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ARC Centre of Excellence for Climate Extremes

Legacy Report 2024

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The ARC Centre of Excellence for Climate Extremes improved Australia's national capacity to understand the processes underlying climate extremes and the broader effects of weather and climate on our lives and society.

About us

Legacy Report 2024

Funded by

The Australian Research Council (ARC) Centre of Excellence for Climate Extremes was financially supported by a Major Investment Grant (CE170100023) from the ARC. The Centre was financed and hosted by the University of New South Wales. Collaborating institutions were Monash University, the University of Melbourne, the Australian National University and the University of Tasmania. They provided significant financial and in-kind support. The National Computational Infrastructure provided significant in-kind support. The Centre also received financial support from the New South Wales Research Attraction and Acceleration Program, the New South Wales Department of Climate Change, Energy, the Environment and Water, the Department of Agriculture, Water and the Environment, the Bureau of Meteorology and Sydney Water.

The Centre's five collaborating partner universities

National partner organisations

International partner organisations

Acknowledgment of the Traditional Owners

The ARC Centre of Excellence for Climate Extremes respectfully acknowledges the Traditional Owners of Country throughout Australia. We pay our respects to their Elders past, present and emerging, and recognise their continuous connection to Country and the contributions and sophistication of traditional knowledge.

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A message from our Director

Professor Andrew Pitman

Welcome to the legacy report by the ARC Centre of Excellence for Climate Extremes.

Our legacy is multifaceted. A whole community of outstanding early career researchers exist in Australia thanks to the Centre. A coordinated program of lectures, winter schools, training in writing, presentations, interview preparation, CV presentation, and much more exists thanks to our Graduate program led by Professor Melissa Hart. Australia will enjoy the benefits of this program for decades as graduates build careers in CSIRO, the Bureau of Meteorology, business, government and industry.

Our legacy exists in our establishment of enhanced software engineering standards, and our publication of code and data that now form a foundation for future research. The NCRIS-funded ACCESS National Research Infrastructure initiative carries that mantle forward at a scale that aligns well with the needs of climate modelling, climate projections and the research community.

Our legacy is enhanced by our impact, via reports, briefing notes, submissions to federal and state inquiries and our support for an uplift in science literacy across our stakeholders.

Finally, an ARC Centre of Excellence for Climate Extremes would hardly be complete without high-impact publications in outstanding international journals and we have published more than 1200 of these. We are proud that so many of these were led by students and early career research fellows. This research builds across many themes that have transformed our understanding of climate extremes and our capacity to predict them in the future.

The ARC Centre of Excellence for Climate Extremes achieved its goals because the chief investigators and our partner investigators strove for excellence. More than that, our community proved again our ability to collaborate, share, engage respectfully while retaining the ability to argue, confront and contest ideas. I would thank the chief investigators and partner investigators for sustaining effort and engagement over seven years.

I would also thank the leadership team in the Centre: Professor Julie Arblaster and Professor Todd Lane who were deputy directors at different times. Our advisory board, chaired by Tony Press, was always there to support us when we needed help with anything from strategy to operations and helped keep me focussed on our overarching goals. I would also thank the two Chief Operations Officers: Vilia Co and Stephen Gray without whom I have no idea where we would now be. Key portfolio leads were also instrumental in achieving our successes including Paola Petrelli, Claire Carouge, Ian Macadam, Angela Kaplish, Victoria Tichá, Alvin Stone, and "JB" Brown.

So the ARC Centre of Excellence for Climate Extremes comes to an end, except that it is not the end for coordinated weather and climate research across the sector. The ARC Centre of Excellence for the Weather of the 21st Century is now up and running under the leadership of Professor Christian Jakob - someone who was profoundly important to the successes in the ARC Centre of Excellence for Climate Extremes and earlier, the ARC Centre of Excellence for Climate System Science. I very much look forward to seeing our research advanced further, and new and innovative research established, as well as the continuation of our community and its pivotal role in Australian climate science. Good luck Christian!

Professor Andrew Pitman, AO, FAA,

Director, ARC Centre of Excellence for Climate Extremes

Introduction

The Australian Research Council (ARC) Centre of Excellence for Climate Extremes (the Centre) was the world's first research centre focused explicitly on the understanding and prediction of climate extremes. Its legacy has been to shape and advance our collective understanding of the processes behind extreme events, including their dependence on climate change and climate variability. The Centre demonstrated exceptional scientific discovery and technical innovation, whose legacy will endure.

Operating between 2017 and 2024, the Centre was set against a backdrop of increased public awareness of climate and weather, as various extremes began to dominate the media. Long-term funding from the ARC cemented Australia's leadership in climate extremes research at a time of pressing need. The Centre focused on five key research areas: Weather and Climate Interactions, Attribution and Risk, Drought, Ocean Extremes and Modelling.

Drought in rural Australia Source: Unsplash

The Centre's publications appeared in prestigious journals, with their impact evidenced by ongoing citations. For example, the Centre produced a review of the attribution of extreme events to climate change in the Australian region, gathering experts from across the fields of climate science and event attribution. In a 2020 paper on meteorological drought, the Centre's researchers demonstrated how the Coupled-Model Intercomparison Project Phase Six simulations provided more robust projections of meteorological drought compared to mean precipitation, giving clearer direction for water resource planning.

Other groundbreaking insights into drought showed that the difference between severe drought or at least partial recovery is less than ten days of heavy rainfall annually. In a world-first piece of fundamental research, a global assessment of the drivers of marine heatwaves found they had increased by 50% over the past century – often instigated thousands of kilometres away and sometimes in entirely different ocean basins.

Through an inclusive and diverse culture of national and international collaboration across multiple disciplines, the Centre's published research has been world-class, becoming synonymous with academic research excellence. Pivotal internationally collaborative research examined how the atmospheric component of the El Niño-Southern Oscillation, known as the Pacific Walker Circulation, is influenced by climate change and volcanic eruptions which can temporarily weaken the Walker Circulation.

The Centre's greatest achievement has been nurturing the next generation of climate researchers to continue the legacy of the Centre. Ongoing training and mentorship of early and mid-career researchers saw many progress into multiple fields, including consultancy, government, industry and tenured positions in elite Australian and global institutions. Underpinned by an outstanding and enviable graduate program, the Centre's alumni remain in high demand.

