Fierro Arcos, a CLEX PhD student, we have launched the CLEX Code Collection and the CLEX Data Collection to present all data and software published by CLEX on a common portal.

Following an idea of our data manager, Paola Petrelli, four community-led working groups have been created to develop practical solutions to current accessibility issues of climate data. Members of these groups come from varied institutions and industry.

Finally, we have assisted our researchers with their data analyses via improvements to the Consortium for Ocean Sea Ice Modelling in Australia (COSIMA) Cookbook; the development and publication of the xMHW software for the detection and analysis of marine heatwaves in ocean model data; and the automatic calculation of climate indices on large data sets, via the Climpact software. We continued to maintain and expand a suite of Python packages for data analysis and we revitalised our training offering.

HIGHLIGHTS

New land-atmosphere model: CABLE-NUWRF

Annette Hirsch and Claire Carouge have released the latest version of CABLE-NUWRF, a regional atmospheric model coupled to the Australian land model, CABLE, via NASA's Land Information Systems. This new model allows our researchers to perform high-resolution land-atmosphere simulations with the CABLE model that is specifically developed for Australian conditions and vegetation. The new version improves on the previous one by integrating an improved version of CABLE for the groundwater simulation, and it has been successfully tested, for the first time, over a range of spatial resolutions up to about 10 kilometres. During the year, Annette and Claire have also made significant improvements to the benchmarking of both CABLE-NUWRF and CABLE and contributed to the JULES-and-CABLE (JAC) project in collaboration with CSIRO.

Data working groups

In April, Paola Petrelli oversaw the creation of four climate-community-led working groups on climate data. These groups result from the workshop "Creating a collaborative approach to climate data" at the AMOS conference led by Paola. The aim of the workshop was to individuate issues that are making access to climate data difficult and foster collaboration to implement creative but achievable solutions where possible. As a result the four groups are focusing on creating a climate data discovery portal, guidelines to follow FAIR principles, guidelines to work with big and challenging datasets and finally looking at requirements to enable access to climate data across institutions. Participants are all involved in climate research, with various roles and from different institutions, as well as industry.

Promoting FAIR data and software

We held different initiatives to promote the adoption of the FAIR principles at CLEX. Paola Petrelli completely redesigned our data-related documentation for easier navigation. Our FAIR data training was also completely updated to follow the same workflow as the documentation. While its delivery was affected by Covid-19-19, we intend to push this training forward in the next year. At the same time, we created the CLEX Code Collection and the CLEX Data Collection on Zenodo. The aim of these collections is to present all our data and code from a common portal, independently of where it is published. Particularly, the CLEX Code Collection is our unique option for software publication. The collections are accompanied by policies around authorship, retention and updates, the goal of these policies being to further increase transparency and help contributors make the right choices.

ACCESS-CM2 simplified aerosols and chemistry

While the ACCESS-CM2 model is a great step forward in climate modelling, it also comes with an increased cost in the computer time that's needed to run it. In order to be able to run interesting new experiments with the model, such as running both the atmosphere and ocean at higher resolutions, this cost needs to be managed. Accordingly, Scott Wales has investigated the effect on cost of simplifying the aerosol and chemistry schemes of the model, enabling high-resolution runs to be run efficiently at the cost of losing some detail in the atmosphere.

ACCESS-ESM1.5

Building on last year's effort, Holger Wolff and Scott Wales added three more supported configurations for ACCESS-ESM1.5 driven by Payu:

- An atmosphere-only AMIP configuration
- A Last Millennium configuration
- An SSP585 configuration.

The AMIP configuration is the first uncoupled configuration and, as such, necessitated particular attention. The Last Millennium configuration, part of the Paleoclimate Intercomparison Project 4, required elaborate modifications to allow time-varying land use and orbital parameters.

COSIMA

COSIMA has developed a suite of global ocean/ice models, and provided a number of important model output data sets, both of which are used extensively in CLEX. Part of this effort has been providing infrastructure, the COSIMA Cookbook, to make the data easily searchable and usable by the community. Aidan Heerdegen has contributed development work to improve the Cookbook database interface, and helped support the MOM5 Community ocean model with testing infrastructure and code upgrades and maintenance.

ACCESS-CM2-025

The medium resolution (global 0.25°) eddy-permitting ocean model from the COSIMA ACCESS-OM2 suite has been coupled to the ACCESS-CM2 model, Australia's premier coupled global climate model. This is a collaboration between CLEX and CSIRO. Aidan Heerdegen (CLEX) altered the ocean model configuration to be compatible with the fully coupled ACCESS-CM2 model.

XMHW

To help the CLEX marine heatwave researchers, we released and published the XMHW Python package based on the MarineHeatWave package from Eric Olivier, widely used by this community. XMHW improves on the original by using parallel computing to process larger data sets, working on multi-dimensional grids and producing annotated output. New features are regularly added, based on researchers' requests. While it has been available for a relatively short time, it has already been used both in CLEX and by external collaborators.

accessdev move to new NCI cloud infrastructure

The Centre makes heavy use of our partner NCI's computing facilities to run our models. Alongside the Bureau of Meteorology (BoM) and CSIRO, we maintain a cloud computer node named 'accessdev' to assist with running the ACCESS models. Early in the year, NCI upgraded its cloud facilities, which affected the 'accessdev' node. With NCI's help, Scott Wales, Martin Dix (CSIRO) and Wenming Lu (BoM) were able to migrate 'accessdev' to the new infrastructure with minimal downtime, allowing this critical piece of infrastructure to remain supported into the future.

Climpact

Climpact is a software package developed by the Centre for calculating climate indices, like 'how much rain fell during the rainiest five-day stretch of the year'. Paola Petrelli and Scott Wales have automated the use of this tool so that it can be run on large model intercomparison data sets – including CMIP6 and CORDEX – thereby enabling the performance of various models in predicting extreme weather to be compared.

Training and CodeBreak

Over the last few years, the CMS team has built a comprehensive library of training material and videos (available on the CMS Youtube channel). As such, we decided to re-energise our training offering by switching to fortnightly Q&A sessions called CodeBreak. At those sessions, the CMS team provides hands-on help to the attendees on their current computational issues.

3 PARTNERSHIPS, ENGAGEMENT AND IMPACT

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. Our Partner Organisations enable us to collaborate on cutting-edge science and model development and to advance our engagement and impact ambitions.

Despite the ongoing curtailment of both international and domestic travel in 2021, CLEX was able to maintain strong links to its Partner Organisations, resulting in significant progress across a number of initiatives.

ENGAGEMENT AND IMPACT

CLEX is committed to having influence and impact beyond academia. To this end, 2021 saw a major revision of the CLEX Engagement and Impact Implementation Plan. We engage with non-academic stakeholders, including governments, industry bodies, businesses, schools and the public. CLEX's Engagement and Impact Implementation Plan explains how the Centre's strategic objective of strong engagement beyond academia will be delivered. The plan will be updated at least annually to reflect emerging opportunities for furthering CLEX's engagement and impact ambitions and to manage any emerging risks.

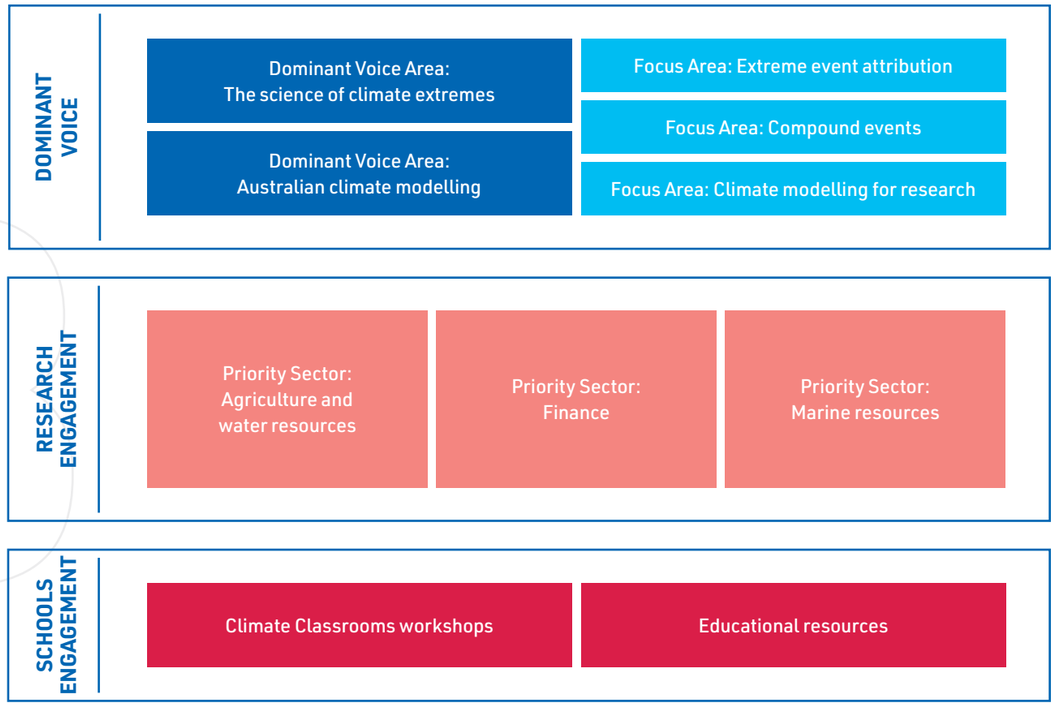
The implementation plan has three main components:

1) We strive to be a **Dominant Voice** in selected areas of climate science where we have sufficient expertise namely, the science of climate extremes and Australian climate modelling. Within these spheres we focus specifically on extreme-event attribution, compound events and climate modelling for research. We communicate this expertise via the media, online channels, select social media and via the activities of the Knowledge Brokerage Team.

2) Via our **Research Engagement** we achieve impact by maintaining a two-way dialogue on our research plans with a selection of government and business stakeholders in priority sectors, to ensure that we deliver science that is helpful to them. We focus on three priority sectors: agriculture and water resources, finance, and marine resources.

3) We achieve impact in schools through our **School Engagement** program, in which we work with secondary school teachers to help them teach the Australian Science, Technology, Engineering and Mathematics (STEM) curriculum, using examples from our science. We achieve this through targeted workshops and by developing educational resources.

In the chapters that follow, we highlight the year's major achievements from our Media and Communications portfolio and from our Knowledge Brokerage Team.



Overview of CLEX Engagement and Impact Implementation Plan

FEEDBACK FOR THE KNOWLEDGE BROKERAGE TEAM

'These notes are excellent. They are concise, well referenced and very well written. Keep them coming.'

'These briefings are really helpful and appreciated.'

'Today was terrific – thank you. You might like to know that after you left, we resolved to come up with an action plan on climate change.'

'I just want to say how impressive your synthesis of the IPCC report was … Clear information that gives Directors information that they can act on. Well done!'

KNOWLEDGE BROKERAGE TEAM

The revision of the ARC Centre of Excellence for Climate Extremes (CLEX) Engagement and Impact Plan was accompanied by both an expansion of the Knowledge Brokerage Team (KBT) and greater recognition of Centre researchers who go above-and-beyond in engaging beyond academia. Allyson Crimp, a skilled graphic designer, joined the KBT in June 2021 and has brought a new standard of professionalism to the Centre's reports, briefing notes and infographics. In addition, the Centre of Excellence has introduced a new prize to recognise the efforts of early career researchers in engaging beyond academia.

Later in the year, in August, the Intergovernmental Panel on Climate Change (IPCC) released its Sixth Assessment Report on the physical science of climate change. CLEX was instrumental in translating the key conclusions of the report for the benefit of Australian governments and businesses. We produced three Briefing Notes on the report, including one crafted specifically for the Tasmanian Government. These were very well received and led to opportunities for a quick-response team of CLEX Chief Investigators to individually brief Federal and State ministers and other parliamentarians and their staff, as well as influential industry bodies.

The Dominant Voice component of our Engagement Plan also expressed itself through Briefing Notes relevant to November's United Nations Framework Convention on Climate Change Conference of the Parties 26 (UNFCCC COP26) climate change conference in Glasgow. Circulated widely, these Briefing Notes were about the infeasibility of limiting global warming to 1.5°C, the tipping points in the climate system and the limited time left for greenhouse-gas-emissions reductions to meet the Paris Agreement global warming targets. CLEX Briefing Notes also supported a pre-COP26 call for an international next-generation climate modelling centre from the Royal Society. The proposal from the Royal Society, co-authored by CLEX Chief Investigator Christian Jakob, called for a facility 'with a role similar to that of CERN in particle physics' to revolutionise the quality of information available for mitigating and adapting to climate extremes and climate change.

Some of our engagement is highly targeted at developing a dialogue on our research with priority sectors in government and industry. There was a particular focus on agriculture and water resources in 2021. An array of CLEX researchers from different research programs and career levels have given presentations to the Forewarned is Forearmed Community of Practice. This agriculture sector group, assembled under the auspices of one of our Australian Partner Organisations, the Managing Climate Variability Program, includes extension officers from government departments and industry group representatives. CLEX presentations earlier in the year on drought led to invitations to give presentations on Indian Ocean influences on the climate of Australia and on Atmospheric Rivers. Following the success of the Centre's Briefing Notes on the IPCC report, the Water Services Association of Australia also sought out CLEX, to ask for briefings on the latest climate science. Representatives of the agriculture and water sector have also been invited as guest presenters to our research program meetings.

Centre of Excellence Director, Professor Andy Pitman, gave numerous briefings to the finance sector on assessing climate risk during 2021. For example, in March, Prof Pitman joined Tanya Fiedler, a business expert at University of Sydney, in briefing financial services firm UBS on the use of climate models in assessing business risk.

In relation to the marine resources sector, researchers from our Ocean Extremes research program have engaged with the Commission for the Conservation of Antarctic Marine Living Resources, Austral Fisheries (one of Australia's largest integrated commercial fishing companies) and ShellMAP (a public-private initiative designed to ensure the competitiveness and safety of the Tasmanian shellfish industry).

Our work engaging with schools continued during 2021 under the leadership of research fellow and KBT member Sanaa Hobeichi. Early in the year, CLEX became a partner in TROP ICSU, an international project that aims to provide educators across the globe with teaching resources on climate change. With collaborators at the Monash Climate Change Communication Research Hub, CLEX delivered an online Climate Classrooms workshop attended by teachers and climate scientists from across the country. The workshop was supported by numerous CLEX professional staff and affiliates, including many PhD students. CLEX plans to run more workshops for teachers in the future. A further highlight of our engagement with science teachers' associations was the delivery of a session on climate modelling at the Science Teachers' Association of New South Wales Stage 6 Conference, by Sanaa Hobeichi and CLEX Chief Investigator Gab Abramowitz.

During 2021 the KBT contributed to research papers with policy implications. First was an Environmental Research cCommunications paper led by CLEX Partner Organisation, NSW Department of Planning, Industry and Environment, on projections of future changes in climate extremes that occur, on average, once every 20 years. These are more interesting to government, and others who manage climate risk, than oft-analysed, but generally less damaging, annual extreme events. Later in the year, the team contributed to an Environmental Research Letters paper led by epidemiologists from the Kirby Institute, UNSW, exploring the impact of climate change on dengue-fever transmission in Bangladesh, with results that have important implications for public health policy.

Finally, as the year was drawing to a close, the KBT was assisting the CLEX postdoctoral cohort in the production of the first annual CLEX State of Extremes report. This report will be produced annually and will provide a retrospective account of extreme climate and weather events over Australia over the preceding twelve months.

MEDIA AND COMMUNICATIONS

In spite of Covid-19-related interruptions, 2021 saw a re-orientation of our media and communications strategy following the mid-term review of the ARC Centre of Excellence for Climate Extremes (CLEX) in 2020. While CLEX has always played a prominent role in public discussions around climate, we were asked to increase our influence in policy and business spheres. As a consequence, our media and communications work became even more tightly co-ordinated with the work of the Knowledge Brokerage Team, with some very positive outcomes.

We were able to capitalise on this early in the year when the paper, Business risk and the emergence of climate analytics, was published in Nature Climate Change. The paper directly examined the role of climate models and how they were being misused by those assessing future risks for business. Our media release for business - and the accompanying plain-language summary - had international reach. This led to CLEX researchers delivering special presentations across a range of Australian industry sectors and key international entities, including the US Federal Reserve; World Business Council for Sustainability Development; the technical team of the US Senate Committee on Banking, Housing, and Urban Affairs; and Lazard Asset Management, New York.

Another opportunity to influence policymakers and present our expertise to industry came in the form of the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) Working Group 1, which was released in early August. We worked closely with the Knowledge Brokerage Team and assembled a rapid-response team of researchers and media experts to put together a media release, graphics and a briefing note over those two days. As a consequence, CLEX was a dominant voice in the media, with 30 separate interviews given. Following this, we took part in special briefings to Federal and State politicians. These were organised initially by making direct contact with the offices of parliamentarians in highly relevant portfolios or in electorates close to the five CLEX Institutions. The number of briefings our fast-response team gave increased as word-of-mouth recommendations led to more opportunities.

The rise in our influence, particularly in terms of media engagement, was also seen when Chief Investigator Dr Sarah Perkins-Kirkpatrick was one of three researchers selected to speak to the National Press Club of Australia about the United Nations Framework Convention on Climate Change -- Conference of the Parties 26 climate talks in Glasgow, with her comments widely reported.

Outside of this focus on direct influence we have also engaged with Cimpatico Studios to produce a CLEX-branded video series about our work. The series will eventually be made up of 12 half-hour episodes that feature our researchers and stakeholders talking about a range of climate subjects and answering questions live on-air from the host, Lee Constable, and afterwards from the online audience. Each professionally produced episode is live streamed, and edited recordings are then made available on our website. This series will continue into 2022.

Despite Covid-19 lockdowns and the many challenges these have brought, our researchers have continued to appear prominently in the media here and around the world. As in past years, the list includes every major media outlet in Australia and leading international broadcasters and mastheads, such as the BBC, The Washington Post, The New York Times and CNN.

Finally, in December we said a sad farewell to our Media and Communications Manager, Alvin Stone, who moved on to the NSW Environmental Protection Authority. He has helped many of our staff and students become better communicators and given them the confidence to talk about their science in a public space. We are extremely grateful to Alvin for his many years of contributions. Our new Media and Communications Advisor has been recruited and commences in early 2022.

CLEX Website

The website continued to see growth over 2021. Over the course of the year, we have seen:

- 56,000 unique users
- 75,600 sessions
- 115,000 page views
- Top five countries: Australia (31%), US (17%), UK (7%), India (4%) and Germany (4%).

The most popular page on the website continues to be the communications article, 10 Tips to Write an Opinion Piece People Actually Read. This shows the importance of evergreen content that will continue to be relevant to our researchers and to visitors to the website.

The most popular news articles on the website included our briefing note on the IPCC AR6, the above-mentioned piece on climate analytics and business risk, and our briefing note on whether global warming can still be limited to 1.5°C.

At the time of writing, our website was in the midst of a major overhaul. This includes a fresh new design and improvements to the accessibility of content that is relevant to our key stakeholders.

Social Media

Our social media presence continues to climb across all platforms. Our Twitter followers have now increased to 2982, with more than half a million impressions, while our Facebook page grew to 1545 followers.

Our Twitter feed is aimed at peer networks, while our Facebook page focuses primarily on our internal cohort and immediate stakeholders. This year we also started using LinkedIn more proactively. We created a dedicated CLEX page that had already garnered 690 followers by the end of the year. On it we share examples of our work that are particularly pertinent to decision-makers and industry. Our Director, Professor Andy Pitman, also made a foray into LinkedIn and his posts have been viewed and shared widely.

Media

Unfortunately, with the continuing issues around Covid-19, our cross-Centre media training program had to be put on hold. However, we were able to deliver a social-media seminar and still maintain a strong presence in the media.

Highlights include the IPCC AR6 Working Group 1 report, as noted above, and also a very strong presence in opportunistic media coverage, in particular when the small Canadian town of Lytton at 50° N reached 50°C, and then was gutted by fire the following day. As well as directly commenting on that incident and the role of climate change in a succession of heatwaves, and on floods in Germany and China, we were also able to use some of these extremes to highlight some complex science. An article in The Conversation, by Professor Michael Reeder and Professor Christian Jakob, revealed the atmospheric influences that had led to a succession of heatwaves that occurred from the Mediterranean to California. This article was syndicated around the world. It was just one of almost 20 articles in The Conversation that highlighted our research and wide-ranging expertise in climate.

Other highlights include commentary on NSW floods; some excellent coverage on work by the Ocean Extremes research program that showed how climate change is reorganising the ocean; a range of explainers on what a one-in-a-hundred-year flooding event really means; and, of course our work on the misuse of climate models for business analytics and risk assessment.

4 OUTPUTS AND PERFORMANCE

PUBLICATIONS

BOOK/ENCYCLOPEDIA SECTIONS

Hart, M.A., Cooper, N., Green, D., Lipson, M., 2021. The Synergistic Impacts of Urban Air Pollution Compounding Our Climate Emergency, in: Ren, C., McGregor, G. (Eds.), Urban Climate Science for Planning Healthy Cities, Biometeorology. Springer International Publishing, Cham, pp. 355–378. https://doi.org/10.1007/978-3-030-87598-5_16

Noblet-Ducoudré, N. de, Pitman, A.J., 2021. Terrestrial Processes and Their Roles in Climate Change, in: Oxford Research Encyclopedia of Climate Science. Oxford University Press. https://doi.org/10.1093/acrefore/9780190228620.013.825

JOURNAL ARTICLES

Abram, N.J., Henley, B.J., Sen Gupta, A., Lippmann, T.J.R., Clarke, H., Dowdy, A.J., Sharples, J.J., Nolan, R.H., Zhang, T., Wooster, M.J., Wurtzel, J.B., Meissner, K.J., Pitman, A.J., Ukkola, A.M., Murphy, B.P., Tapper, N.J., Boer, M.M., 2021. Connections of climate change and variability to large and extreme forest fires in southeast Australia. Communications Earth & Environment 2, 1–17. https://doi.org/10.1038/s43247-020-00065-8

Ackermann, L., Huang, Y., Siems, S., Manton, M., Lang, F., Chubb, T., Peace, A., Speirs, J., Suzanne, K., Protat, A., Alexander, S.P., 2021. Wintertime Precipitation over the Australian Snowy Mountains: Observations from an Intensive Field Campaign 2018. Journal of Hydrometeorology 22, 2193–2211. https://doi.org/10.1175/JHM-D-20-0283.1

Aguiar, W., Meissner, K.J., Montenegro, A., Prado, L., Wainer, I., Carlson, A.E., Mata, M.M., 2021. Magnitude of the 8.2 ka event freshwater forcing based on stable isotope modelling and comparison to future Greenland melting. Scientific Reports 11, 5473. https://doi.org/10.1038/s41598-021-84709-5

Amengual, A., Hermoso, A., Carrió, D.S., Homar, V., 2021. The Sequence of Heavy Precipitation and Flash Flooding of 12 and 13 September 2019 in Eastern Spain. Part II: A Hydrometeorological Predictability Analysis Based on Convection-Permitting Ensemble Strategies. Journal of Hydrometeorology 22, 2153–2177. https://doi.org/10.1175/JHM-D-20-0181.1

Ayat, H., Evans, J.P., Behrangi, A., 2021. How do different sensors impact IMERG precipitation estimates during hurricane days? Remote Sensing of Environment 259, 112417. https://doi.org/10.1016/j.rse.2021.112417

Azorin-Molina, C., McVicar, T.R., Guijarro, J.A., Trewin, B., Frost, A.J., Zhang, G., Minola, L., Son, S.-W., Deng, K., Chen, D., 2021. A Decline of Observed Daily Peak Wind Gusts with Distinct Seasonality in Australia, 1941–2016. Journal of Climate 34, 3103–3127. https://doi.org/10.1175/JCLI-D-20-0590.1

Badlan, R.L., Sharples, J.J., Evans, J.P., McRae, R.H.D., Badlan, R.L., Sharples, J.J., Evans, J.P., McRae, R.H.D., 2021a. Factors influencing the development of violent pyroconvection. Part I: fire size and stability. Int. J. Wildland Fire 30, 484–497. https://doi.org/10.1071/WF20040

Badlan, R.L., Sharples, J.J., Evans, J.P., McRae, R.H.D., Badlan, R.L., Sharples, J.J., Evans, J.P., McRae, R.H.D., 2021b. Factors influencing the development of violent pyroconvection. Part II: fire geometry and intensity. Int. J. Wildland Fire 30, 498–512. https://doi.org/10.1071/WF20041

Bai, H., Xiao, D., Wang, B., Liu, D.L., Feng, P., Tang, J., 2021. Multi-model ensemble of CMIP6 projections for future extreme climate stress on wheat in the North China plain. International Journal of Climatology 41, E171–E186. https://doi.org/10.1002/joc.6674

Barton, N., Metzger, E.J., Reynolds, C.A., Ruston, B., Rowley, C., Smedstad, O.M., Ridout, J.A., Wallcraft, A., Frolov, S., Hogan, P., Janiga, M.A., Shriver, J.F., McLay, J., Thoppil, P., Huang, A., Crawford, W., Whitcomb, T., Bishop, C.H., Zamudio, L., Phelps, M., 2021. The Navy's Earth System Prediction Capability: A New Global Coupled Atmosphere-Ocean-Sea Ice Prediction System Designed for Daily to Subseasonal Forecasting. Earth and Space Science 8, e2020EA001199. https://doi.org/10.1029/2020EA001199

Behrens, E., Hogg, A.M., England, M.H., Bostock, H., 2021. Seasonal and Interannual Variability of the Subtropical Front in the New Zealand Region. Journal of Geophysical Research: Oceans 126, e2020JC016412. https://doi.org/10.1029/2020JC016412

Beischer, T.A., Gregory, P., Dayal, K., Brown, J.R., Charles, A.N., Wang, W.X.D., Brown, J.N., 2021. Scope for predicting seasonal variation of the SPCZ with ACCESS-S1. Clim Dyn 56, 1519–1540. https://doi.org/10.1007/s00382-020-05550-6

Bell, J.D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S., Dessert, M., Gehlen, M., Gorgues, T., Hampton, J., Hanich, Q., Harden-Davies, H., Hare, S.R., Holmes, G., Lehodey, P., Lengaigne, M., Mansfield, W., Menkes, C., Nicol, S., Ota, Y., Pasisi, C., Pilling, G., Reid, C., Ronneberg, E., Sen Gupta, A., Seto, K.L., Smith, N., Taei, S., Tsamenyi, M., Williams, P., 2021. Pathways to sustaining tuna-dependent Pacific Island economies during climate change. Nat Sustain 4, 900–910. https://doi.org/10.1038/s41893-021-00745-z

Bengtson, S.A., Menviel, L.C., Meissner, K.J., Missiaen, L., Peterson, C.D., Lisiecki, L.E., Joos, F., 2021. Lower oceanic 13C during the last interglacial period compared to the Holocene. Clim. Past 17, 507–528. https://doi.org/10.5194/cp-17-507-2021

Bladwell, C., Holmes, R.M., Zika, J.D., 2021. Internal salt content: a useful framework for understanding the oceanic branch of the water cycle. Journal of Physical Oceanography 51, 2167–2179. https://doi.org/10.1175/JPO-D-20-0212.1

Blunn, L.P., Coceal, O., Nazarian, N., Barlow, J.F., Plant, R.S., Bohnenstengel, S.I., Lean, H.W., 2021. Turbulence Characteristics Across a Range of Idealized Urban Canopy Geometries. Boundary-Layer Meteorol 182, 275–307. https://doi.org/10.1007/s10546-021-00658-6

Blyth, E.M., Arora, V.K., Clark, D.B., Dadson, S.J., De Kauwe, M.G., Lawrence, D.M., Melton, J.R., Pongratz, J., Turton, R.H., Yoshimura, K., Yuan, H., 2021. Advances in Land Surface Modelling. Curr Clim Change Rep 7, 45–71. https://doi.org/10.1007/s40641-021-00171-5

Brook, J.P., Protat, A., Soderholm, J., Carlin, J.T., McGowan, H., Warren, R.A., 2021. HailTrack–Improving Radar-Based Hailfall Estimates by Modeling Hail Trajectories. Journal of Applied Meteorology and Climatology 60, 237–254. https://doi.org/10.1175/JAMC-D-20-0087.1

Cai, W., Ng, B., Geng, T., Wu, L., Santoso, A., McPhaden, M.J., 2021a. Addendum: Butterfly effect and a self-modulating El Niño response to global warming. Nature 591, E14–E15. https://doi.org/10.1038/s41586-021-03261-4

Cai, W., Santoso, A., Collins, M., Dewitte, B., Karamperidou, C., Kug, J.-S., Lengaigne, M., McPhaden, M.J., Stuecker, M.F., Taschetto, A.S., Timmermann, A., Wu, L., Yeh, S.-W., Wang, G., Ng, B., Jia, F., Yang, Y., Ying, J., Zheng, X.-T., Bayr, T., Brown, J.R., Capotondi, A., Cobb, K.M., Gan, B., Geng, T., Ham, Y.-G., Jin, F.-F., Jo, H.-S., Li, X., Lin, X., McGregor, S., Park, J.-H., Stein, K., Yang, K., Zhang, L., Zhong, W., 2021b. Changing El Niño–Southern Oscillation in a warming climate. Nat Rev Earth Environ 2, 628–644. https://doi.org/10.1038/s43017-021-00199-z

Cai, W., Yang, K., Wu, L., Huang, G., Santoso, A., Ng, B., Wang, G., Yamagata, T., 2021c. Opposite response of strong and moderate positive Indian Ocean Dipole to global warming. Nature Climate Change 11, 27–32. https://doi.org/10.1038/s41558-020-00943-1

Carrió, D.S., Bishop, C.H., Kotsuki, S., 2021. Empirical determination of the covariance of forecast errors: An empirical justification and reformulation of hybrid covariance models. Quarterly Journal of the Royal Meteorological Society 147, 2033–2052. https://doi.org/10.1002/qj.4008

Casselman, J.W., Taschetto, A.S., Domeisen, D.I.V., 2021. Nonlinearity in the Pathway of El Niño–Southern Oscillation to the Tropical North Atlantic. Journal of Climate 34, 7277–7296. https://doi.org/10.1175/JCLI-D-20-0952.1

Chang, Z., Hobeichi, S., Wang, Y.-P., Tang, X., Abramowitz, G., Chen, Y., Cao, N., Yu, M., Huang, H., Zhou, G., Wang, G., Ma, K., Du, S., Li, S., Han, S., Ma, Y., Wigneron, J.-P., Fan, L., Saatchi, S.S., Yan, J., 2021. New Forest Aboveground Biomass Maps of China Integrating Multiple Datasets. Remote Sensing 13, 2892. https://doi.org/10.3390/rs13152892

Cherian, D.A., Whitt, D.B., Holmes, R.M., Lien, R.-C., Bachman, S.D., Large, W.G., 2021. Off-Equatorial Deep-Cycle Turbulence Forced by Tropical Instability Waves in the Equatorial Pacific. Journal of Physical Oceanography 51, 1575–1593. https://doi.org/10.1175/JPO-D-20-0229.1

Constantinou, N.C., Hogg, A.M., 2021. Intrinsic Oceanic Decadal Variability of Upper-Ocean Heat Content. Journal of Climate 34, 6175–6189. https://doi.org/10.1175/JCLI-D-20-0962.1

Constantinou, N.C., Wagner, G.L., Siegelman, L., Pearson, B.C., Palóczy, A., 2021. GeophysicalFlows.jl: Solvers for geophysical fluid dynamics problems in periodic domains on CPUs & GPUs. Journal of Open Source Software 6, 3053. https://doi.org/10.21105/joss.03053

Couldrey, M.P., Gregory, J.M., Boeira Dias, F., Dobrohotoff, P., Domingues, C.M., Garuba, O., Griffies, S.M., Haak, H., Hu, A., Ishii, M., Jungclaus, J., Köhl, A., Marsland, S.J., Ojha, S., Saenko, O.A., Savita, A., Shao, A., Stammer, D., Suzuki, T., Todd, A., Zanna, L., 2021. What causes the spread of model projections of ocean dynamic sea-level change in response to greenhouse gas forcing? Clim Dyn 56, 155–187. https://doi.org/10.1007/s00382-020-05471-4

Cowley, R., Killick, R.E., Boyer, T., Gouretski, V., Reseghetti, F., Kizu, S., Palmer, M.D., Cheng, L., Storto, A., Le Menn, M., Simoncelli, S., Macdonald, A.M., Domingues, C.M., 2021. International Quality-Controlled Ocean Database (IQuOD) v0.1: The Temperature Uncertainty Specification. Frontiers in Marine Science 8, 689695. https://doi.org/10.3389/fmars.2021.689695

Crockart, C.K., Vance, T.R., Fraser, A.D., Abram, N.J., Criscitiello, A.S., Curran, M.A.J., Favier, V., Gallant, A.J.E., Kittel, C., Kjær, H.A., Klekociuk, A.R., Jong, L.M., Moy, A.D., Plummer, C.T., Vallelonga, P.T., Wille, J., Zhang, L., 2021. El Niño–Southern Oscillation signal in a new East Antarctic ice core, Mount Brown South. Climate of the Past 17, 1795–1818. https://doi.org/10.5194/cp-17-1795-2021

Cyriac, A., Phillips, H.E., Bindoff, N.L., Mao, H., Feng, M., 2021. Observational Estimates of Turbulent Mixing in the Southeast Indian Ocean. Journal of Physical Oceanography 51, 2103–2128. https://doi.org/10.1175/JPO-D-20-0036.1