The Centre was integral to the establishment and success of critical Australian research infrastructure by harnessing high-performance computing. The Centre was an enthusiastic first adopter of Gadi, based at the National Computational Infrastructure (NCI) supercomputer, which became operational in 2019. Support by the NCI was fundamental to our ability to deliver outstanding research through the Centre's lifetime. The Centre actively supported the establishment of the Australian Community Climate and Earth System Simulator - National Research Infrastructure (ACCESS-NRI). This was created to support the development and research of a suite of Australian climate models, funded via the National Collaborative Research Infrastructure Strategy (NCRIS). The Centre was proud to be part of world-class Earth system modelling research infrastructure to predict Australia's weather and climate.

The Centre's Computational Modelling Support team was fundamental in enabling the software and infrastructure for the production and distribution of climate data. Through technical support in climate model development, data analysis and data management for researchers, the team played a crucial role in making research analysis more efficient and reliable. The Centre's research community is indebted to their diligent and tireless work.

Our contribution to improved weather and climate projections will provide better information for policymakers, industries and public services. Importantly, our legacy of breakthrough science, enhanced predictions, a culture of collaboration and a new generation of science leaders will shape the Australian community for decades to come, helping to inform strategies and policies to reduce national and global vulnerability to climate extremes.

Centre achievements

People

138
PhDs completed

30
Masters completed

81
Honors completed

59
Postdoctoral researchers

Research

>1200
Total publications

>36,000
No of citations

692
No of international collaborations

67%
Centre publications in the top 10% of journals

26%
Centre publications in top 10% most cited publications

Outreach

56
Workshops

51
Briefing notes

3
State of Extremes reports

120
Media releases

20
Government submissions

7
Government hearings

>20,000
Media mentions

>130
Government briefings

>100
Industry briefings

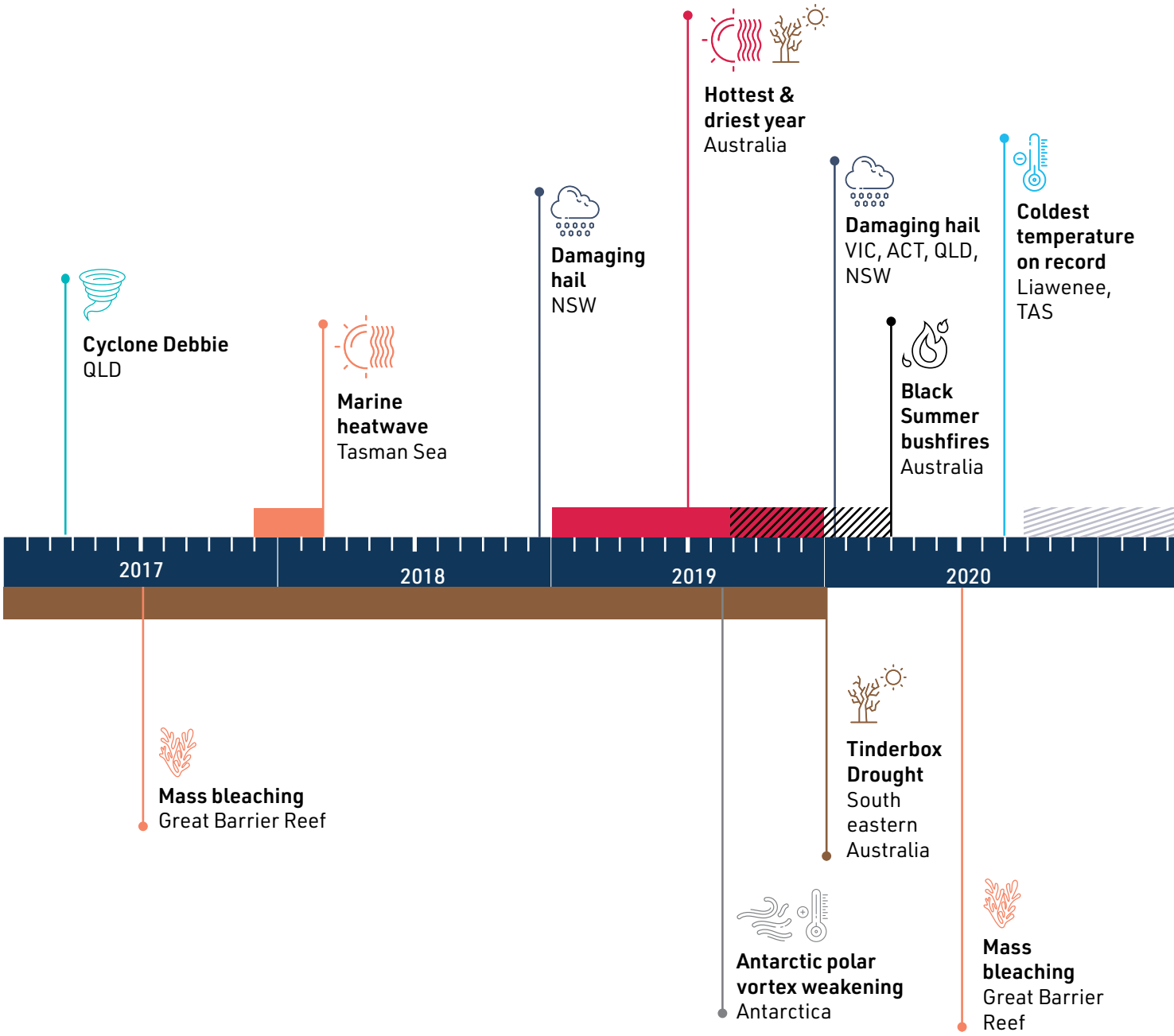
>400
Training sessions

8
Annual reports

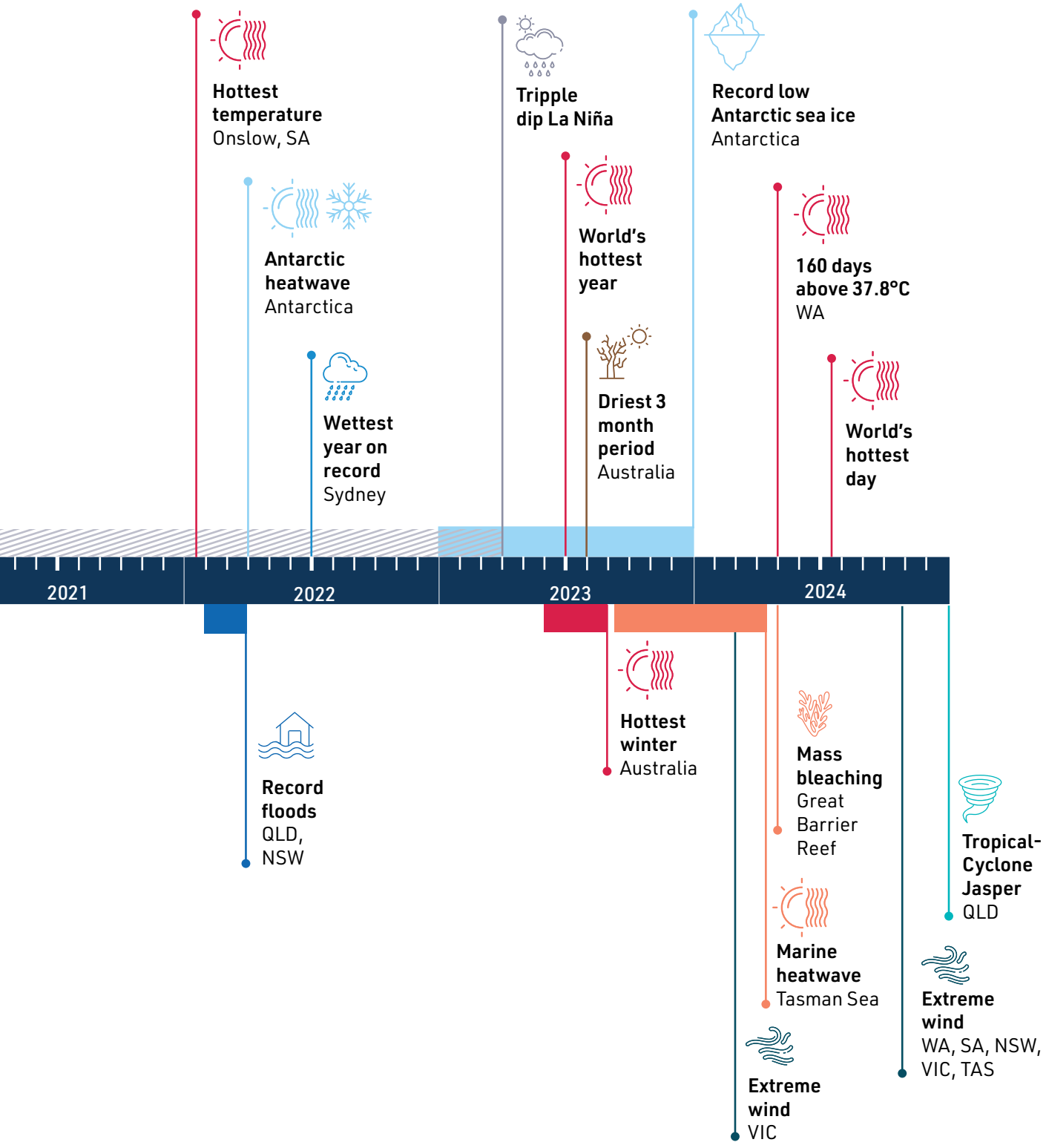
Data as at early December 2024.

Timeline of extreme events 2017 - 2024

During the lifetime of the ARC Centre of Excellence for Climate Extremes, Australia experienced many extreme events. These included compound rain and flood events, record-breaking heatwaves, intense drought and fires, as well as extreme marine heatwaves. The impacts of these events were devastating, resulting in significant damage, environmental impacts and loss of life.



Timeline of the major Australian extreme events which occurred during the life of the Centre.
Source: ARC Centre of Excellence for Climate Extremes.


Hottest temperature
Onslow, SA
Antarctic heatwave
Antarctica
Wettest year on record
Sydney
Record floods
QLD, NSW
Tripple dip La Niña
World's hottest year
Driest 3 month period
Australia
Hottest winter
Australia
Record low Antarctic sea ice
Antarctica
160 days above 37.8°C
WA
World's hottest day
Mass bleaching
Great Barrier Reef
Marine heatwave
Tasman Sea
Extreme wind
VIC
Tropical-Cyclone Jasper
QLD
Extreme wind
WA, SA, NSW, VIC, TAS
2021
2022
2023
2024

Our research programs

Drought research program

The Drought research program sought to understand what controls the frequency, intensity and duration of drought in Australia in the past, present and future.

A key aim of the Drought research program was to develop our understanding of how Australian droughts develop. It examined the processes behind the onset, persistence and termination of droughts, and investigated the 2017-2019 drought in eastern Australia. Over the program's duration, 20 graduate students and multiple postdoctoral researchers contributed input.

By combining observations and climate models, researchers showed that drought conditions are usually linked to reduced moisture supply from the oceans surrounding Australia[1]. This applied to the 2017-2019 eastern Australian drought, where atypical atmospheric circulation drew atmospheric moisture away from the region[2]. The new insights are important for improving short-term forecasts and the long-term impacts of climate change on Australian rainfall.

In research on multi-year droughts, researchers found that natural variability can produce "mega-droughts" lasting 20 years or more, which are longer than any droughts experienced over the last century. Additionally, they found that Australian droughts in the 20th century (1900–2000) lasted longer than those in pre-industrial times in southwestern and eastern Australia[3]. This suggests an emerging human influence on our climate is altering droughts and has already made southern parts of Australia more drought-prone.

The Drought program brought together ocean, atmosphere and land research to understand a broader perspective. Research highlighted the important role of groundwater in buffering vegetation impacts during multi-year droughts[4] .

A centrepiece of the program was the analysis of the Tinderbox Drought (2017-2019)[5] in southeast Australia, preceding the devastating Black Summer bushfires (2019-20). This drought was exceptionally extreme, involving a sequence of interwoven events that compounded drying of the atmosphere and land (Figure 1). Research identified that oceanic moisture did not reach the region, and unusually high temperatures and low air humidity amplified the moisture deficit over land. Climate change is estimated to have worsened the drought's intensity by 18%, but there remains considerable uncertainty in attributing individual droughts to climate change.

The Drought program brought new insights to Australian drought behaviour and identified how climate change may be altering this behaviour.