De Kauwe, M.G., Medlyn, B.E., Tissue, D.T., 2021. To what extent can rising [CO2] ameliorate plant drought stress? New Phytologist 231, 2118–2124. https://doi.org/10.1111/nph.17540

Deng, X., Perkins-Kirkpatrick, S.E., Lewis, S.C., Ritchie, E.A., 2021. Evaluation of Extreme Temperatures over Australia in the Historical Simulations of CMIP5 and CMIP6 Models. Earth's Future 9, e2020EF001902. https://doi.org/10.1029/2020EF001902

Deo, A., Chand, S.S., Ramsay, H., Holbrook, N.J., McGree, S., Magee, A., Bell, S., Titimaea, M., Haruhiru, A., Malsale, P., Mulitalo, S., Daphne, A., Prakash, B., Vainikolo, V., Koshiba, S., 2021. Tropical cyclone contribution to extreme rainfall over southwest Pacific Island nations. Clim Dyn 56, 3967–3993. https://doi.org/10.1007/s00382-021-05680-5

Dey, R., Bador, M., Alexander, L.V., Lewis, S.C., 2021. The drivers of extreme rainfall event timing in Australia. International Journal of Climatology 41, 6654–6673. https://doi.org/10.1002/joc.7218

Di Virgilio, G., Hart, M.A., Maharaj, A.M., Jiang, N., 2021. Air quality impacts of the 2019–2020 Black Summer wildfires on Australian schools. Atmospheric Environment 261, 118450. https://doi.org/10.1016/j.atmosenv.2021.118450

Duarte, P., Meyer, A., Moreau, S., 2021. Nutrients in Water Masses in the Atlantic Sector of the Arctic Ocean: Temporal Trends, Mixing and Links With Primary Production. Journal of Geophysical Research: Oceans 126, e2021JC017413. https://doi.org/10.1029/2021JC017413

Dutheil, C., Menkes, C., Lengaigne, M., Vialard, J., Peltier, A., Bador, M., Petit, X., 2021. Fine-scale rainfall over New Caledonia under climate change. Clim Dyn 56, 87–108. https://doi.org/10.1007/s00382-020-05467-0

Eabry, M.D., Taschetto, A.S., Maharaj, A.M., Sen Gupta, A., 2021. What Determines the Lagged ENSO Response in the South-West Indian Ocean? Geophysical Research Letters 48, e2020GL091958. https://doi.org/10.1029/2020GL091958

Echevarria, E.R., Hemer, M.A., Holbrook, N.J., 2021. Global implications of surface current modulation of the wind-wave field. Ocean Modelling 161, 101792. https://doi.org/10.1016/j.ocemod.2021.101792

Ely, K.S., Rogers, A., Agarwal, D.A., Ainsworth, E.A., Albert, L.P., Ali, A., Anderson, J., Aspinwall, M.J., Bellasio, C., Bernacchi, C., Bonnage, S., Buckley, T.N., Bunce, J., Burnett, A.C., Busch, F.A., Cavanagh, A., Cernusak, L.A., Crystal-Ornelas, R., Damerow, J., Davidson, K.J., De Kauwe, M.G., Dietze, M.C., Domingues, T.F., Dusenge, M.E., Ellsworth, D.S., Evans, J.R., Gauthier, P.P.G., Gimenez, B.O., Gordon, E.P., Gough, C.M., Halbritter, A.H., Hanson, D.T., Heskel, M., Hogan, J.A., Hupp, J.R., Jardine, K., Kattge, J., Keenan, T., Kromdijk, J., Kumarathunge, D.P., Lamour, J., Leakey, A.D.B., LeBauer, D.S., Li, Q., Lundgren, M.R., McDowell, N., Meacham-Hensold, K., Medlyn, B.E., Moore, D.J.P., Negrón-Juárez, R., Niinemets, Ü., Osborne, C.P., Pivovaroff, A.L., Poorter, H., Reed, S.C., Ryu, Y., Sanz-Saez, A., Schmiege, S.C., Serbin, S.P., Sharkey, T.D., Slot, M., Smith, N.G., Sonawane, B.V., South, P.F., Souza, D.C., Stinziano, J.R., Stuart-Haëntjens, E., Taylor, S.H., Tejera, M.D., Uddling, J., Vandvik, V., Varadharajan, C., Walker, A.P., Walker, B.J., Warren, J.M., Way, D.A., Wolfe, B.T., Wu, J., Wullschleger, S.D., Xu, C., Yan, Z., Yang, D., 2021. A reporting format for leaf-level gas exchange data and metadata. Ecological Informatics 61, 101232. https://doi.org/10.1016/j.ecoinf.2021.101232

Everingham, S.E., Offord, C.A., Sabot, M.E.B., Moles, A.T., 2021. Time-traveling seeds reveal that plant regeneration and growth traits are responding to climate change. Ecology 102, e03272. https://doi.org/10.1002/ecy.3272

Fan, C.-S., Dommenget, D., 2021. A diagnostic model for the large-scale tropical circulation based on moist static energy balance. Clim Dyn 57, 3159–3181. https://doi.org/10.1007/s00382-021-05861-2

Feng, M., Zhang, Y., Hendon, H.H., McPhaden, M.J., Marshall, A.G., 2021. Niño 4 West (Niño-4W) Sea Surface Temperature Variability. Journal of Geophysical Research: Oceans 126, e2021JC017591. https://doi.org/10.1029/2021JC017591

Fer, I., Gardella, A.K., Shiklomanov, A.N., Campbell, E.E., Cowdery, E.M., De Kauwe, M.G., Desai, A., Duveneck, M.J., Fisher, J.B., Haynes, K.D., Hoffman, F.M., Johnston, M.R., Kooper, R., LeBauer, D.S., Mantooth, J., Parton, W.J., Poulter, B., Quaife, T., Raiho, A., Schaefer, K., Serbin, S.P., Simkins, J., Wilcox, K.R., Viskari, T., Dietze, M.C., 2021. Beyond ecosystem modeling: A roadmap to community cyberinfrastructure for ecological data-model integration. Global Change Biology 27, 13–26. https://doi.org/10.1111/gcb.15409

Fiddes, S.L., Woodhouse, M.T., Lane, T.P., Schofield, R., 2021. Coral-reef-derived dimethyl sulfide and the climatic impact of the loss of coral reefs. Atmos. Chem. Phys. 21, 5883–5903. https://doi.org/10.5194/acp-21-5883-2021

Fiedler, T., Pitman, A.J., Mackenzie, K., Wood, N., Jakob, C., Perkins-Kirkpatrick, S.E., 2021. Business risk and the emergence of climate analytics. Nature Climate Change 11, 87–94. https://doi.org/10.1038/s41558-020-00984-6

Fowler, H.J., Ali, H., Allan, R.P., Ban, N., Barbero, R., Berg, P., Blenkinsop, S., Cabi, N.S., Chan, S., Dale, M., Dunn, R.J.H., Ekström, M., Evans, J.P., Fosser, G., Golding, B., Guerreiro, S.B., Hegerl, G.C., Kahraman, A., Kendon, E.J., Lenderink, G., Lewis, E., Li, X., O'Gorman, P.A., Orr, H.G., Peat, K.L., Prein, A.F., Pritchard, D., Schär, C., Sharma, A., Stott, P.A., Villalobos-Herrera, R., Villarini, G., Wasko, C., Wehner, M.F., Westra, S., Whitford, A., 2021. Towards advancing scientific knowledge of climate change impacts on short-duration rainfall extremes. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 379, 20190542. https://doi.org/10.1098/rsta.2019.0542

Freund, M.B., Marshall, A.G., Wheeler, M.C., Brown, J.N., 2021. Central Pacific El Niño as a Precursor to Summer Drought-Breaking Rainfall Over Southeastern Australia. Geophysical Research Letters 48, e2020GL091131. https://doi.org/10.1029/2020GL091131

Garfinkel, C.I., White, I.P., Gerber, E.P., Adam, O., Jucker, M., 2021. Nonlinear Interaction Between the Drivers of the Monsoon and Summertime Stationary Waves. Geophysical Research Letters 48, e2020GL092321. https://doi.org/10.1029/2020GL092321

Garg, M., Silver, J.D., Schofield, R., Ryan, R.G., 2021. Hourly emission inventories for air toxic emissions for eastern Australian electricity generators derived from energy distribution data. Int. J. Environ. Sci. Technol. https://doi.org/10.1007/s13762-021-03429-5

Gergis, J., Baillie, Z., Ingallina, S., Ashcroft, L., Ellwood, T., 2021. A historical climate dataset for southwestern Australia, 1830–1875. International Journal of Climatology 41, 4898–4919. https://doi.org/10.1002/joc.7105

Gillett, Z.E., Hendon, H.H., Arblaster, J.M., Lim, E.-P., 2021. Tropical and Extratropical Influences on the Variability of the Southern Hemisphere Wintertime Subtropical Jet. Journal of Climate 34, 4009–4022. https://doi.org/10.1175/JCLI-D-20-0460.1

Goyal, R., England, M.H., Jucker, M., Sen Gupta, A., 2021a. Response of Southern Hemisphere Western Boundary Current Regions to Future Zonally Symmetric and Asymmetric Atmospheric Changes. Journal of Geophysical Research: Oceans 126, e2021JC017858. https://doi.org/10.1029/2021JC017858

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

Goyal, R., Jucker, M., Sen Gupta, A., Hendon, H.H., England, M.H., 2021c. Zonal wave 3 pattern in the Southern Hemisphere generated by tropical convection. Nat. Geosci. 14, 732–738. https://doi.org/10.1038/s41561-021-00811-3

Goyal, R., Sen Gupta, A., Jucker, M., England, M.H., 2021d. Historical and Projected Changes in the Southern Hemisphere Surface Westerlies. Geophysical Research Letters 48, e2020GL090849. https://doi.org/10.1029/2020GL090849

Grosfeld, N.H., McGregor, S., Taschetto, A.S., 2021. An Automated Climatology of Cool-Season Cutoff Lows over Southeastern Australia and Relationships with the Remote Climate Drivers. Monthly Weather Review 149, 4167–4181. https://doi.org/10.1175/MWR-D-21-0142.1

Gupta, H.V., Ehsani, M.R., Roy, T., Sans-Fuentes, M.A., Ehret, U., Behrangi, A., 2021. Computing Accurate Probabilistic Estimates of One-D Entropy from Equiprobable Random Samples. Entropy 23, 740. https://doi.org/10.3390/e23060740

Hardy, S., Schwendike, J., Smith, R.K., Short, C.J., Reeder, M.J., Birch, C.E., 2021. Fluctuations in inner-core structure during the rapid intensification of Super Typhoon Nepartak (2016). Monthly Weather Review 141, 221–243. https://doi.org/10.1175/MWR-D-19-0415.1

Hartigan, J., Warren, R.A., Soderholm, J.S., Richter, H., 2021. Simulated Changes in Storm Morphology Associated with a Sea-Breeze Air Mass. Monthly Weather Review 149, 333–351. https://doi.org/10.1175/MWR-D-20-0069.1

Hashihama, F., Kouketsu, S., Kondou, Y., Sasaki, Y., Sugimoto, S., Takahashi, K., Nagai, T., Nishioka, J., Hayashida, H., Hirai, J., 2021. Decadal vision in oceanography 2021: Mid-latitude ocean. Oceanography in Japan 30, 127–154. https://doi.org/10.5928/kaiyou.30.5_127

Hayashida, H., Jin, M., Steiner, N.S., Swart, N.C., Watanabe, E., Fiedler, R., Hogg, A.M., Kiss, A.E., Matear, R.J., Strutton, P.G., 2021. Ice Algae Model Intercomparison Project phase 2 (IAMIP2). Geoscientific Model Development 14, 6847–6861. https://doi.org/10.5194/gmd-14-6847-2021

Heever, S.C. van den, Grant, L.D., Freeman, S.W., Marinescu, P.J., Barnum, J., Bukowski, J., Casas, E., Drager, A.J., Fuchs, B., Herman, G.R., Hitchcock, S.M., Kennedy, P.C., Nielsen, E.R., Park, J.M., Rasmussen, K., Razin, M.N., Riesenberg, R., Dellaripa, E.R., Slocum, C.J., Toms, B.A., Heever, A. van den, 2021. The Colorado State University Convective CLoud Outflows and UpDrafts Experiment (C3LOUD-Ex). Bulletin of the American Meteorological Society 102, E1283–E1305. https://doi.org/10.1175/BAMS-D-19-0013.1

Heidemann, H., Ribbe, J., Cowan, T., Henley, B.J., Pudmenzky, C., Stone, R., Cobon, D.H., 2021. The influence of interannual and decadal Indo-Pacific sea surface temperature variability on Australian monsoon rainfall. Journal of Climate 35, 425–444. https://doi.org/10.1175/JCLI-D-21-0264.1

Herold, N., Downes, S.M., Gross, M.H., Ji, F., Nishant, N., Macadam, I., Ridder, N.N., Beyer, K., 2021. Projected changes in the frequency of climate extremes over southeast Australia. Environ. Res. Commun. 3, 011001. https://doi.org/10.1088/2515-7620/abe6b1

Hirsch, A.L., Evans, J.P., Thomas, C., Conroy, B., Hart, M.A., Lipson, M., Ertler, W., 2021a. Resolving the influence of local flows on urban heat amplification during heatwaves. Environ. Res. Lett. 16, 064066. https://doi.org/10.1088/1748-9326/ac0377

Hirsch, A.L., Ridder, N.N., Perkins-Kirkpatrick, S.E., Ukkola, A., 2021b. CMIP6 MultiModel Evaluation of Present-Day Heatwave Attributes. Geophysical Research Letters 48, e2021GL095161. https://doi.org/10.1029/2021GL095161

Hitchcock, S.M., Lane, T.P., Warren, R.A., Soderholm, J.S., 2021. Linear rainfall features and their association with rainfall extremes near Melbourne, Australia. Monthly Weather Review 149, 3401–3417. https://doi.org/10.1175/MWR-D-21-0007.1

Hobbs, W.R., Roach, C., Roy, T., Sallée, J.-B., Bindoff, N., 2021. Anthropogenic Temperature and Salinity Changes in the Southern Ocean. Journal of Climate 34, 215–228. https://doi.org/10.1175/JCLI-D-20-0454.1

Hobeichi, S., Abramowitz, G., Evans, J.P., 2021. Robust historical evapotranspiration trends across climate regimes. Hydrology and Earth System Sciences 25, 3855–3874. https://doi.org/10.5194/hess-25-3855-2021

Hoffmann, D., Gallant, A.J.E., Hobbins, M., 2021. Flash Drought in CMIP5 Models. Journal of Hydrometeorology 22, 1439–1454. https://doi.org/10.1175/JHM-D-20-0262.1

Holbrook, N.J., Hernaman, V., Koshiba, S., Lako, J., Kajtar, J.B., Amosa, P., Singh, A., 2021. Impacts of marine heatwaves on tropical western and central Pacific Island nations and their communities. Global and Planetary Change 208, 103680. https://doi.org/10.1016/j.gloplacha.2021.103680

Holmes, R.M., Zika, J.D., Griffies, S.M., Hogg, A.McC., Kiss, A.E., England, M.H., 2021. The Geography of Numerical Mixing in a Suite of Global Ocean Models. Journal of Advances in Modeling Earth Systems 13, e2020MS002333. https://doi.org/10.1029/2020MS002333

Hop, H., Wold, A., Meyer, A., Bailey, A., Hatlebakk, M., Kwasniewski, S., Leopold, P., Kuklinski, P., Søreide, J.E., 2021. Winter-Spring Development of the Zooplankton Community Below Sea Ice in the Arctic Ocean. Front. Mar. Sci. 8. https://doi.org/10.3389/fmars.2021.609480

HUANG, Y., Siems, S.T., Manton, M.J., 2021. Wintertime In-situ Cloud Microphysical Properties of Mixed-phase Clouds over the Southern Ocean. JGR: Atmospheres 126, e2021JD034832. https://doi.org/10.1002/essoar.10506364.1

Huasco, W.H., Riutta, T., Girardin, C.A.J., Pacha, F.H., Vilca, B.L.P., Moore, S., Rifai, S.W., Aguila-Pasquel, J. del, Murakami, A.A., Freitag, R., Morel, A.C., Demissie, S., Doughty, C.E., Oliveras, I., Cabrera, D.F.G., Baca, L.D., Amézquita, F.F., Espejo, J.E.S., Costa, A.C.L. da, Mendoza, E.O., Quesada, C.A., Ondo, F.E., Ndong, J.E., Jeffery, K.J., Mihindou, V., White, L.J.T., Bengone, N.N., Ibrahim, F., Addo-Danso, S.D., Duah-Gyamfi, A., Djagbletey, G.D., Owusu-Afriyie, K., Amissah, L., Mbou, A.T., Marthews, T.R., Metcalfe, D.B., Aragão, L.E.O., Marimon-Junior, B.H., Marimon, B.S., Majalap, N., Adu-Bredu, S., Abernethy, K.A., Silman, M., Ewers, R.M., Meir, P., Malhi, Y., 2021. Fine root dynamics across pantropical rainforest ecosystems. Global Change Biology 27, 3657–3680. https://doi.org/10.1111/gcb.15677