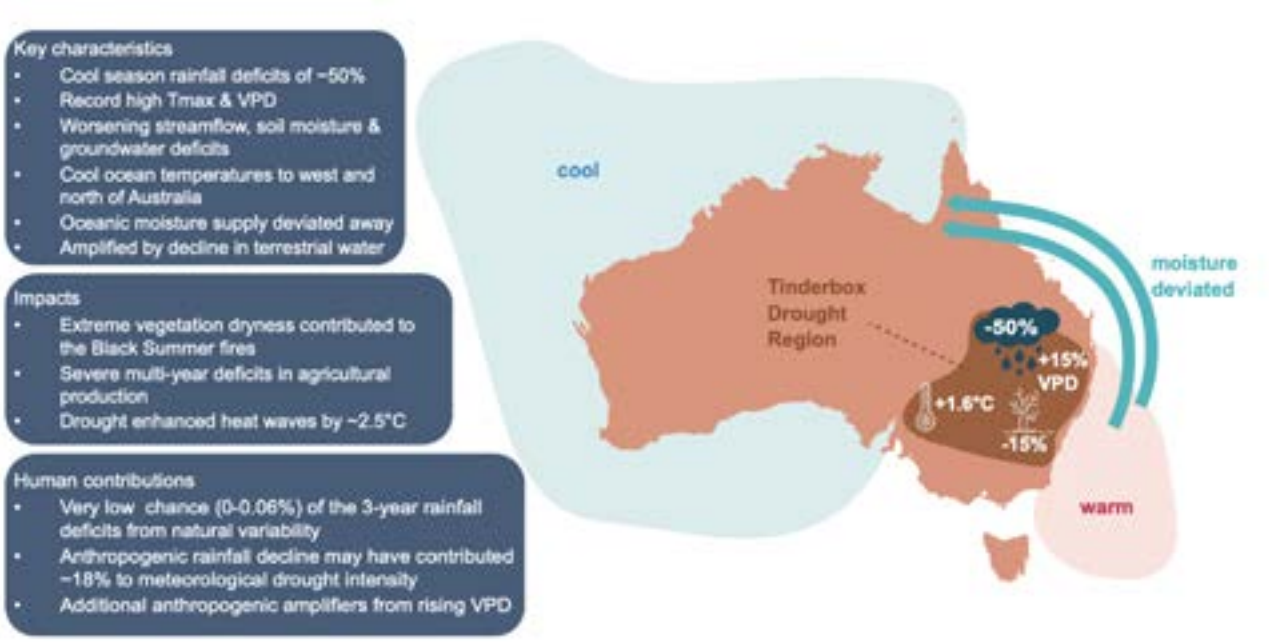


Figure 1: Key characteristics of the Tinderbox Drought. Source: Anjana Devanand et al., 2024[5].

Meet the researchers

Phd student Chenhui Jin
at Mountain First in Grindelwald, Switzerland.

Chenhui Jin was a PhD student at Monash University who was involved in the Centre's Drought program. Chenhui's PhD focused on the roles of synoptic-scale weather systems in drought over south-eastern Australia. His work highlighted the changes in the dynamics of rainfall-producing weather systems over the southern Murray-Darling Basin during the development and recovery of the Millennium Drought[6].

Dr Chiara Holgate
at Scrivener Dam, Canberra, during the unusually wet 2022.

Dr Chiara Holgate, a hydroclimatologist, was a postdoctoral researcher in the Drought program. In 2022, Dr Holgate was named a Superstar of STEM (Science, Technology, Engineering, Maths) by the Minister for Industry and Science, Ed Husic. Dr Holgate's work identified weather patterns leading to drought-breaking rains to understand how droughts terminate, finding that the likelihood of such events may decline with climate change[7]. These insights into how droughts develop and terminate provide a foundation for improving drought forecasts to benefit farmers and water managers.

Attribution and Risk research program

The Attribution and Risk research program focused on understanding how climate extremes are changing and determining the causes of these changes. This included understanding how climate change is affecting extremes and possible future risks.

To do this, the program assessed and improved observation data, enhanced our process understanding, increased the capability of our models to simulate extremes and developed new statistical methods using machine learning.

Researchers investigated the roles of large-scale, regional and local-scale processes in shaping Australian extremes. Our early career researchers led a collaborative investigation of the drivers of the exceptionally wet year of 2022, which resulted in widespread flooding across eastern Australia. They found that 2022 was a perfect storm of large and small-scale drivers aligning to cause record-breaking rainfall, highlighting the complexity of distinguishing the role of climate change from natural variability[1] (Figure 1).

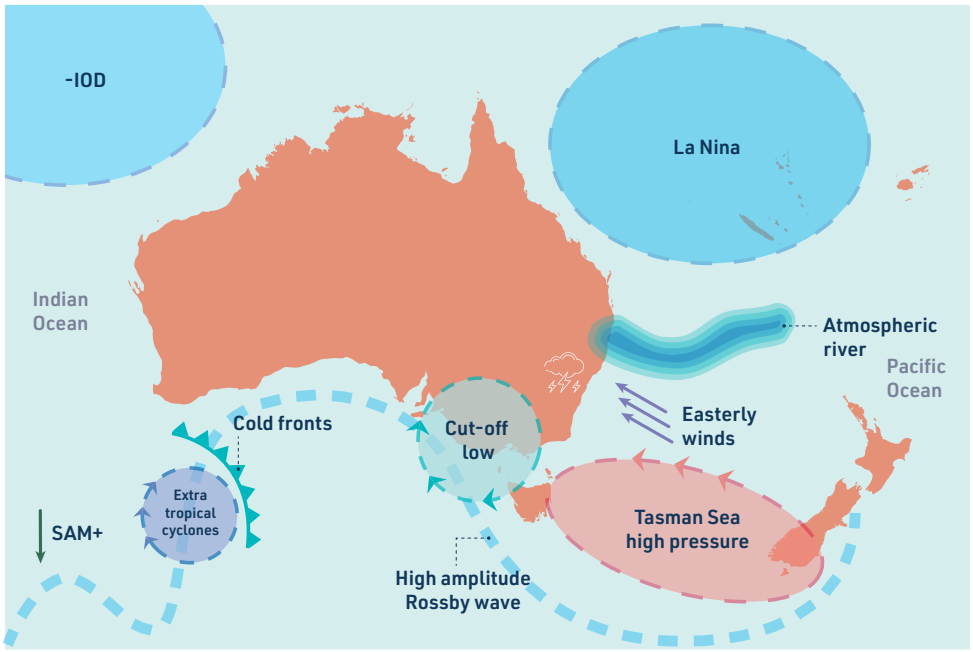


Figure 1: Summary schematic of the drivers of heavy rainfall in eastern Australia. Source: Reid et al., 2024[1].

Various studies in the Attribution and Risk program focused on improving climate models – such as the novel Time Variability Correction method, which can potentially improve the projections of extreme events like heatwaves[2]. Other work developed a standardised benchmarking framework to assess model skill in simulating rainfall[3]. This method can identify fit-for-purpose model simulations to inform adaptation strategies.

Machine learning techniques were developed, utilising advanced statistics to better understand and project climate extremes. Researchers demonstrated that machine learning can be considerably more skilful in capturing the spatial characteristics of extreme events than existing models[4].

The research program collaborated on a review of extreme event attribution[5]. It concluded that in Australia, large-scale heat events over land and ocean can be linked to human-induced climate change with confidence, while smaller-scale phenomena like storms or complex extremes like drought are beyond our current capability. The review provided insight into improving these attribution capabilities.

Researchers attended the World Climate Research Programme (WCRP) Open Science Conference in Rwanda in 2023, and researchers Sarah Perkins-Kirkpatrick and Negin Nazarian were chosen to lead papers for the WCRP.

The Attribution and Risk program made great advances in understanding the drivers of Australian climate extremes using observations and models, and also developed advanced methods that will improve our prediction capability. The program built a community of researchers that will continue this work in the new Australian Research Council Centre of Excellence for the Weather of the 21st Century.

Meet the researchers

Dr Kim Reid
Monash University.

Dr Kim Reid started her journey with the Centre as a masters student, moving to a PhD and then a postdoctoral research position. Her work on atmospheric rivers filled an important gap in our understanding and her expertise has been sought out internationally. She is a prolific communicator and advocate for effective outreach. Dr Reid was one of the biggest contributors to Centre outreach efforts, winning the Director's Prize in 2022.

Master's student Isabelle Greco
at the Centre's annual workshop in 2022.

Masters student Isabelle Greco produced a highly novel Bayesian model of hail probability conditioned on radar observations, which was used to produce a map of hail occurrence frequency in the greater Brisbane region. Isabelle won a prestigious Catastrophe and Reinsurance Symposium award, highlighting the practical application of this research for the insurance sector, and is now working in a government position in Canberra.

Ocean Extremes research program

The Ocean Extremes research program investigated marine heatwaves and key ocean circulation features that have significant impacts on marine environments. A key focus was to improve the prediction and modelling of marine heatwaves to better understand future risks. Additionally, advances in understanding how ocean fronts, meanders and eddies impact the climate system were achieved. These ocean features play significant roles in heat and carbon fluxes, ocean productivity and marine ecosystems.

Chief investigator Professor Neil Holbrook provided the first global assessment of marine heatwaves under a consistent framework by combining a confidence assessment of the historical refereed literature from 1950 to February 2016, together with the analysis of marine heatwaves determined from daily satellite sea surface temperatures from 1982–2016, to identify the important local processes, large-scale climate modes and teleconnections that are associated with marine heatwaves regionally[1]. Holbrook et al., then made the case for the importance of understanding marine heatwave predictability, and hence advanced warnings from improved prediction systems, to potentially reduce risks to marine fisheries and ecosystems[2].

PhD student Jake Weis was part of research that demonstrated the importance of airborne dust and wildfire aerosols in fertilising ocean productivity[3].

As climate change influences aridity, and the prevalence and intensity of wildfires, this knowledge helps us understand the impact on the ocean, sometimes far removed from the fire or dust source.

Chief investigator Dr Amelie Meyer contributed to a review of Southern Ocean fronts, led by collaborator Christopher Chapman (CSIRO), on how to define ocean fronts and their impacts in a changing climate[4]. Ocean fronts play an important role in the climate system and are hotspots for marine biodiversity. Appropriately defining ocean fronts is a challenge given the many methods and applications that exist. The review compared front identification methods and provided valuable advice on what definitions to use across disciplines, from ocean dynamical studies to ecosystems applications.

The Ocean Extremes research program has built significant Australian capacity for the study of marine heatwaves, mesoscale physics and ocean biogeochemistry. Some of this work will continue on in the Centre of Excellence for the Weather of the 21st Century, and some is helping to launch future Centre of Excellence bids and large collaborative initiatives. Our student and postdoctoral diaspora is continuing the work and collaborations at institutions worldwide to better understand our ocean ecosystems.

Ocean Extremes chief investigators Professor Neil Holbrook, Dr Amelie Meyer and Professor Peter Strutton, at the University of Tasmania.

Meet the researchers

Dr Jules Kajtar
University of Tasmania.

Dr Jules Kajtar joined the Centre as a postdoctoral researcher in 2019, and spent four productive years at the University of Tasmania studying marine heatwaves. His research highlights included a detailed analysis of the 2017/18 Tasman Sea marine heatwave, cataloguing marine heatwave metrics around Australia and contributing to other studies of marine heatwave projections and implications in the Pacific and Australian regions. Another study, funded in part by the Tasmanian Government but supported by the Centre, involved conversations to determine stakeholder needs on possible marine heatwave futures. The Centre has been prominent in supporting critical marine heatwaves research happening around the world.

Dr Hakase Hayashida
camping in Chigasaki, Japan 2024.

Dr Hakase Hayashida was a Centre postdoctoral researcher from 2019 to 2022, working on biogeochemical modelling, in close collaboration with the Consortium for Ocean-Sea Ice Modelling in Australia (COSIMA) group. Dr Hayashida produced two well-cited papers on the future trajectory of marine heatwaves in high-resolution models and on the factors that determine the biogeochemical response of an ecosystem to marine heatwaves.

Weather and Climate Interactions research program

The Weather and Climate interactions research program, which involved 76 students over the life of the Centre, investigated the physical mechanisms causing weather extremes.

The program sought to understand how weather systems produce extremes, and how these weather systems are affected by longer-term variability, such as the El Niño-Southern Oscillation (ENSO) and climate change.

Focusing on the causes of rainfall variability, researchers identified the weather systems most responsible for rainfall in south-eastern Australia, and how the mix differs from dry to wet years.

They found that two components of low-pressure systems account for most of the difference: regions of strongly ascending warm moist air and elongated regions of rotating motion in the upper atmosphere[1].

In a related study, researchers investigated how springtime rainfall from low-pressure systems over south-eastern Australia changes from La Niña to El Niño[2] (Figure 1). During La Niña, a high-pressure system lies to the south-east of Australia, making conditions favourable for rainfall. In contrast, during El Niño, a high-pressure system lies over the Australian continent, reducing the rainfall in eastern Australia.