Hwong, Y.-L., Song, S., Sherwood, S., Stirling, A., Rio, C., Roehrig, R., Daleu, C.L., Plant, R.S., Fuchs, D., Maher, P., Touzé-Peiffer, L., 2021. Characterizing Convection Schemes Using Their Responses to Imposed Tendency Perturbations. Journal of Advances in Modeling Earth Systems 13, e2021MS002461. https://doi.org/10.1029/2021MS002461

Irving, D., Hobbs, W., Church, J., Zika, J., 2021. A Mass and Energy Conservation Analysis of Drift in the CMIP6 Ensemble. Journal of Climate 34, 3157–3170. https://doi.org/10.1175/JCLI-D-20-0281.1

Isaza, A., Kay, M., Evans, J.P., Bremner, S., Prasad, A., 2021. Validation of Australian atmospheric aerosols from reanalysis data and CMIP6 simulations. Atmospheric Research 264, 105856. https://doi.org/10.1016/j.atmosres.2021.105856

Iwamoto, Y., Aiki, H., Isoguchi, O., Obayashi, Y., Kondo, F., Kondo, Y., Nishioka, and J., 2021. Decadal vision in oceanography 2021: Air–sea boundary. Oceanography in Japan 30, 199–225. https://doi.org/10.5928/kaiyou.30.5_199

Jha, P.K., Materia, S., Zizzi, G., Costa-Saura, J.M., Trabucco, A., Evans, J., Bregaglio, S., 2021. Climate change impacts on phenology and yield of hazelnut in Australia. Agricultural Systems 186, 102982. https://doi.org/10.1016/j.agsy.2020.102982

Jiao, T., Williams, C.A., De Kauwe, M.G., Schwalm, C.R., Medlyn, B.E., 2021. Patterns of post-drought recovery are strongly influenced by drought duration, frequency, post-drought wetness, and bioclimatic setting. Global Change Biology 27, 4630–4643. https://doi.org/10.1111/gcb.15788

Jucker, M., 2021. Scaling of Eliassen-Palm flux vectors. Atmospheric Science Letters 22, e1020. https://doi.org/10.1002/asl.1020

Jucker, M., Reichler, T., Waugh, D.W., 2021. How Frequent Are Antarctic Sudden Stratospheric Warmings in Present and Future Climate? Geophysical Research Letters 48, e2021GL093215. https://doi.org/10.1029/2021GL093215

Jyoteeshkumar reddy, P., Sharples, J.J., Lewis, S.C., Perkins-Kirkpatrick, S.E., 2021. Modulating influence of drought on the synergy between heatwaves and dead fine fuel moisture content of bushfire fuels in the Southeast Australian region. Weather and Climate Extremes 31, 100300. https://doi.org/10.1016/j.wace.2020.100300

Kageyama, M., Sime, L.C., Sicard, M., Guarino, M.-V., de Vernal, A., Stein, R., Schroeder, D., Malmierca-Vallet, I., Abe-Ouchi, A., Bitz, C., Braconnot, P., Brady, E.C., Cao, J., Chamberlain, M.A., Feltham, D., Guo, C., LeGrande, A.N., Lohmann, G., Meissner, K.J., Menviel, L., Morozova, P., Nisancioglu, K.H., Otto-Bliesner, B.L., O'ishi, R., Ramos Buarque, S., Salas y Melia, D., Sherriff-Tadano, S., Stroeve, J., Shi, X., Sun, B., Tomas, R.A., Volodin, E., Yeung, N.K.H., Zhang, Q., Zhang, Z., Zheng, W., Ziehn, T., 2021. A multi-model CMIP6-PMIP4 study of Arctic sea ice at 127 ka: sea ice data compilation and model differences. Clim. Past 17, 37–62. https://doi.org/10.5194/cp-17-37-2021

Kajtar, J.B., Holbrook, N.J., Hernaman, V., Kajtar, J.B., Holbrook, N.J., Hernaman, V., 2021a. A catalogue of marine heatwave metrics and trends for the Australian region. JSHESS 71, 284–302. https://doi.org/10.1071/ES21014

Kajtar, J.B., Santoso, A., Collins, M., Taschetto, A.S., England, M.H., Frankcombe, L.M., 2021b. CMIP5 Intermodel Relationships in the Baseline Southern Ocean Climate System and With Future Projections. Earth's Future 9, e2020EF001873. https://doi.org/10.1029/2020EF001873

Kelly, R., Evans, K., Alexander, K., Bettiol, S., Corney, S., Cullen-Knox, C., Cvitanovic, C., de Salas, K., Emad, G.R., Fullbrook, L., Garcia, C., Ison, S., Ling, S., Macleod, C., Meyer, A., Murray, L., Murunga, M., Nash, K.L., Norris, K., Oellermann, M., Scott, J., Stark, J.S., Wood, G., Pecl, G.T., 2021. Connecting to the oceans: supporting ocean literacy and public engagement. Rev Fish Biol Fisheries. https://doi.org/10.1007/s11160-020-09625-9

Khan, S.S., Echevarria, E.R., Hemer, M.A., 2021. Ocean Swell Comparisons Between Sentinel-1 and WAVEWATCH III Around Australia. Journal of Geophysical Research: Oceans 126, e2020JC016265. https://doi.org/10.1029/2020JC016265

Kim, Y., Evans, J.P., Sharma, A., Rocheta, E., 2021. Spatial, Temporal, and Multivariate Bias in Regional Climate Model Simulations. Geophysical Research Letters 48, e2020GL092058. https://doi.org/10.1029/2020GL092058

King, A.D., Borowiak, A.R., Brown, J.R., Frame, D.J., Harrington, L.J., Min, S.-K., Pendergrass, A., Rugenstein, M., Sniderman, J.M.K., Stone, D.A., 2021a. Transient and Quasi-Equilibrium Climate States at 1.5°C and 2°C Global Warming. Earth's Future 9, e2021EF002274. https://doi.org/10.1029/2021EF002274

King, A.D., Perkins-Kirkpatrick, S.E., Wehner, M.F., Lewis, S.C., 2021b. Reply to Comment by Mandel et al. on "Numerically Bounded Linguistic Probability Schemes Are Unlikely to Communicate Uncertainty Effectively." Earth's Future 9, e2020EF001757. https://doi.org/10.1029/2020EF001757

King, A.D., Sniderman, J.M.K., Dittus, A.J., Brown, J.R., Hawkins, E., Ziehn, T., 2021c. Studying climate stabilization at Paris Agreement levels. Nat. Clim. Chang. 11, 1010–1013. https://doi.org/10.1038/s41558-021-01225-0

King, M.J., Reeder, M.J., 2021. Extreme heat events from an object viewpoint with application to south-east Australia. International Journal of Climatology 41, 2693–2709. https://doi.org/10.1002/joc.6984

Kulinich, M., Fan, Y., Penev, S., Evans, J.P., Olson, R., 2021. A Markov chain method for weighting climate model ensembles. Geoscientific Model Development 14, 3539–3551. https://doi.org/10.5194/gmd-14-3539-2021

Lane, T.P., 2021. Does Lower-Stratospheric Shear Influence the Mesoscale Organization of Convection? Geophysical Research Letters 48, e2020GL091025. https://doi.org/10.1029/2020GL091025

Lang, F., Huang, Y., Protat, A., Truong, S.C.H., Siems, S.T., Manton, M.J., 2021. Shallow Convection and Precipitation Over the Southern Ocean: A Case Study During the CAPRICORN 2016 Field Campaign. Journal of Geophysical Research: Atmospheres 126, e2020JD034088. https://doi.org/10.1029/2020JD034088

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

Lian, X., Piao, S., Chen, A., Huntingford, C., Fu, B., Li, L.Z.X., Huang, J., Sheffield, J., Berg, A.M., Keenan, T.F., McVicar, T.R., Wada, Y., Wang, X., Wang, T., Yang, Y., Roderick, M.L., 2021. Multifaceted characteristics of dryland aridity changes in a warming world. Nat Rev Earth Environ 2, 232–250. https://doi.org/10.1038/s43017-021-00144-0

Lim, E.-P., Hendon, H.H., Shi, L., de Burgh-Day, C., Hudson, D., King, A., Trewin, B., Griffiths, M., Marshall, A., 2021a. Tropical forcing of Australian extreme low minimum temperatures in September 2019. Clim Dyn 56, 3625–3641. https://doi.org/10.1007/s00382-021-05661-8

Lim, E.-P., Hudson, D., Wheeler, M.C., Marshall, A.G., King, A., Zhu, H., Hendon, H.H., de Burgh-Day, C., Trewin, B., Griffiths, M., Ramchurn, A., Young, G., 2021b. Why Australia was not wet during spring 2020 despite La Niña. Sci Rep 11, 18423. https://doi.org/10.1038/s41598-021-97690-w

Liu, S., Nazarian, N., Hart, M.A., Niu, J., Xie, Y., de Dear, R., 2021. Dynamic thermal pleasure in outdoor environments - temporal alliesthesia. Science of The Total Environment 771, 144910. https://doi.org/10.1016/j.scitotenv.2020.144910

Lott, F.C., Ciavarella, A., Kennedy, J.J., King, A.D., Stott, P.A., Tett, S.F.B., Wang, D., 2021. Quantifying the contribution of an individual to making extreme weather events more likely. Environ. Res. Lett. 16, 104040. https://doi.org/10.1088/1748-9326/abe9e9

Lozano-Durán, A., Constantinou, N.C., Nikolaidis, M.-A., Karp, M., 2021. Cause-and-effect of linear mechanisms sustaining wall turbulence. Journal of Fluid Mechanics 914, A8. https://doi.org/10.1017/jfm.2020.902

Luca, A.D., Argüeso, D., Sherwood, S., Evans, J.P., 2021. Evaluating Precipitation Errors Using the Environmentally Conditioned Intensity-Frequency Decomposition Method. Journal of Advances in Modeling Earth Systems 13, e2020MS002447. https://doi.org/10.1029/2020MS002447

Maher, N., Power, S.B., Marotzke, J., 2021. More accurate quantification of model-to-model agreement in externally forced climatic responses over the coming century. Nature Communications 12, 788. https://doi.org/10.1038/s41467-020-20635-w

Malhi, Y., Girardin, C., Metcalfe, D.B., Doughty, C.E., Aragão, L.E.O.C., Rifai, S.W., Oliveras, I., Shenkin, A., Aguirre-Gutiérrez, J., Dahlsjö, C.A.L., Riutta, T., Berenguer, E., Moore, S., Huasco, W.H., Salinas, N., da Costa, A.C.L., Bentley, L.P., Adu-Bredu, S., Marthews, T.R., Meir, P., Phillips, O.L., 2021. The Global Ecosystems Monitoring network: Monitoring ecosystem productivity and carbon cycling across the tropics. Biological Conservation 253, 108889. https://doi.org/10.1016/j.biocon.2020.108889

Marais, E.A., Roberts, J.F., Ryan, R.G., Eskes, H., Boersma, K.F., Choi, S., Joiner, J., Abuhassan, N., Redondas, A., Grutter, M., Cede, A., Gomez, L., Navarro-Comas, M., 2021. New observations of NO2 in the upper troposphere from TROPOMI. Atmospheric Measurement Techniques 14, 2389–2408. https://doi.org/10.5194/amt-14-2389-2021

Marin, M., Bindoff, N.L., Feng, M., Phillips, H.E., 2021a. Slower Long-Term Coastal Warming Drives Dampened Trends in Coastal Marine Heatwave Exposure. Journal of Geophysical Research: Oceans 126, e2021JC017930. https://doi.org/10.1029/2021JC017930

Marin, M., Feng, M., Phillips, H.E., Bindoff, N.L., 2021b. A Global, Multiproduct Analysis of Coastal Marine Heatwaves: Distribution, Characteristics, and Long-Term Trends. Journal of Geophysical Research: Oceans 126, e2020JC016708. https://doi.org/10.1029/2020JC016708

Marshall, A.G., Gregory, P.A., de Burgh-Day, C.O., Griffiths, M., 2021a. Subseasonal drivers of extreme fire weather in Australia and its prediction in ACCESS-S1 during spring and summer. Clim Dyn 58, 523–553. https://doi.org/10.1007/s00382-021-05920-8

Marshall, A.G., Hendon, H.H., Hudson, D., Marshall, A.G., Hendon, H.H., Hudson, D., 2021b. Influence of the Madden-Julian Oscillation on multiweek prediction of Australian rainfall extremes using the ACCESS-S1 prediction system. JSHESS 71, 159–180. https://doi.org/10.1071/ES21001

Martin, P.E., Arbic, B.K., Hogg, A.M., 2021. Drivers of Atmospheric and Oceanic Surface Temperature Variance: A Frequency Domain Approach. Journal of Climate 34, 3975–3990. https://doi.org/10.1175/JCLI-D-20-0557.1

Martínez-Moreno, J., Hogg, A.M., England, M.H., Constantinou, N.C., Kiss, A.E., Morrison, A.K., 2021. Global changes in oceanic mesoscale currents over the satellite altimetry record. Nature Climate Change 11, 397–403. https://doi.org/10.1038/s41558-021-01006-9

McDermid, S.S., Cook, B.I., De Kauwe, M.G., Mankin, J., Smerdon, J.E., Williams, A.P., Seager, R., Puma, M.J., Aleinov, I., Kelley, M., Nazarenko, L., 2021. Disentangling the Regional Climate Impacts of Competing Vegetation Responses to Elevated Atmospheric CO2. J Geophys Res Atmos 126, e2020JD034108. https://doi.org/10.1029/2020JD034108

McDougall, T.J., Barker, P.M., Holmes, R.M., Pawlowicz, R., Griffies, S.M., Durack, P.J., 2021. The interpretation of temperature and salinity variables in numerical ocean model output and the calculation of heat fluxes and heat content. Geoscientific Model Development 14, 6445–6466. https://doi.org/10.5194/gmd-14-6445-2021

McKay, R.C., Arblaster, J.M., Hope, P., Lim, E.-P., 2021. Exploring atmospheric circulation leading to three anomalous Australian spring heat events. Clim Dyn 56, 2181–2198. https://doi.org/10.1007/s00382-020-05580-0

Meehl, G.A., Hu, A., Castruccio, F., England, M.H., Bates, S.C., Danabasoglu, G., McGregor, S., Arblaster, J.M., Xie, S.-P., Rosenbloom, N., 2021a. Atlantic and Pacific tropics connected by mutually interactive decadal-timescale processes. Nat. Geosci. 14, 36–42. https://doi.org/10.1038/s41561-020-00669-x

Meehl, G.A., Richter, J.H., Teng, H., Capotondi, A., Cobb, K., Doblas-Reyes, F., Donat, M.G., England, M.H., Fyfe, J.C., Han, W., Kim, H., Kirtman, B.P., Kushnir, Y., Lovenduski, N.S., Mann, M.E., Merryfield, W.J., Nieves, V., Pegion, K., Rosenbloom, N., Sanchez, S.C., Scaife, A.A., Smith, D., Subramanian, A.C., Sun, L., Thompson, D., Ummenhofer, C.C., Xie, S.-P., 2021b. Initialized Earth System prediction from subseasonal to decadal timescales. Nat Rev Earth Environ 2, 340–357. https://doi.org/10.1038/s43017-021-00155-x

Meissner, K.J., Brook, E., Finkelstein, S.A., Rae, J., 2021. Carbon cycle dynamics during episodes of rapid climate change. Environ. Res. Lett. 16, 040201. https://doi.org/10.1088/1748-9326/abeade

Misra, R., Sérazin, G., Meissner, K.J., Sen Gupta, A., 2021. Projected Changes to Australian Marine Heatwaves. Geophysical Research Letters 48, e2020GL091323. https://doi.org/10.1029/2020GL091323

Mondol, M.A.H., Zhu, X., Dunkerley, D., Henley, B.J., 2021. Observed meteorological drought trends in Bangladesh identified with the Effective Drought Index (EDI). Agricultural Water Management 255, 107001. https://doi.org/10.1016/j.agwat.2021.107001

Morrison, H., Peters, J.M., Chandakar, K.K., Sherwood, S.C., 2021a. Influences of environmental relative humidity and horizontal scale of sub-cloud ascent on deep convective initiation. Journal of the Atmospheric Sciences 79, 337–359. https://doi.org/10.1175/JAS-D-21-0056.1