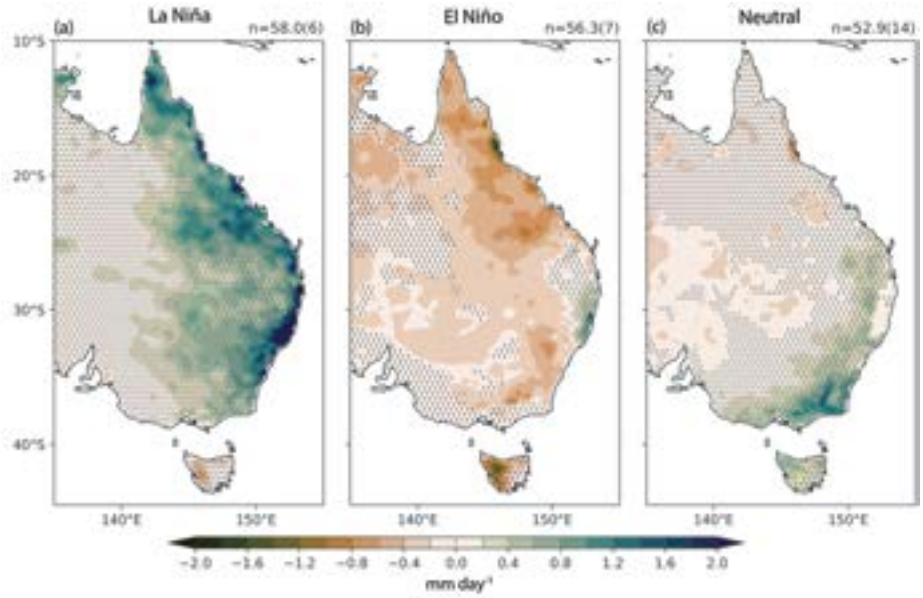


Figure 1 : Precipitation anomalies on spring cyclone days during (a) La Niña, (b) El Niño, (c) Neutral El Niño-Southern Oscillation years. Source: Gillett et al., 2023[2].

Researchers teamed up with the radar group at the Bureau of Meteorology to investigate precipitation extremes. They found that short-duration, intense rainfall events have increased by 40% over the past 20 years in the Sydney region[3]. These results underscore the need to consider our changing climate in adaptation measures for society.

The Weather and Climate Interactions program contributed to the development of a high-resolution configuration of the Australian Community Climate and Earth System Simulator model, known as the AUS2200 model, which supported the research within the program. This new modelling infrastructure will be further developed in the Centre of Excellence for the Weather of the 21st Century.

The Weather and Climate Interactions research program has improved our understanding of how weather extremes develop and how climate change affects extreme weather in Australia. It has also pointed to new challenges at the intersection of weather and climate, many of which will be taken up by the new Centre of Excellence for the Weather of the 21st Century.

Meet the researchers

Dr Michael Barnes,
Monash University.

Formerly of the South African Meteorological Service, postdoctoral researcher Dr Michael Barnes is an expert in synoptic meteorology. He led Centre research that discovered how slow-moving weather systems in the upper troposphere are important for heavy rainfall over Australia's east coast. Dr Barnes' research points to the specific types of systems that climate models must simulate accurately to reliably project heavy rainfall in the future.

PhD student Thi Dao Lan,
University of Melbourne.

PhD student Thi Dao Lan, who started her project remotely during COVID-19 lockdowns in September 2021, has focused on the combined influence of ENSO and the Madden Julian Oscillation (MJO) on northeast Australian rainfall. Dao Lan, who utilised the AUS2200 model, found that the MJO has a larger influence on rainfall under El Niño than under La Niña[4].

Modelling research program

The Modelling research program developed tools to support the Centre's research agenda now and into the future. In collaboration with colleagues in CSIRO, the Bureau of Meteorology and many others, the Centre saw achievements in areas including the following:

- development of a new regional model configuration called the AUS2200;
- improved the ocean model (MOM);
- improved the land model (CABLE); and
- development of a system to manage software packages called the CONDA environment, which supports researchers.

A central achievement of the Modelling program was the development of AUS2200. This is a high-resolution regional atmospheric modelling framework that covers the entire Australian continent and surrounding oceans. Written and developed by a host of researchers across multiple agencies, it is a game changer for weather and climate information. The AUS2200 model was built using the Australian Community Climate and Earth System Simulator (ACCESS), which is used by the Bureau of Meteorology, CSIRO and the research community for climate prediction and weather forecasting. It currently runs on the Gadi supercomputer at the National Computational Infrastructure (NCI) at the Australian National University and is now under the custodianship of the ACCESS National Research Infrastructure facility, which is supported by the National Collaborative Research Infrastructure Strategy (NCRIS).

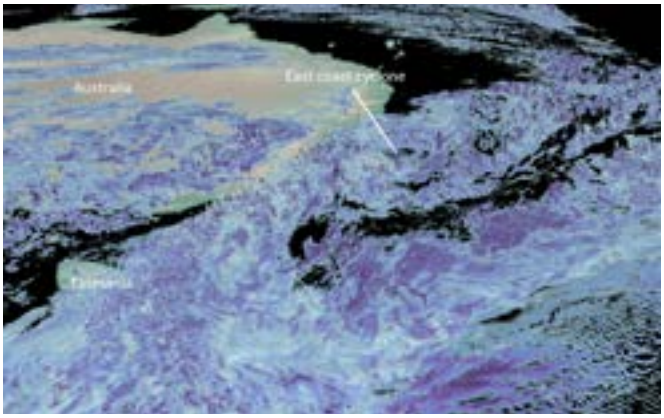


Figure 1 : AUS2200 simulation of clouds showing an Australian east-coast cyclone in June 2016 near New South Wales. Our simulations demonstrate how the exceptional sea surface temperatures in the Coral and Tasman Seas at the time produced a stronger storm and contributed to widespread flooding impacts. Image credit: Dr Chris Chambers.

The AUS2200 model has allowed a large community of researchers to access and use modelling for their work, resulting in faster results for domains across Australia. The project provided a common platform that facilitated research and modelling activities to advance scientific understanding of atmospheric processes, from continent-wide to kilometre scales (2.2km) (Figure 1).

The Centre also contributed to ocean modelling, in partnership with the Consortium for Ocean-Sea Ice Modelling in Australia (COSIMA). In addition to being active contributors to the COSIMA ecosystem, Centre researchers have used the COSIMA ocean models for advancing our understanding of a range of physical and biological processes, from the processes that take up and transport heat through the ocean, to the impacts of this on the marine environment. Notably, two Centre doctoral candidates developed a software package to streamline the complicated process of setting up high-resolution regional simulations using the Modular Ocean Model. The package has allowed Centre researchers to study the dynamics of marine heat waves on Australia's eastern seaboard (Figure 2).

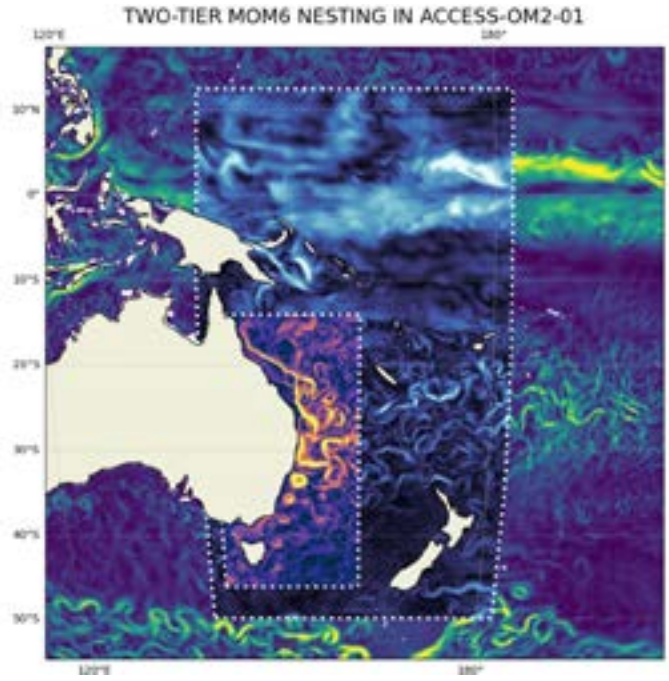


Figure 2 : The nested model domains used to create high-resolution simulations of marine heat waves on Australia's East Coast. Image credit: Dr John Reilly.

Advances in land surface process-based understanding occurred, linked with the Community Atmosphere-Biosphere Land Exchange (CABLE) land model. This included the incorporation of groundwater processes, which were used to examine drought. Other cutting-edge modelling occurred around vegetation mortality and hydraulics, which helps inform future research directions. A key to land modelling is model benchmarking, and we supported the development of modelevaluation.org to provide a community-wide environment for model development. Many of our land science innovations are now under the custodianship of ACCESS NRI, an NCRIS-funded software engineering initiative.

Exciting developments in the modelling space are ongoing, with additional model system features already under development at ACCESS-NRI. The innovation and implementation of the modelling capability developed at the Centre will be a lasting legacy for the climate research community both at home and internationally. It is a testament to the ingenuity and world-class research which takes place in Australia.

Meet the researchers

Dr Hooman Ayat,
University of New South Wales.

Dr Hooman Ayat was a postdoctoral researcher at the Centre and used AUS2200 simulations to examine the weather conditions that led to the 2020 New Year's Eve fires in south-eastern Victoria. In particular, Dr Ayat investigated the source of the extremely dry but localised air that travelled ahead of the approaching cold front, which is thought to have been an important contributor to the severity of the conditions.

Dr Mengyuan Mu
presenting her poster at the Centre's annual workshop in 2022.

Dr Mengyuan Mu began as a PhD student in 2018, focusing on developing and enhancing Australia's CABLE land surface model while investigating the role of groundwater dynamics[1]. Dr Mu continued as a postdoctoral researcher from 2022, exploring land-atmosphere feedbacks during Australia's Tinderbox drought via the atmosphere-land WRF-LIS-CABLE coupled model.

Supporting our Centre

Our commitment to Equity, Diversity and Inclusion

The ARC Centre of Excellence for Climate Extremes strove to be an exemplar in the equity and diversity space, enabling all staff and students, regardless of background, to do their best work in a professional and compassionate environment. The Centre was serious about creating a respectful research environment for its diverse population of researchers, ensuring staff and students could reach their full potential.

The Centre was committed to making a meaningful contribution to addressing historical prejudices and inequality in Science, Technology, Engineering and Mathematics disciplines. The Diversity and Culture committee was responsible for developing and implementing a range of initiatives in the Centre to raise awareness and enhance equity and inclusion across the spectrums of gender, ethnic and cultural background, sexual orientation, physical ability and neurodiversity. The committee was also responsible for providing advice and developing initiatives on issues such as mental health, work-life balance and the Centre's culture.

While significant progress has been made in advancing gender representation, it is important that Australian research institutions continue to embrace diversity with a multidimensional lens. Accelerating progress is important to ensure that equal opportunities are accessible for diverse groups.

Graduate and Researcher Development program

The Graduate and Researcher Development program has further developed Australia's national capacity in climate science by training and mentoring the next generation of researchers.

The program equipped researchers with the intellectual and technical capacity required to take on the research challenges of the future and become the next generation of adaptable climate science leaders prepared for employment across a range of sectors. The program integrated breadth of knowledge, collegiality and impact, building on a foundation of in-depth research training. It complemented opportunities offered at our node universities.

Graduate program

The programs were developed and led by our graduate director, Professor Melissa Hart, who also acted as a point of contact, advisor and advocate for the Centre's students and postdoctoral researchers. A total of 385 graduate students and 59 postdoctoral research fellows took part in the program over the life of the Centre as at December 2024.

All graduates and researchers have moved on to successful positions across a range of sectors globally, after completing their research with the Centre. The Centre's researcher development program built the next generation of climate science leaders.

Of our graduating PhD students, 43% have moved on to positions in universities, 31% have taken up positions in research institutions, 8% to government and 18% to jobs in the private sector, including those in data sciences, insurance companies and environmental consultancies.

Students at the 2019 winter school, held at the University of Melbourne.

1. Winter schools

Winter schools were a cornerstone of our graduate program and formed an annual event for our researchers. They allowed graduate students who had highly specialised knowledge in their own area of research to experience a broad understanding of the discipline as a whole. The theme of the winter school changed each year, and shifted from broader, relevant-to-everyone topics, to more focused topics requiring prerequisite knowledge.

Themes covered included:

- Climate extremes and high-impact weather
- Modelling the climate system
- Atmosphere and ocean dynamics
- Observations in the climate system
- Weather and climate interactions.

In 2021, we ran an atmosphere and ocean dynamics winter school remotely because of COVID-19. This included one of our postdoctoral researchers running spin tank experiments from his living room, while the rest of us had non-rotating fluid on our work from home desks.