Morrison, H., Peters, J.M., Sherwood, S.C., 2021b. Comparing growth rates of simulated moist and dry convective thermals. Journal of Atmospheric Sciences 78, 797–816. https://doi.org/10.1175/JAS-D-20-0166.1

Mu, M., De Kauwe, M.G., Ukkola, A.M., Pitman, A.J., Gimeno, T.E., Medlyn, B.E., Or, D., Yang, J., Ellsworth, D.S., 2021a. Evaluating a land surface model at a water-limited site: implications for land surface contributions to droughts and heatwaves. Hydrology and Earth System Sciences 25, 447–471. https://doi.org/10.5194/hess-25-447-2021

Mu, M., De Kauwe, M.G., Ukkola, A.M., Pitman, A.J., Guo, W., Hobeichi, S., Briggs, P.R., 2021b. Exploring how groundwater buffers the influence of heatwaves on vegetation function during multi-year droughts. Earth System Dynamics 12, 919–938. https://doi.org/10.5194/esd-12-919-2021

Nash, D.J., Adamson, G.C.D., Ashcroft, L., Bauch, M., Camenisch, C., Degroot, D., Gergis, J., Jusopović, A., Labbé, T., Lin, K.-H.E., Nicholson, S.D., Pei, Q., del Rosario Prieto, M., Rack, U., Rojas, F., White, S., 2021. Climate indices in historical climate reconstructions: a global state of the art. Climate of the Past 17, 1273–1314. https://doi.org/10.5194/cp-17-1273-2021

Nazarian, N., Lee, J.K.W., 2021. Personal assessment of urban heat exposure: a systematic review. Environ. Res. Lett. 16, 033005. https://doi.org/10.1088/1748-9326/abd350

Nazarian, N., Liu, S., Kohler, M., Lee, J.K.W., Miller, C., Chow, W.T., Alhadad, S.B.B., Martilli, A., Quintana, M., Sunden, L., Norford, L., 2021. Project Coolbit: Can your watch predict heat stress and thermal comfort sensation? Environ. Res. Lett. 16, 034031. https://doi.org/10.1088/1748-9326/abd130

Neme, J., England, M.H., Hogg, A.McC., 2021. Seasonal and Interannual Variability of the Weddell Gyre From a High-Resolution Global Ocean-Sea Ice Simulation During 1958–2018. Journal of Geophysical Research: Oceans 126, e2021JC017662. https://doi.org/10.1029/2021JC017662

Neske, S., McGregor, S., Zeller, M., Dommenget, D., 2021. Wind Spatial Structure Triggers ENSO's Oceanic Warm Water Volume Changes. Journal of Climate 34, 1985–1999. https://doi.org/10.1175/JCLI-D-20-0040.1

Nguyen, P.-L., Min, S.-K., Kim, Y.-H., 2021. Combined impacts of the El Niño-Southern Oscillation and Pacific Decadal Oscillation on global droughts assessed using the standardized precipitation evapotranspiration index. International Journal of Climatology 41, E1645–E1662. https://doi.org/10.1002/joc.6796

Nicholls, Z., Lewis, J., Makin, M., Nattala, U., Zhang, G.Z., Mutch, S.J., Tescari, E., Meinshausen, M., 2021. Regionally aggregated, stitched and de-drifted CMIP-climate data, processed with netCDF-SCM v2.0.0. Geoscience Data Journal 8, 154–198. https://doi.org/10.1002/gdj3.113

Nishant, N., Evans, J.P., Virgilio, G.D., Downes, S.M., Ji, F., Cheung, K.K.W., Tam, E., Miller, J., Beyer, K., Riley, M.L., 2021. Introducing NARCliM1.5: Evaluating the Performance of Regional Climate Projections for Southeast Australia for 1950–2100. Earth's Future 9, e2020EF001833. https://doi.org/10.1029/2020EF001833

Nishant, N., Sherwood, S.C., 2021. How Strongly Are Mean and Extreme Precipitation Coupled? Geophysical Research Letters 48, e2020GL092075. https://doi.org/10.1029/2020GL092075

Odo, D.B., Yang, I.A., Green, D., Knibbs, L.D., 2021. Women's empowerment and household fuel use in 31 African countries: a cross-sectional analysis of households in the Demographic and Health Survey. Environ. Res. Lett. 16, 025012. https://doi.org/10.1088/1748-9326/abdd59

Oliver, E.C.J., Benthuysen, J.A., Darmaraki, S., Donat, M.G., Hobday, A.J., Holbrook, N.J., Schlegel, R.W., Sen Gupta, A., 2021. Marine Heatwaves. Annual Review of Marine Science 13, 313–342. https://doi.org/10.1146/annurev-marine-032720-095144

O'Neill, C.M., Hogg, A.M., Ellwood, M.J., Opdyke, B.N., Eggins, S.M., 2021. Sequential changes in ocean circulation and biological export productivity during the last glacial–interglacial cycle: a model–data study. Climate of the Past 17, 171–201. https://doi.org/10.5194/cp-17-171-2021

Osbrough, S.L., Frederiksen, J.S., 2021. Interdecadal changes in Southern Hemisphere winter explosive storms and Southern Australian rainfall. Clim Dyn 56, 3103–3130. https://doi.org/10.1007/s00382-021-05633-y

Otto-Bliesner, B.L., Brady, E.C., Zhao, A., Brierley, C.M., Axford, Y., Capron, E., Govin, A., Hoffman, J.S., Isaacs, E., Kageyama, M., Scussolini, P., Tzedakis, P.C., Williams, C.J.R., Wolff, E., Abe-Ouchi, A., Braconnot, P., Ramos Buarque, S., Cao, J., de Vernal, A., Guarino, M.V., Guo, C., LeGrande, A.N., Lohmann, G., Meissner, K.J., Menviel, L., Morozova, P.A., Nisancioglu, K.H., O'ishi, R., Salas y Mélia, D., Shi, X., Sicard, M., Sime, L., Stepanek, C., Tomas, R., Volodin, E., Yeung, N.K.H., Zhang, Q., Zhang, Z., Zheng, W., 2021. Large-scale features of Last Interglacial climate: results from evaluating the lig127k simulations for the Coupled Model Intercomparison Project (CMIP6)–Paleoclimate Modeling Intercomparison Project (PMIP4). Clim. Past 17, 63–94. https://doi.org/10.5194/cp-17-63-2021

Palmer, M.D., Domingues, C.M., Slangen, A.B.A., Dias, F.B., 2021. An ensemble approach to quantify global mean sea-level rise over the 20th century from tide gauge reconstructions. Environ. Res. Lett. 16, 044043. https://doi.org/10.1088/1748-9326/abdaec

Paul, K.K., Macadam, I., Green, D., Regan, D.G., Gray, R.T., 2021. Dengue transmission risk in a changing climate: Bangladesh is likely to experience a longer dengue fever season in the future. Environ. Res. Lett. 16, 114003. https://doi.org/10.1088/1748-9326/ac2b60

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

Pihl, E., Alfredsson, E., Bengtsson, M., Bowen, K.J., Broto, V.C., Chou, K.T., Cleugh, H., Ebi, K., Edwards, C.M., Fisher, E., Friedlingstein, P., Godoy-Faúndez, A., Gupta, M., Harrington, A.R., Hayes, K., Hayward, B.M., Hebden, S.R., Hickmann, T., Hugelius, G., Ilyina, T., Jackson, R.B., Keenan, T.F., Lambino, R.A., Leuzinger, S., Malmaeus, M., McDonald, R.I., McMichael, C., Miller, C.A., Muratori, M., Nagabhatla, N., Nagendra, H., Passarello, C., Penuelas, J., Pongratz, J., Rockström, J., Romero-Lankao, P., Roy, J., Scaife, A.A., Schlosser, P., Schuur, E., Scobie, M., Sherwood, S.C., Sioen, G.B., Skovgaard, J., Obregon, E.A.S., Sonntag, S., Spangenberg, J.H., Spijkers, O., Srivastava, L., Stammer, D.B., Torres, P.H.C., Turetsky, M.R., Ukkola, A.M., Vuuren, D.P. van, Voigt, C., Wannous, C., Zelinka, M.D., 2021. Ten new insights in climate science 2020 – a horizon scan. Global Sustainability 4, 1–18. https://doi.org/10.1017/sus.2021.2

Poddar, S., Evans, J.P., Kay, M., Prasad, A., Bremner, S., 2021. Estimation of future changes in photovoltaic potential in Australia due to climate change. Environ. Res. Lett. 16, 114034. https://doi.org/10.1088/1748-9326/ac2a64

Pohl, B., Favier, V., Wille, J., Udy, D.G., Vance, T.R., Pergaud, J., Dutrievoz, N., Blanchet, J., Kittel, C., Amory, C., Krinner, G., Codron, F., 2021. Relationship Between Weather Regimes and Atmospheric Rivers in East Antarctica. Journal of Geophysical Research: Atmospheres 126, e2021JD035294. https://doi.org/10.1029/2021JD035294

Potgieter, J., Nazarian, N., Lipson, M.J., Hart, M.A., Ulpiani, G., Morrison, W., Benjamin, K., 2021. Combining High-Resolution Land Use Data With Crowdsourced Air Temperature to Investigate Intra-Urban Microclimate. Frontiers in Environmental Science 9, 385. https://doi.org/10.3389/fenvs.2021.720323

Pourasghar, F., Oliver, E.C.J., Holbrook, N.J., 2021. Influence of the MJO on daily surface air temperature over Iran. International Journal of Climatology 41, 4562–4573. https://doi.org/10.1002/joc.7086

Prasad, A.A., Yang, Y., Kay, M., Menictas, C., Bremner, S., 2021. Synergy of solar photovoltaics-wind-battery systems in Australia. Renewable and Sustainable Energy Reviews 152, 111693. https://doi.org/10.1016/j.rser.2021.111693

Purich, A., Boschat, G., Liguori, G., 2021. Assessing the impact of suppressing Southern Ocean SST variability in a coupled climate model. Sci Rep 11, 22069. https://doi.org/10.1038/s41598-021-01306-2

Purich, A., England, M.H., 2021. Historical and Future Projected Warming of Antarctic Shelf Bottom Water in CMIP6 Models. Geophysical Research Letters 48, e2021GL092752. https://doi.org/10.1029/2021GL092752

Raavi, P.H., Walsh, K.J.E., 2021. Response of Tropical Cyclone Frequency to Sea Surface Temperatures Using Aqua-Planet Simulations. Oceans 2, 785–810. https://doi.org/10.3390/oceans2040045

Rathore, S., Bindoff, N.L., Ummenhofer, C.C., Phillips, H.E., Feng, M., Mishra, M., 2021. Improving Australian Rainfall Prediction Using Sea Surface Salinity. Journal of Climate 34, 2473–2490. https://doi.org/10.1175/JCLI-D-20-0625.1

Raut, B.A., Jackson, R., Picel, M., Collis, S.M., Bergemann, M., Jakob, C., 2021. An Adaptive Tracking Algorithm for Convection in Simulated and Remote Sensing Data. Journal of Applied Meteorology and Climatology 60, 513–526. https://doi.org/10.1175/JAMC-D-20-0119.1

Reddy, P.J., Perkins-Kirkpatrick, S.E., Sharples, J.J., 2021a. Interactive influence of ENSO and IOD on contiguous heatwaves in Australia. Environ. Res. Lett. 17, 014004. https://doi.org/10.1088/1748-9326/ac3e9a

Reddy, P.J., Perkins Kirkpatrick, S.E., Sharples, J.J., 2021b. Intensifying Australian Heatwave Trends and Their Sensitivity to Observational Data. Earth's Future 9, e2020EF001924. https://doi.org/10.1029/2020EF001924

Reeder, M.J., Spengler, T., Spensberger, C., 2021. The Effect of Sea Surface Temperature Fronts on Atmospheric Frontogenesis. Journal of the Atmospheric Sciences 78, 1753–1771. https://doi.org/10.1175/JAS-D-20-0118.1

Reid, K.J., O'Brien, T.A., King, A.D., Lane, T.P., 2021a. Extreme Water Vapor Transport During the March 2021 Sydney Floods in the Context of Climate Projections. Geophysical Research Letters 48, e2021GL095335. https://doi.org/10.1029/2021GL095335

Reid, K.J., Rosier, S.M., Harrington, L.J., King, A.D., Lane, T.P., 2021b. Extreme rainfall in New Zealand and its association with atmospheric rivers. Environ. Res. Lett. 16, 044012. https://doi.org/10.1088/1748-9326/abeae0

Renner, M., Kleidon, A., Clark, M., Nijssen, B., Heidkamp, M., Best, M., Abramowitz, G., 2021. How Well Can Land-Surface Models Represent the Diurnal Cycle of Turbulent Heat Fluxes? Journal of Hydrometeorology 22, 77–94. https://doi.org/10.1175/JHM-D-20-0034.1

Ridder, N.N., Pitman, A.J., Ukkola, A.M., 2021. Do CMIP6 Climate Models Simulate Global or Regional Compound Events Skillfully? Geophysical Research Letters 48, e2020GL091152. https://doi.org/10.1029/2020GL091152

Ridout, J.A., Barton, N.P., Janiga, M.A., Reynolds, C.A., May, J.C., Rowley, C., Bishop, C.H., 2021. Surface Radiative Flux Bias Reduction Through Regionally Varying Cloud Fraction Parameter Nudging in a Global Coupled Forecast System. Journal of Advances in Modeling Earth Systems 13, e2019MS002006. https://doi.org/10.1029/2019MS002006

Roca, R., Haddad, Z.S., Akimoto, F.F., Alexander, L., Behrangi, A., Huffman, G., Kato, S., Kidd, C., Kirstetter, P.-E., Kubota, T., Kummerow, C., L'Ecuyer, T., Levizzani, V., Maggioni, V., Massari, C., Masunaga, H., Schröder, M., Tapiador, F.J., Turk, F.J., Utsumi, N., 2021. The Joint IPWG/GEWEX Precipitation Assessment. WCRP Publication No.: 2/2021. https://doi.org/10.13021/gewex.precip

Ryan, R.G., Silver, J.D., Schofield, R., 2021. Air quality and health impact of 2019–20 Black Summer megafires and COVID-19 lockdown in Melbourne and Sydney, Australia. Environmental Pollution 274, 116498. https://doi.org/10.1016/j.envpol.2021.116498

Ryan, S., Ummenhofer, C.C., Gawarkiewicz, G., Wagner, P., Scheinert, M., Biastoch, A., Böning, C.W., 2021. Depth Structure of Ningaloo Niño/Niña Events and Associated Drivers. Journal of Climate 34, 1767–1788. https://doi.org/10.1175/JCLI-D-19-1020.1

Saini, H., Kvale, K., Chase, Z., Kohfeld, K.E., Meissner, K.J., Menviel, L., 2021. Southern Ocean Ecosystem Response to Last Glacial Maximum Boundary Conditions. Paleoceanography and Paleoclimatology 36, e2020PA004075. https://doi.org/10.1029/2020PA004075

Sauermilch, I., Whittaker, J.M., Klocker, A., Munday, D.R., Hochmuth, K., Bijl, P.K., LaCasce, J.H., 2021. Gateway-driven weakening of ocean gyres leads to Southern Ocean cooling. Nature Communications 12, 6465. https://doi.org/10.1038/s41467-021-26658-1

Savita, A., Zika, J.D., Domingues, C.M., Marsland, S.J., Evans, G.D., Dias, F.B., Holmes, R.M., Hogg, A.M., 2021. Super Residual Circulation: a new perspective on ocean vertical heat transport. Journal of Physical Oceanography 51, 2443–2462. https://doi.org/10.1175/JPO-D-21-0008.1

Schofield, R., Utembe, S., Gionfriddo, C., Tate, M., Krabbenhoft, D., Adeloju, S., Keywood, M., Dargaville, R., Sandiford, M., 2021. Atmospheric mercury in the Latrobe Valley, Australia: Case study June 2013. Elementa: Science of the Anthropocene 9, 00072. https://doi.org/10.1525/elementa.2021.00072

Schwendike, J., Berry, G.J., Fodor, K., Reeder, M.J., 2021. On the Relationship Between the Madden-Julian Oscillation and the Hadley and Walker Circulations. Journal of Geophysical Research: Atmospheres 126, e2019JD032117. https://doi.org/10.1029/2019JD032117

Sen Gupta, A., Stellema, A., Pontes, G.M., Taschetto, A.S., Vergés, A., Rossi, V., 2021. Future changes to the upper ocean Western Boundary Currents across two generations of climate models. Sci Rep 11, 9538. https://doi.org/10.1038/s41598-021-88934-w

Sérazin, G., Di Luca, A., Sen Gupta, A., Rogé, M., Jourdain, N.C., Argüeso, D., Bull, C.Y.S., 2021. East Australian Cyclones and Air-Sea Feedbacks. Journal of Geophysical Research: Atmospheres 126, e2020JD034391. https://doi.org/10.1029/2020JD034391

Shahrokhishahraki, N., Rayner, P.J., Silver, J.D., Thomas, S., Schofield, R., 2021. High-resolution modeling of gaseous air pollutants over Tehran and validation with surface and satellite data. Atmospheric Environment 270, 118881. https://doi.org/10.1016/j.atmosenv.2021.118881

Shakespeare, C.J., Arbic, B.K., Hogg, A.M., 2021a. Dissipating and reflecting internal waves. Journal of Physical Oceanography 51, 2517–2531. https://doi.org/10.1175/JPO-D-20-0261.1

Shakespeare, C.J., Arbic, B.K., Hogg, A.M., 2021b. The Impact of Abyssal Hill Roughness on the Benthic Tide. Journal of Advances in Modeling Earth Systems 13, e2020MS002376. https://doi.org/10.1029/2020MS002376

Shakespeare, C.J., Roderick, M.L., 2021. The clear-sky downwelling long-wave radiation at the surface in current and future climates. Quarterly Journal of the Royal Meteorological Society 147, 4251–4268. https://doi.org/10.1002/qj.4176

Sherwood, S., Hoskins, B., 2021. Clarion call from climate panel. Science 373, 719–719. https://doi.org/10.1126/science.abl8490

Shin, N.-Y., Kug, J.-S., McCormack, F.S., Holbrook, N.J., 2021. The Double-Peaked El Niño and Its Physical Processes. Journal of Climate 34, 1291–1303. https://doi.org/10.1175/JCLI-D-20-0402.1

Slivinski, L.C., Compo, G.P., Sardeshmukh, P.D., Whitaker, J.S., McColl, C., Allan, R.J., Brohan, P., Yin, X., Smith, C.A., Spencer, L.J., Vose, R.S., Rohrer, M., Conroy, R.P., Schuster, D.C., Kennedy, J.J., Ashcroft, L., Brönnimann, S., Brunet, M., Camuffo, D., Cornes, R., Cram, T.A., Domínguez-Castro, F., Freeman, J.E., Gergis, J., Hawkins, E., Jones, P.D., Kubota, H., Lee, T.C., Lorrey, A.M., Luterbacher, J., Mock, C.J., Przybylak, R.K., Pudmenzky, C., Slonosky, V.C., Tinz, B., Trewin, B., Wang, X.L., Wilkinson, C., Wood, K., Wyszyński, P., 2021. An evaluation of the performance of the 20th Century Reanalysis version 3. Journal of Climate 34, 1417–1438. https://doi.org/10.1175/JCLI-D-20-0505.1

Slot, M., Rifai, S.W., Winter, K., 2021. Photosynthetic plasticity of a tropical tree species, Tabebuia rosea, in response to elevated temperature and [CO2]. Plant, Cell & Environment 44, 2347–2364. https://doi.org/10.1111/pce.14049

Smith, K.E., Burrows, M.T., Hobday, A.J., Sen Gupta, A., Moore, P.J., Thomsen, M., Wernberg, T., Smale, D.A., 2021. Socioeconomic impacts of marine heatwaves: Global issues and opportunities. Science 374, 6566. https://doi.org/10.1126/science.abj3593

Sohail, T., Irving, D.B., Zika, J.D., Holmes, R.M., Church, J.A., 2021. Fifty Year Trends in Global Ocean Heat Content Traced to Surface Heat Fluxes in the Sub-Polar Ocean. Geophysical Research Letters 48, e2020GL091439. https://doi.org/10.1029/2020GL091439

Stewart, K.D., Hogg, A.McC., England, M.H., Waugh, D.W., Kiss, A.E., 2021. The Ekman Streamfunction and the Eulerian and Residual Overturning Circulations of the Southern Ocean. Geophysical Research Letters 48, e2021GL093438. https://doi.org/10.1029/2021GL093438

Su, C.-H., Eizenberg, N., Jakob, D., Fox-Hughes, P., Steinle, P., White, C.J., Franklin, C., 2021. BARRA v1.0: kilometre-scale downscaling of an Australian regional atmospheric reanalysis over four midlatitude domains. Geoscientific Model Development 14, 4357–4378. https://doi.org/10.5194/gmd-14-4357-2021

Su, J., Strutton, P.G., Schallenberg, C., 2021. The subsurface biological structure of Southern Ocean eddies revealed by BGC-Argo floats. Journal of Marine Systems 220, 103569. https://doi.org/10.1016/j.jmarsys.2021.103569

Su, Z., Pilo, G.S., Corney, S., Holbrook, N.J., Mori, M., Ziegler, P., 2021. Characterizing Marine Heatwaves in the Kerguelen Plateau Region. Front. Mar. Sci. 7. https://doi.org/10.3389/fmars.2020.531297

Tang, W., Llort, J., Weis, J., Perron, M.M.G., Basart, S., Li, Z., Sathyendranath, S., Jackson, T., Sanz Rodriguez, E., Proemse, B.C., Bowie, A.R., Schallenberg, C., Strutton, P.G., Matear, R., Cassar, N., 2021. Widespread phytoplankton blooms triggered by 2019–2020 Australian wildfires. Nature 597, 370–375. https://doi.org/10.1038/s41586-021-03805-8

Teckentrup, L., De Kauwe, M.G., Pitman, A.J., Goll, D.S., Haverd, V., Jain, A.K., Joetzjer, E., Kato, E., Lienert, S., Lombardozzi, D., McGuire, P.C., Melton, J.R., Nabel, J.E.M.S., Pongratz, J., Sitch, S., Walker, A.P., Zaehle, S., 2021a. Assessing the representation of the Australian carbon cycle in global vegetation models. Biogeosciences 18, 5639–5668. https://doi.org/10.5194/bg-18-5639-2021

Teckentrup, L., De Kauwe, M.G., Pitman, A.J., Smith, B., 2021b. Examining the sensitivity of the terrestrial carbon cycle to the expression of El Niño. Biogeosciences 18, 2181–2203. https://doi.org/10.5194/bg-18-2181-2021

Trebilco, R., Fleming, A., Hobday, A.J., Melbourne-Thomas, J., Meyer, A., McDonald, J., McCormack, P.C., Anderson, K., Bax, N., Corney, S.P., Dutra, L.X.C., Fogarty, H.E., McGee, J., Mustonen, K., Mustonen, T., Norris, K.A., Ogier, E., Constable, A.J., Pecl, G.T., 2021. Warming world, changing ocean: mitigation and adaptation to support resilient marine systems. Rev Fish Biol Fisheries. https://doi.org/10.1007/s11160-021-09678-4

Tselioudis, G., Rossow, W.B., Jakob, C., Remillard, J., Tropf, D., Zhang, Y., 2021. Evaluation of Clouds, Radiation, and Precipitation in CMIP6 Models Using Global Weather States Derived from ISCCP-H Cloud Property Data. Journal of Climate 34, 7311–7324. https://doi.org/10.1175/JCLI-D-21-0076.1

Udy, D.G., Vance, T.R., Kiem, A.S., Holbrook, N.J., Curran, M.A.J., 2021. Links between large-scale modes of climate variability and synoptic weather patterns in the southern Indian Ocean. Journal of Climate 34, 883–899. https://doi.org/10.1175/JCLI-D-20-0297.1

Uhe, P., Mitchell, D., Bates, P.D., Allen, M.R., Betts, R.A., Huntingford, C., King, A.D., Sanderson, B.M., Shiogama, H., 2021. Method-uncertainty is essential for reliable confidence statements of precipitation projections. Journal of Climate 34, 1227–1240. https://doi.org/10.1175/JCLI-D-20-0289.1

Ukkola, A.M., De Kauwe, M.G., Roderick, M.L., Burrell, A., Lehmann, P., Pitman, A.J., 2021. Annual precipitation explains variability in dryland vegetation greenness globally but not locally. Global Change Biology 27, 4367–4380. https://doi.org/10.1111/gcb.15729

Ummenhofer, C.C., Murty, S.A., Sprintall, J., Lee, T., Abram, N.J., 2021. Heat and freshwater changes in the Indian Ocean region. Nat Rev Earth Environ 2, 525–541. https://doi.org/10.1038/s43017-021-00192-6

Urquiza Muñoz, J.D., Magnabosco Marra, D., Negrón-Juarez, R.I., Tello-Espinoza, R., Alegría-Muñoz, W., Pacheco-Gómez, T., Rifai, S.W., Chambers, J.Q., Jenkins, H.S., Brenning, A., Trumbore, S.E., 2021. Recovery of Forest Structure Following Large-Scale Windthrows in the Northwestern Amazon. Forests 12, 667. https://doi.org/10.3390/f12060667

van Oldenborgh, G.J., van der Wiel, K., Kew, S., Philip, S., Otto, F., Vautard, R., King, A., Lott, F., Arrighi, J., Singh, R., van Aalst, M., 2021. Pathways and pitfalls in extreme event attribution. Climatic Change 166, 13. https://doi.org/10.1007/s10584-021-03071-7

Villalobos, Y., Rayner, P.J., Silver, J.D., Thomas, S., Haverd, V., Knauer, J., Loh, Z.M., Deutscher, N.M., Griffith, D.W.T., Pollard, D.F., 2021. Was Australia a sink or source of CO2 in 2015? Data assimilation using OCO-2 satellite measurements. Atmospheric Chemistry and Physics 21, 17453–17494. https://doi.org/10.5194/acp-21-17453-2021

Walker, A.P., De Kauwe, M.G., Bastos, A., Belmecheri, S., Georgiou, K., Keeling, R.F., McMahon, S.M., Medlyn, B.E., Moore, D.J.P., Norby, R.J., Zaehle, S., Anderson Teixeira, K.J., Battipaglia, G., Brienen, R.J.W., Cabugao, K.G., Cailleret, M., Campbell, E., Canadell, J.G., Ciais, P., Craig, M.E., Ellsworth, D.S., Farquhar, G.D., Fatichi, S., Fisher, J.B., Frank, D.C., Graven, H., Gu, L., Haverd, V., Heilman, K., Heimann, M., Hungate, B.A., Iversen, C.M., Joos, F., Jiang, M., Keenan, T.F., Knauer, J., Körner, C., Leshyk, V.O., Leuzinger, S., Liu, Y., MacBean, N., Malhi, Y., McVicar, T.R., Penuelas, J., Pongratz, J., Powell, A.S., Riutta, T., Sabot, M.E.B., Schleucher, J., Sitch, S., Smith, W.K., Sulman, B., Taylor, B., Terrer, C., Torn, M.S., Treseder, K.K., Trugman, A.T., Trumbore, S.E., Mantgem, P.J. van, Voelker, S.L., Whelan, M.E., Zuidema, P.A., 2021. Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO2. New Phytologist 229, 2413–2445. https://doi.org/10.1111/nph.16866

Wang, G., Hope, P., Lim, E.-P., Hendon, H.H., Arblaster, J.M., 2021. An Initialized Attribution Method for Extreme Events on Subseasonal to Seasonal Time Scales. Journal of Climate 34, 1453–1465. https://doi.org/10.1175/JCLI-D-19-1021.1

Wang, Z., Zhao, Z., Wang, C., 2021. Random forest analysis of factors affecting urban carbon emissions in cities within the Yangtze River Economic Belt. PLOS ONE 16, e0252337. https://doi.org/10.1371/journal.pone.0252337

Warren, R.A., Jakob, C., Hitchcock, S.M., White, B.A., 2021a. Heavy versus extreme rainfall events in southeast Australia. Quarterly Journal of the Royal Meteorological Society 147, 3201–3226. https://doi.org/10.1002/qj.4124

Warren, R.A., Richter, H., Thompson, R.L., 2021b. Spectrum of Near-Storm Environments for Significant Severe Right-Moving Supercells in the Contiguous United States. Monthly Weather Review 149, 3299–3323. https://doi.org/10.1175/MWR-D-21-0006.1

Waterman, S., Meyer, A., Polzin, K.L., Garabato, A.C.N., Sheen, K.L., 2021. Antarctic Circumpolar Current Impacts on Internal Wave Life Cycles. Geophysical Research Letters 48, e2020GL089471. https://doi.org/10.1029/2020GL089471

Waugh, D.W., Stewart, K., Hogg, A.M., England, M.H., 2021. Interbasin Differences in Ocean Ventilation in Response to Variations in the Southern Annular Mode. Journal of Geophysical Research: Oceans 126, e2020JC016540. https://doi.org/10.1029/2020JC016540

Webb, D.J., Spence, P., Holmes, R.M., England, M.H., 2021. Planetary-Wave-Induced Strengthening of the AMOC Forced by Poleward Intensified Southern Hemisphere Westerly Winds. Journal of Climate 34, 7073–7090. https://doi.org/10.1175/JCLI-D-20-0858.1

White, I.P., Garfinkel, C.I., Cohen, J., Jucker, M., Rao, J., 2021. The Impact of Split and Displacement Sudden Stratospheric Warmings on the Troposphere. Journal of Geophysical Research: Atmospheres 126, e2020JD033989. https://doi.org/10.1029/2020JD033989

Williams, S., Wright, N.M., Cannon, J., Flament, N., Müller, R.D., 2021. Reconstructing seafloor age distributions in lost ocean basins. Geoscience Frontiers 12, 769–780. https://doi.org/10.1016/j.gsf.2020.06.004

Wu, G., Guan, K., Li, Y., Novick, K.A., Feng, X., McDowell, N.G., Konings, A.G., Thompson, S.E., Kimball, J.S., De Kauwe, M.G., Ainsworth, E.A., Jiang, C., 2021. Interannual variability of ecosystem iso/anisohydry is regulated by environmental dryness. New Phytologist 229, 2562–2575. https://doi.org/10.1111/nph.17040

Xie, H., Fischer, A.M., Strutton, P., 2021. Generalized linear models to assess environmental drivers of paralytic shellfish toxin blooms (Southeast Tasmania, Australia). Continental Shelf Research 223, 104439. https://doi.org/10.1016/j.csr.2021.104439

Yang, D., Arblaster, J.M., Meehl, G.A., England, M.H., 2021. The Role of Coupled Feedbacks in the Decadal Variability of the Southern Hemisphere Eddy-Driven Jet. Journal of Geophysical Research: Atmospheres 126, e2021JD035023. https://doi.org/10.1029/2021JD035023

Yang, L., Nikurashin, M., Hogg, A.M., Sloyan, B.M., 2021. The impact of lee waves on the Southern Ocean circulation. Journal of Physical Oceanography 51, 2933–2950. https://doi.org/10.1175/JPO-D-20-0263.1

Yang, Y., McVicar, T.R., Yang, D., Zhang, Y., Piao, S., Peng, S., Beck, H.E., 2021a. Low and contrasting impacts of vegetation CO2 fertilization on global terrestrial runoff over 1982–2010: accounting for aboveground and belowground vegetation–CO2 effects. Hydrology and Earth System Sciences 25, 3411–3427. https://doi.org/10.5194/hess-25-3411-2021

Yang, Y., Roderick, M.L., Yang, D., Wang, Z., Ruan, F., McVicar, T.R., Zhang, S., Beck, H.E., 2021b. Streamflow stationarity in a changing world. Environ. Res. Lett. 16, 064096. https://doi.org/10.1088/1748-9326/ac08c1

Yeung, N.K.-H., Menviel, L., Meissner, K.J., Taschetto, A.S., Ziehn, T., Chamberlain, M., 2021. Land–sea temperature contrasts at the Last Interglacial and their impact on the hydrological cycle. Climate of the Past 17, 869–885. https://doi.org/10.5194/cp-17-869-2021

Yeung, N.K.H., Sherwood, S.C., Protat, A., Lane, T.P., Williams, C., 2021. A Doppler radar study of convective draft lengths over Darwin, Australia. Monthly Weather Review 149, 2965–2974. https://doi.org/10.1175/MWR-D-20-0390.1

Zeller, M., McGregor, S., van Sebille, E., Capotondi, A., Spence, P., 2021. Subtropical-tropical pathways of spiciness anomalies and their impact on equatorial Pacific temperature. Clim Dyn 56, 1131–1144. https://doi.org/10.1007/s00382-020-05524-8

Zhang, G., Azorin-Molina, C., Chen, D., McVicar, T.R., Guijarro, J.A., Kong, F., Minola, L., Deng, K., Shi, P., 2021. Uneven Warming Likely Contributed to Declining Near-Surface Wind Speeds in Northern China Between 1961 and 2016. Journal of Geophysical Research: Atmospheres 126, e2020JD033637. https://doi.org/10.1029/2020JD033637

Zhang, Y., Du, Y., Qu, T., Hong, Y., Domingues, C.M., Feng, M., 2021. Changes in the Subantarctic Mode Water Properties and Spiciness in the Southern Indian Ocean based on Argo Observations. Journal of Physical Oceanography 51, 2203–2221. https://doi.org/10.1175/JPO-D-20-0254.1

Zhao, W., Huang, Y., Siems, S., Manton, M., 2021. The Role of Clouds in Coral Bleaching Events Over the Great Barrier Reef. Geophysical Research Letters 48, e2021GL093936. https://doi.org/10.1029/2021GL093936

Zhao, Z., Zhang, X., 2021. Evaluation of methods to detect and quantify the bimodal precipitation over Central America and Mexico. International Journal of Climatology 41, E897–E911. https://doi.org/10.1002/joc.6736

PUBLISHED DATA SETS

Braghiere, R., 2020. Data for: Sun zenith angular impact of vegetation clumping on site level photosynthesis. Mendeley. https://doi.org/10.17632/kkvjjrggpy.1

Constantinou, N.C., Parker, J.B., 2020. Dedalus output from 2D incompressible MHD fluid on a magnetized beta plane. https://doi.org/10.5281/zenodo.3892089

Delage, F., Narsey, S., Chung, C., Katjar, J., Lyu, K., Rashid, H.A., Grose, M.R., Rauniyar, S., Bador, M., Wales, S., Freund, M., Boschat, G., 2020. CMIP6 analysis code for publication: Insights from CMIP6 for Australia's future climate. Zenodo. https://doi.org/10.5281/zenodo.3698369

Druken, K., 2020a. 400m resolution ACCESS limited-area simulation over Australia v1. NCI Australia. https://doi.org/10.25914/5F1E4E3E3DE2E

Druken, K., 2020b. Derived Optimal Linear Combination Evapotranspiration - DOLCE v2.1. NCI. https://doi.org/10.25914/5F1664837EF06

Druken, K., 2020c. Derived Optimal Linear Combination Evapotranspiration - DOLCE v2.1. NCI. https://doi.org/10.25914/5F1664837EF06

Druken, K., 2020d. PLUMBER2: forcing and evaluation datasets for a model intercomparison project for land surface models v1.0. NCI Australia. https://doi.org/10.25914/5FDB0902607E1

Druken, K., 2020e. WRF-LIS-CABLE model output from the physics sensitivity experiment v1.0. NCI. https://doi.org/10.25914/5F35D28ACA112

Eabry, M., 2020. Repository of Analysis Code for the Manuscript entitled: " What Determines the Lagged ENSO Response in the South-West Indian Ocean?" by M. D. Eabry, A. S. Taschetto, A. M. Maharaj and A. Sen Gupta, submitted to Geophysical Research Letters. Zenodo. https://doi.org/10.5281/zenodo.4301000

Hirsch, A., 2020. Repository of Analysis Code for the Manuscript entitled: "Atmospheric and land surface contributions to heatwaves: an Australian perspective" by Annette L. Hirsch and Malcolm King submitted to Journal of Geophysical Research - Atmospheres. Zenodo. https://doi.org/10.5281/zenodo.3945542

Hobeichi, S., 2020. Derived Optimal Linear Combination Evapotranspiration - DOLCE v2.0. NCI. https://doi.org/10.25914/5EAB8F533AEAE

Konecky, B.L., McKay, N.P., Churakova (Sidorova), O.V., Comas-Bru, L., Dassié, E.P., DeLong, K.L., Falster, G.M., Fischer, M.J., Jones, M.D., Jonkers, L., Kaufman, D.S., Leduc, G., Managave, S.R., Martrat, B., Opel, T., Orsi, A.J., Partin, J.W., Sayani, H.R., Thomas, E.K., Thompson, D.M., Tyler, J.J., Abram, N.J., Atwood, A.R., Cartapanis, O., Conroy, J.L., Curran, M.A., Dee, S.G., Deininger, M., Divine, D.V., Kern, Z., Porter, T.J., Stevenson, S.L., von Gunten, L., Iso2k Project Members, 2020. Iso2k Database Global Common Era Paleo-d18O and d2H Records. https://doi.org/10.25921/57j8-vs18

Petrelli, P., 2020. coecms/era5: python base codes to interface the CDS api and automate ERA5 download: v0.5. Zenodo. https://doi.org/10.5281/zenodo.3972437

Wales, S., 2020. 400m resolution ACCESS limited-area simulation over Australia.

Wales, S., Petrelli, P., 2020. CleF - Climate Finder. Zenodo. https://doi.org/10.5281/zenodo.4060776

IMPACT, ENGAGEMENT, AWARDS & SERVICE

ENGAGEMENT WITH INDUSTRY, GOVERNMENT AND NGOs

Abramowitz, G. Online session with Science Teachers' Association of NSW

Alexander, L. Presentation to UNEP Finance Initiative on "Using climate observations and models in assessments of risk: challenges and opportunities"

Alexander, L. Briefing on findings of IPCC AR6 to Member for Wentworth Dave Sharma. With Andy Pitman, Katrin Meissner and Steve Sherwood.

Alexander, L. Briefing on findings of IPCC AR6 to Member for Kingsford Smith Matt Thistlethwaite

Alexander, L. Public Webinar on behalf of WMO on supporting climate action through climate indices online

Ashcroft, L. Webinar for Mornington Peninsula Council: Climate Change - What is it and what can we do about it?

Evans, J. Presented to the JARDEN group about climate change and future climate risks

Evans, J. Webinar on "Impacts of climate change on extreme event hydrology" for the Australian Water School. Attendees are largely practising engineers

Gallant, A. Webinar briefing to audience including government "Climate variability and change – past, present and future"

Henley, B. Advisor, Queensland Flood and Drought project

Hobeichi, S. Published an article in SEN, the journal of the Science Teacher's Association of NSW on Climate Classrooms collaboration

Hobeichi, S. Published an article in SCIOS, the journal of the Science Teacher's Association of Western Australia on Climate Classrooms collaboration

Holbrook, N. Briefing of the Tasmanian Premier's Office on 'IPCC AR6 report and what does it mean for Tasmania'

Holbrook, N. CLEX CI's Amelie Meyer, Pete Strutton and Neil Holbrook had a briefing with UTAS Vice Chancellor Rufus Black about the IPCC AR6 WG1 report

Jakob, C. Release of a Royal Society Brief on the future of climate modelling to the Glasgow COP meeting that I co-authored

King, A. Briefing on the findings of the IPCC sixth assessment report to Senator Janet Rice.

King, A. Presentation on the IPCC AR6 report and the implications of COP26 as part of the CitySwitch National Signatory Event

Lane, T. Presented Keynote at the Victorian Physics Teachers Conference. Entitled: "Telling the future: climate science and climate modelling"

Macadam, I. With Lisa Alexander, Gab Abramowitz and Sanaa Hobeichi, meeting with Risk Frontiers on climdex and AR machine learning work

Macadam, I. Discussions around use of and access to CMIP6 data with Deloitte

Macadam, I. Submission to Transport for NSW "have your say" on Future Transport consultative draft document on resilient transport networks .

Macadam, I. Submission on Natural Hazards Research Australia draft research priorities

Meyer, A. Invited talk at the Tasmanian Climate Change Symposium, funded by Tas Hydro. 'Climate change - A Tasmanian perspective'

Meyer, A. Briefing of the Tasmanian Premier's Office on 'IPCC AR6 report and what does it mean for Tasmania'

Meyer, A. Presented an IPCC briefing to Tasmanian The Greens MPs

Meyer, A. Briefing to Tasmanian Opposition Leader 'The IPCC AR6 report: What does it mean for Tasmania?'

Parker, T. Invited presentation at BoM webinar: "Heatwave resilience and mitigation in Australia"

Patel, R. With Pete Strutton, met with Australian Fisheries and Australian Longline industry on environmental changes in fishing zones

Pitman, A. Briefed representatives from the Monetary Authority of Singapore on the use of climate information to assess climate risk to financial institutions

Pitman, A. Briefing to Clean Energy Finance Corporation on the IPCC AR6 report

Pitman, A. Met with Facebook to discuss their plans around regional information portals for climate extremes

Pitman, A. Gave a talk to the Banking and finance research group at University of Sydney: "Climate change: Opportunities for research impact & engagement"

Pitman, A. Briefed the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) on the use of climate models for assessing risk

Pitman, A. Briefed Bloomberg/BNEF on the utility of climate models in assessing climate risk

Pitman, A. Webinar to brief UBS on the use of climate models in assessing business risk

Pitman, A. Briefed the technical team of the US Senate Committee on Banking, Housing, and Urban Affairs

on the use of climate models in assessing financial risk."

Pitman, A. Lazard Asset Management, New York, on the use and misuse of climate modelsin the financial sector"

Pitman, A. Briefing to World Business Council for Sustainability Development, on the use of climate models and climate projections in assessing risk

Pitman, A. Briefing to the WA Department of Primary Industries and Regional Development on the role of land cover in influencing rainfall over Western Australia

Pitman, A. Presentation to the Australian Council of Learned Academies (ACOLA) to the Parliamentary Library on IPCC AR6 Report

Pitman, A. Briefing on findings of IPCC AR6 to Member for Wentworth Dave Sharma

Pitman, A. Briefing on findings of IPCC AR6 to Member for Kingsford Smith Matt Thistlethwaite

Pitman, A. Briefing on findings of IPCC AR6 to Member for NSW Environment Minister

Pitman, A. Submitted detailed feedback to APRA on their draft CPG 229 Climate Change Financial Risks Practice Guide

Pitman, A. Briefed Office of the Chief Executive, Sustainable finance, part of the New Zealand government, on the use of climate models for financial risk disclosure

Pitman, A. Presented to TERN (Terrestrial Environmental Research Network, an NCRIS facility) on the current state of climate modelling in Australia

Pitman, A. Presentation on IPCC AR6 report to the NSW/ACT branch of the Clean Air Society of Australian and New Zealand (CASANZ)

Pitman, A. Advice to Engineers Australia in support of their Climate Position statement

Pitman, A. Advice to Monetary Authority of Singapore on downscaling of global models in assessing risk

Pitman, A. Presentation to the Actuaries Institute on IPCC AR6 report

Pitman, A. Presentation to the TERN (an NCRIS facility) on the current state of climate modelling in Australia

Raupach, T. Presentation to Risk Frontiers about hailstorms and their possible responses to climate change

Reid, K. Presented at the Forewarned is Forearmed Community of Practice seminar

Santoso, A. Expert input to insurance companies Finity and Suncorp on the topic: importance of understanding natural climate variability

Santoso, A. Webinar briefing to audience including government "Climate variability and change – past, present and future"

Santoso, A. Online presentation for Monetary Authority of Singapore on climate downscaling and ENSO projections

Sherwood, S. Briefing on findings of IPCC AR6 to Member for Wentworth Dave Sharma

Sherwood, S. Briefing on findings of IPCC AR6 to Member for Kingsford Smith Matt Thistlethwaite

Strutton, P. Spotlight document on Argo and modelling to the Forum for Operational Oceanography

Strutton, P. Presentation on biogeochemical Argo and modelling to the Defence Science and Technology Group.

Strutton, P. Briefing of the Tasmanian Premier's Office on 'IPCC AR6 report and what does it mean for Tasmania'

Strutton, P. Briefing to Tasmanian Opposition Leader 'The IPCC AR6 report: What does it mean for Tasmania?'

Strutton, P. Met with the Tasmanian Department of Primary Industries, Parks, Water and Environment to develop a student project on aquaculture water quality

Taschetto, A. Co-authored briefing note 17 "Could understanding the Indian Ocean improve climate predictions for Australia?"

Taschetto, A. Talk to 'Forewarned is Forarmed' Community of Practice: "What is going on in the Indian Ocean?"

Taschetto, A. Talk at The Forewarned is Forearmed (FWFA) Project Webinar Series on "ENSO diversity and Australian rainfall variability"

Taschetto, A. Talk on ENSO Modoki and Australian rainfall impacts to the 2021 Winter Cropping Climate Outlook Workshop organised by AgEcon

Taschetto, A. Briefing to the Australian Science Media Centre on the La Niña and wet weather this season

Taschetto, A. Talk on ENSO diversity impacts on Australian climate at the University of East Anglia, UK.

Vincent, C. Invited talk at AMOS Workshop: Probabilistic Weather Forecasting for the Energy Industry

PUBLIC TALKS, OUTREACH AND SCHOOL ENGAGEMENT

Arblaster, J. Climate expert panellist for the Young Australians in International Affairs

Arblaster, J. Presentation on climate change to Rotary Ballarat club

Arblaster, J. Talk on climate change to Rotary Club of Ballarat East

Ashcroft, L. Benalla Rotary Club. Past, present and future climate change.

Ashcroft, L. Featured in a video by Melbourne Museum on the climate stripes

Ashcroft, L. Invited talk at the Monash School of Earth, Atmosphere and Environmental Science for International Women's Day

Bador, M. Introduction to climate change Cambon Public Primary School in Rodez, France

Bongiovanni, K. Interactive workshop on "Volcanoes and Climate" for Year 10 students as part of their work experience program at the University of Melbourne

Bongiovanni, K. 3-minute presentation on how "Volcanoes rock the world and the climate" as part of the FameLab Victoria semi-finals

Constantinou, N. Participated at ANU's RSES in the Pub

Constantinou, N. Participated in Atlas of Life South Coast. National Science Week event

Evans, J. National First Peoples Gathering on Climate Change

Fallon, K. Research Engagement and Impact Network (REIN) group at University of Melbourne

Fierro Arcos, D. Women in Data Science (WiDs) virtual meeting, Ecuador

Hart, M. Speaker at Women's Climate Congress, Women's climate conversation- Climate science, women and kindness – connecting the dots

Hart, M. Rapid Urbanisation and Population Health (RUPH) webinar: City Resilience, Climate Change and Population Health- panelist

Henley, B. Presentation to Western English Language School

Henley, B. Quantum Victoria and AIPS Tall Poppy Outreach Experience

Henley, B. Talk to refugees and new immigrants at Western English Language School at Braybrook

Hobeichi, S. Guest speaker at the annual conference of the Science Teachers Association STA NSW

Hobeichi, S. Published lesson plan. Mathematics Year 11 & 12 Bivariate data and sea-level rise

Hogg, A. Hosted ANU's World Oceans Day event

King, A. Climate change and extreme weather to students as part of the University of Melbourne's Indonesian lecture series.

Lane, T. Panelist, Melbourne Climate Futures - Climate 2021 public event

Lestari, S. Finalist, three minute thesis competition, University of Melbourne

Libera, S. Student engagement and outreach in the Huon Valley STEM expo organized at the Huonville High School.

Libera, S. Volunteering and science public engagement/outreach in the Beaker Street Festival

Lopez-Bravo, C. Earth ciences virtual seminar. National Autonomous University of Mexico (UNAM).

Macadam, I. With Sanaa Hobeichi, attended Office of Climate Education "The Teachers' COP" brainstorming session.

Meyer, A. ABC TOP 5 Science for 2021 Residency Program

Meyer, A. Presentation to UTAS all staff and students 'Climate change, climate action and sustainability'

Perkins-Kirkpatrick, S. National Press Club address

Petrelli, P. Talk on data management to ARDC Data Management Plan Interest group

Petrelli, P. Volunteering to help with a python coding course for grade5 and 6 at Albuera St primary school Hobart

Ridder, N. Presentation on Extreme Events under Climate Change to Women's Club Sydney

Ridder, N. Participated as a member of a panel at the German high school climate summit "SchülerZukunftsGipfel"

Strutton, P. Beer Aquatic, a monthly science in the pub event

Strutton, P. The UTas CLEX group, including PhD student Maya Jakes, contributed to UTas open day.

Strutton, P. Presentation to year 8 classes at St Virgils College about climate change.

Udy, D. Roving scientist at Beaker St Science Festival, Hobart

Udy, D. Presented research at the Ice Core Young Scientist (ICYS) international ice-core seminar series

EDITORSHIPS AND COMMITTEE MEMBERSHIPS

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

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. Member, WCRP Joint Steering Committee

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

Alexander, L. International Association of Meteorology and Atmospheric Science (IAMAS) Executive Council - Member at Large

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

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

Arblaster, J. Member National Climate Science Advisory Committee

Arblaster, J. National Committee for Earth System Science

Brown, J. Contributing Author to IPCC AR6 WG1 report (Chapter 8).

Brown, J. Chair of the AMOS Expert Group on Climate Variability

Evans, J. Fellow of the Modelling and Simulation Society of Australia and New Zealand

Evans, J. Fellow of the Royal Society of NSW

Evans, J. Member of WCRP CORDEX Science Advisory Team

Evans, J. Editor of the Journal of Climate

Green, D. Editorial Board, Environmental Research Letters

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

Henley, B. Executive Domain Editor, Paleoclimates and Current Trends, WIREs Climate Change

Hogg, A. American Meteorological Society Oceanographic Research Awards Committee

Jakob, C. GEWEX Scientific Steering Group member

Macadam, I. NESP2 data subgroup

Meissner, K. Editorial Board, Environmental Research Letters

Meyer, A. Advisory Committee for the Climate Science theme of the Environmental Research Conference 2021, IOP Publishing

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

Perkins-Kirkpatrick, S. Editor Weather and Climate Extremes

Pitman, A. Member, AGU Global engagement Committee

Pitman, A. Monash Foundation Scholarships

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

Pitman, A. TERN Science Advisory Committee member

Pitman, A. Elected as a Fellow of the Australian Academy of Science

Pitman, A. TERN Science Advisory Committee member

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

Ridder, N. Member, Interim Coordinating Committee of WCRP Home Regional Information for Society (RifS)

Ridder, N. Member, Interim Coordinating Committee of WCRP Home Regional Information for Society (RifS)

Santoso, A. Appointed Associate Editor for the Journal of Climate for a second term

Santoso, A. Special issue Editor, Frontiers in Climate

Santoso, A. Editor, Journal of Climate

Sen Gupta, A. National Committee for Earth System Science

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

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

Taschetto, A. Member of CLIVAR Pacific Region Panel

Taschetto, A. Associate Editor of the Journal of Southern Hemisphere Earth System Science (JSHESS)

PRIZES AND AWARDS

Alexander, L. 2021 Clarivate Highly Cited Researcher

Ashcroft, L. Victorian 2021 Young Tall Poppy Science Award

Bador, M. European Marie-Curie fellowship

Brown, J. 2020 AGU Editors' Citation for Excellence in Refereeing - Earth's Future

Eizenberg, N. Bureau of Meteorology graduate student top-up scholarship

Evans, J. Biennial Medal by the Modelling and Simulation Society of Australia and New Zealand

Hayashida, H. CLEX Prize for Best Paper by an ECR

Hogg, A. ANU College of Science Award for Excellence in Supervision

Libera, S. Logo competition winner: SCAR's scientific research program AntClimNow

Libera, S. Best student poster in the Australian Antarctic Program Partnership Symposium

Martinez Moreno, J. CLEX Prize for Best Paper by a Student

Perkins-Kirkpatrick, S. 2021 Clarivate Highly Cited Researcher

Perkins-Kirkpatrick, S. Awarded the Australian Academy of Science Dorothy Hill Medal 2021

Reid, K. Royal Society of Victoria Young Scientist Research Prize in the Earth Sciences category

Reid, K. Outstanding Student Presentation Award at AGU

Reid, K. CLEX Engagement Prize

Ridder, N. 1st price in Allianz Climate Risk Research Award 2021

Udy, D. Student Presentation prize at the Australasian Quaternary Association (AQUA) e-conference

Udy, D. AMOS best student oral presentation

2021 KEY PERFORMANCE INDICATORS

Standard Key Performance Indicators for *ARC Centres of Excellence*
ARC Centre of Excellence for Climate Extremes

Performance Measure	Reporting Frequency	Target 2021	Achieved 2021
Number of research outputs	Annually		
Journal articles		80	222
Book chapters		5	2
Software modules published		2	10
Data sets published		2	16
social media@facebook posts		52	51
Centre website updates		25	86
Science explainer videos		2	4
Quality of research outputs	Annually		
Percentage of publications in journals with impact factors greater than 2.0		80	97
Percentage of publications in journals with impact factors greater than 4.0		60	65
Number of papers in journals with impact factors greater than 10		10	23
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	45
Percentage of students/ECRs attending researcher development activities		90%	84%
Number of workshops/conferences held/offered by the Centre	Annually		
National workshop		1	1
International conference/workshop		1	0
Topical/Research Program workshops		3	5

Number of additional researchers working on Centre research	Annually		
Postdoctoral researchers		14	8[1]
Honours students		10	19
HDR students		20	32
Associate Investigators		32	11
Number of PhD completions	Annually	14	15
Number of Masters by Research completions		4	1
Number of Honours student completions		10	8
Percentage completing PhD students submitting within 4 years (FTE)		100%	50% [2]
Number of mentoring programs offered by the Centre	Annually and at mid-term review	1	1
We have an integrated researcher development program for HDR students and early-mid career researchers. It includes a personalised skills needs assessment and induction, an annual calendar of workshops and training opportunities, an annual winter school covering science fundamentals, cross-node and partner organisation supervision, and a mentoring circle initiative involving all centre researchers and students allowing a range of mentoring and networking opportunities.			
Number of presentations/briefings	Annually		
To the public		10	44
To government		10	24
To industry/business/end-users		5	33
To non-government organisations		5	1
To professional organisations and bodies		5	3
Number of new organisations collaborating with, or involved in, the Centre	Annually	-	-

Centre-specific Key Performance Indicators for the ARC Centre of Excellence for Climate Extremes

Performance Measure	Reporting Frequency	Target 2021	Achieved 2021
Percentage of female graduate students	Annually	50%	45%
Percentage of female research fellows		50%	61%
Percentage of senior female research fellows		50%	n/a[3]
Percentage of Centre leaders who are female		50%	43%
Percentage of administration team who are female		50%	70%
Percentage of board members who are female		50%	22%
Percentage of keynote speakers at workshops and conferences who are female		50%	50%

Centre-specific Key Performance Indicators for the ARC Centre of Excellence for Climate Extremes (continued)

Computational Modelling Support	Annually		
New/refined/enhanced software modules for the climate models developed and served to the community.		2	11
New/refined/updated software tools for data analysis developed and served to the community.		2	5
New/refined/updated data sets served to the community.		2	18
Monthly bulletin to all researchers on CMS-related updates		12	18
Explainer videos on key CMS issues		4	1
Percentage of students with cross node and/or partner organisation supervision	Annually	80	34%
Percentage of students/ECRs making a research visit to other nodes and/or Australian partner organisations	Annually	70	3% [4]
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	1%[4]
Number of undergraduate summer scholarships offered	Annually	15	16
Regular Research Program videoconference meetings p/a	Annually	10	72
Media KPIs	Annually		
Media Releases		15	14
Website – Unique Hits		35000	57362
Website – Page Views		45000	88002
Stories in media		300	
Social Media – Twitter (New followers)		400	579
Social Media – Facebook (New followers)		250	208
Knowledge Brokerage Team	Annually and at mid-term review		
Establishment of significant partnerships		1	0
Data sets provided to stakeholders		1	1
Strategic advice provided to stakeholder		1	9
Demonstrated examples of model improvements available for use in national modelling systems	Annually and at mid-term review	2	2

Footnotes:

1: 17 positions were advertised in mid-2021. Many candidates requested commencement dates in early 2022

2: This metric is clear evidence of the detrimental effect the Covid-19 pandemic had on the work capacity and wellbeing of our graduate students

3: The Centre did not have any senior research fellows employed in 2021

4: The Covid-19 pandemic curtailed physical travel in 2021

2021 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 2021, CLEx received $6,755,823 (109%) income compared to the full-year budget of $6,194,319. In terms of the Centre's expenditure, $4,576,733 (91%) was spent compared to the full-year budget of $5,007,010.

In 2021, personnel accounted for the highest proportion of expenditure of $3,857,699 (83.4%), followed by scholarship expenditure of $402,263 (8.8%). Overall, the Centre's cash balance in 2021 is $2,179,090.

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.

2021 INCOME

Cash income totalled $6,755,823 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 Agriculture, Water and the Environment . 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 $4,678,106. 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 3 years (2021-2023) of funding totalling $300,000 in 2021.

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 2021.

2.4 Department of Agriculture, Water and the Environment

Funds of $4,000 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 $1,600,020, as follows:

$675,077	UNSW
$146,763	ANU
$211,438	University of Melbourne
$314,432	University of Tasmania
$252,310	Monash University

4: In-kind Contributions

In-kind support totalled $7,467,852 in 2021. The Centre is grateful for $5,151,054 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 $2,316,798. Again, this was mainly personnel time.

Organisation	In Kind Budget	In Kind Actual
ANU	882,850	576,257
BOM	150,366	150,366
CSIRO	346,500	354,209
LATMOS CNRS/INSU/IPSL	13,400	13,400
Max Planck Inst. For Meteorology	20,000	20,000
Met Office UK	150,000	150,000
Monash	854,469	875,652
NASA Goddard Space Flight Center	42,729	42,729
NCAR	118,738	118,738
NCI	892,000	960,000
NOAA	30,000	30,000
DPIE	312,785	312,785
Risk Frontiers Grp	45,000	45,000
Swiss Federal Inst of Tech	62,781	62,781
UMEL	948,047	976,438
Uni of Arizona, USA	56,790	56,790
UNSW	1,890,871	2,054,342
UTAS	459,497	668,366
TOTAL	7,276,823	7,467,852

2021 LEVERAGE

The Centre's 2021 cash income of $6,755,823 and in-kind support of $7,467,852 total $14,223,675 with ARC funding accounting for $4,678,106 of the total income. The Centre's leverage of $9,545,568 equates to $2.04 of external funding and in-kind contributions for each $1.00 received from the ARC.

2021 EXPENDITURE

In 2021 the Centre expended $4,576,733, analysed below:

Personnel (including on-costs)	$3,857,699	84.3%
Scholarships	$402,2638.8%	
Equipment and Maintenance	$45,276	1.0%
Consumables and Events	$172,4523.8%	
Travel	$99,043	2.2%

2021 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 2021.The Centre's cash expenditure of $4,576,733 was below income of $6,755,823 by $2,179,090. The Centre will carry over a balance of $2,179,090 to 2022. The carry-over by institution is as follows:

University of New South Wales	$1,179,513	surplus
Australian National University	$303,999	surplus
University of Melbourne	$71,464	surplus
University of Tasmania	$288,946	surplus
Monash University	$335,167	surplus

In summary, as at 31 December, 2021, the financial position for the life of CLEx after its fifth year of operation is as follows:

Total Cash Income	$6,755,823
Total Expenditure	$4,576,733
Surplus carried forward to 2022	**$2,179,090**

Figure above: CLEX researchers at The University of Tasmania

CASH INCOME AND EXPENDITURE

	Actual					Budget/ Forecast			
1. Cash Income	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**TOTAL**
Australian Research Council- Centre of Excellence	4,350,000	4,250,000	4,250,001	4,300,000	4,300,000	4,300,000	4,300,000	0	**30,050,000**
Australian Research Council- Centres of Excellence Indexation	65,250	128,456	211,645	295,388	378,106	0	0	0	**1,078,845**
Bureau of Meteorology	10,000	20,000	30,000	30,000	30,000	20,000	20,000	0	**160,000**
NSW Department of Planning and Environment	100,000	100,000	100,000	165,000	300,000	0	0	0	**765,000**
NSW Department of Industry/ RAAP	143,000	143,000	142,857	143,000	143,000	142,857	142,857	0	**1,000,571**
University Node Cash Contributions	1,103,142	1,285,737	1,253,234	1,236,647	1,600,020	1,069,377	1,226,495	0	**8,774,652**
Other (Interest Distribution)	0	15,871	19,146	3,087	696	0	0	0	**38,800**
Department of Agriculture, Water and the Environment	0	0	4,523	0	4,000				**8,523**
Sydney Water Corporation	0	200,000	0	0	0	0	0	0	**200,000**
Total	**5,771,392**	**6,143,064**	**6,011,406**	**6,173,122**	**6,755,822**	**5,532,234**	**5,689,352**	**0**	**42,076,391**
2. ARC Expenditure	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**TOTAL**
Personnel	114,662	1,941,921	3,354,377	3,350,987	2,992,974	4,857,590	4,647,628	4,255,705	**25,515,843**
Scholarship	6,358	90,723	158,714	191,388	217,551	325,224	324,138	222,342	**1,536,436**
Equipment and Maintenance	0	5,105	33,216	12,814	3,500	13,650	13,700	50,000	**131,985**
Consumables and Events	16,369	165,632	160,379	110,198	128,817	270,836	270,443	308,846	**1,431,519**
Travel - Conference, workshops and meetings (Staff, AI)	12,634	133,395	210,647	48,557	10,454	271,721	270,771	224,279	**1,182,458**
Travel - Conference, workshops and meetings (Postdocs and Students)	0	40,497	178,653	49,316	26,531	97,681	97,753	79,662	**570,093**
Travel - Visitor travel to the Centre and other	1,336	38,236	31,324	22,335	0	120,292	125,989	108,873	**448,385**
Travel - New staff relocation expenses	0	0	0	0	0	0	0	0	**-**
Travel - Research Visits (Staff, AI)	0	9,585	34,451	7,153	-2,004	61,487	61,487	37,653	**209,812**
Travel - Research Visits (Postdocs and Students)	1,341	380	3,484	1,802	0	35,787	35,787	23,731	**102,313**
Total	**152,701**	**2,425,476**	**4,165,244**	**3,794,550**	**3,377,822**	**6,054,267**	**5,847,695**	**5,311,090**	**31,128,845**
3. Nodes Expenditure	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**TOTAL**
Personnel	65	311,556	615,789	475,725	603,844	816,125	775,053	1,050,397	**4,648,554**
Scholarship	10,706	61,092	132,039	120,983	105,712	379,388	379,388	388,180	**1,577,488**
Equipment and Maintenance	6,182	48,972	46,325	17,274	41,776	46,853	41,853	41,166	**290,403**
Consumables and Events	4,575	43,568	53,831	48,424	43,636	61,568	63,343	56,637	**375,581**
Travel - Conference, workshops and meetings (Staff, AI)	12,901	49,055	67,758	21,570	14,943	163,936	163,809	144,661	**638,632**
Travel - Conference, workshops and meetings (Postdocs and Students)	2,969	60,341	104,294	18,986	13,011	175,768	175,128	157,288	**707,785**
Travel - Visitor travel to the Centre and other	0	9,570	41,971	9,881	0	29,828	29,501	32,236	**152,987**
Travel - New staff relocation expenses	7,354	55,163	22,719	2,193	37,490	19,825	2,000	5,967	**152,711**
Travel - Research Visits (Staff, AI)	5,132	8,979	22,952	4,320	-2,677	27,500	27,500	22,954	**116,661**
Travel - Research Visits (Postdocs and Students)	0	10,981	13,860	8,446	1,296	29,700	29,700	19,868	**113,851**
Total	**49,885**	**659,276**	**1,121,538**	**727,802**	**859,030**	**1,750,492**	**1,687,275**	**1,919,354**	**8,774,652**

CASH INCOME AND EXPENDITURE (CONTINUED)

	Actual					Budget/ Forecast			
4. Others	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**TOTAL**
Personnel	61,192	192,341	272,939	338,433	260,881	341,830	348,666	193,088	**2,009,371**
Scholarship	0	10,000	14,000	10,000	79,000	20,000	20,000	10,000	**163,000**
Equipment and Maintenance	0	0	0	0	0	0	0	0	**-**
Consumables and Events	0	0	0	0	0	0	0	0	**-**
Travel - Conference, workshops and meetings (Staff, AI)	0	0	0	0	0	0	0	0	**-**
Travel - Conference, workshops and meetings (Postdocs and Students)	0	0	523	0	0	0	0	0	**523**
Travel - Visitor travel to the Centre and other	0	0	0	0	0	0	0	0	**-**
Travel - New staff relocation expenses	0	0	0	0	0	0	0	0	**-**
Travel - Research Visits (Staff, AI)	0	0	0	0	0	0	0	0	**-**
Travel - Research Visits (Postdocs and Students)	0	0	0	0	0	0	0	0	**-**
Total	**61,192**	**202,341**	**287,462**	**348,433**	**339,881**	**361,830**	**368,666**	**203,088**	**2,172,894**
5. Summary Income Vs. Expenditure / Carry Over	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**TOTAL**
ARC									
Total Income	4,415,250	4,378,456	4,461,646	4,595,388	4,678,106	4,300,000	4,300,000	0	**31,128,845**
Total Expenditure	152,701	2,425,476	4,165,244	3,794,550	3,377,822	6,054,267	5,847,695	5,311,090	**31,128,845**
Income less Expenditure	4,262,549	1,952,980	296,402	800,838	1,300,284	-1,754,267	-1,547,695	-5,311,090	**-0**
Nodes									
Total Income	1,103,142	1,285,737	1,253,234	1,236,647	1,600,020	1,069,377	1,226,495	0	**8,774,652**
Total Expenditure	49,885	659,276	1,121,538	727,802	859,030	1,750,492	1,687,275	1,919,354	**8,774,652**
Income less Expenditure	1,053,257	626,461	131,696	508,845	740,990	-681,115	-460,780	-1,919,354	**0**
Other									
Total Income	253,000	478,871	296,526	341,087	477,696	162,857	162,857	0	**2,172,894**
Total Expenditure	61,192	202,341	287,462	348,433	339,881	361,830	368,666	203,088	**2,172,894**
Income less Expenditure	191,808	276,530	9,064	-7,346	137,815	-198,973	-205,809	-203,088	**0**
Carry over surplus / deficit	**5,507,614**	**2,855,971**	**437,162**	**1,302,337**	**2,179,088**	**-2,634,355**	**-2,214,284**	**-7,433,532**	**0**

climate extremes
ARC centre of excellence

Australian Government
Australian Research Council

Follow *Climate Extremes:*