Participants in the atmosphere and ocean dynamics winter school in 2021.

At-home spin tank experiment in 2021, during COVID-19.

2. Science Fundamentals lectures

In addition to our winter schools, the Centre ran regular Science Fundamentals online lectures, to provide vital breadth of knowledge. The lectures would often attract participants from our partner organisations, both nationally and internationally, giving our Centre researchers a different perspective.

3. Professional development

Our researchers received training and development opportunities in key skills that would ensure they were job-ready for whichever career path they wished. This included the following: statistics, machine learning, communicating to different stakeholders, CV and interview preparation, building a community-of-care, data visualisation, task management and media training.

4. Undergraduate summer scholarships

Every year, the program offered highly competitive scholarships intended to provide undergraduate students from Australian universities an introduction to cutting-edge climate science research at one of our five Centre universities, or at one of our national partner organisations. Projects were primarily supervised by our early career researchers, giving them vital supervisory experience.

5. Early Career Researchers Committee

Our Early Career Researchers (ECR) committee was composed of one student and one postdoctoral representative from each of the five Centre nodes. Its mission was to facilitate, encourage and contribute to the development of all Centre researchers. This included those undertaking postgraduate or honours study or who were nominally five years post-PhD (taking into account career breaks, parental/carers' leave or part-time status). The ECR committee provided formal and informal communication channels between its members and the Centre Executive committee.

Our researcher development program was a testament to all the early career researchers who participated with enthusiasm over the years; to the support of the Centre executive; and to the tireless work of the Graduate Director, Professor Melissa Hart. The program is proud to have trained the climate science leaders of the future.

Students with Professor Melissa Hart at the 2024 Winter School, held at Monash University, Melbourne.

Computational Modelling Systems

The Computational Modelling Systems (CMS) team provided technical support in climate model development, data analysis and data management for researchers. The work of the CMS team underpinned research efforts at the Centre, making research analysis faster and more reliable, while also delivering data analysis tools and data sets to the climate science community.

The team supported the adoption of GPU-enabled (graphics processing unit) machine learning algorithms on National Computational Infrastructure (NCI) systems, assisting researchers with code utilisation and performance. They developed machine learning tutorials and data sets focused on addressing climate change challenges and delivered training sessions at the Centre and at Australian Community Climate and Earth System Simulator - National Research Infrastructure (ACCESS-NRI) community workshops.

The CMS team provided and maintained new configurations of the ACCESS climate model. This work allowed researchers to answer new scientific questions while providing a more user-friendly experience and often notable increases in model performance.

The work of the CMS team lowered the barriers to students' ability to use ACCESS. These improvements applied to both the single model components and the coupled versions.

The team supported new configurations of the land surface component. This included extensive efforts to integrate the Community Atmosphere Biosphere Land Exchange (CABLE) model with the Joint UK Land Environment Simulator framework and the integration of a groundwater module in the latest CABLE version.

On the ocean side, the team harmonised the Modular Ocean Model between different ACCESS configurations, made improvements to the ocean model efficiency in outputting data and participated in developing the Consortium for Ocean Sea Ice Modelling in Australia (COSIMA) - the COSIMA "cookbook" used to manage and analyse the model output.

The team provided a simplified and faster setup for ACCESS-ESM1.5 (Earth System Model) and maintained several new configurations using the same setup. This allowed paleoclimate simulations to run, including some that contributed to the sixth phase of the Coupled Model Intercomparison Project (CMIP6), an international modelling project.

Research Infrastructure Achievements

Each year of the Centre:

300
Helpdesk queries answered

40
Online help sessions held

13
New datasets downloaded

6
Model or analysis tools built

85
Datasets published

52
Software codes published

Overall during the 7 years:

57
Blogs published

72
Youtube videos publishedd

790
NCI users have access to our Python Conda (software) environments

2
Petabytes of storage used by Centre researchers managed

The team played a major role in the development and optimisation of a high-resolution atmosphere-only version of ACCESS. In particular, the optimisation work done for AUS2200 allowed the model to run 30 times faster. This enabled the CMS to run several simulations of past climate extremes events and to study the three El Niño-Southern Oscillation phases, which wouldn't otherwise have been possible.

On the data and software side, the CMS team has helped the Centre during all the stages of research. CMS made available and actively managed several reference climate data sets to be used as input for analysis and model simulations. The team also provided tools to facilitate finding, selecting and accessing the available data. They installed and centrally managed several software packages used for climate research. The team also helped develop and use specialised analysis tools: to calculate climate indices, detect atmospheric fronts, detect and calculate statistics of marine heatwaves, downscale model output using machine learning techniques and perform analysis on ocean model output and many others.

The CMS team members were spread across the Centre's nodes. Their friendly, useful and constructive advice regularly helped researchers on a range of topics.

To make the research data FAIR (Findable, Accessible, Interoperable and Reproducible), the CMS team provided both extensive guidelines and practical tools to help apply standards to files and to create data-management plans. They provided examples and templates of best practice in our guidelines to enable the adoption of FAIR with minimum disruption. The team helped publish research data output on the NCI data collection, but also established two collections on Zenodo to make the data and code more widely available and discoverable.

The CMS team members were the backbone of the Centre's research community, the unsung heroes of data-rich environments, who enabled the software and infrastructure that helped connect users of climate data with the best available information. They developed and supported the multi-institutional collaboration and systems by improving workflows and producing quality software, making research faster and more reliable.

Engagement and Impact

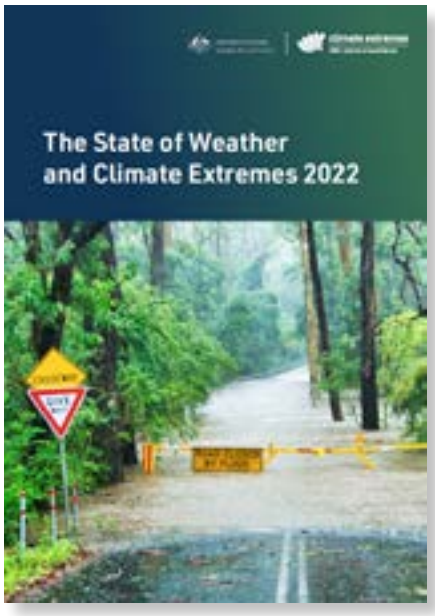
The Engagement and Impact team was a multidisciplinary team that brought together knowledge brokering, graphic design and communications capabilities to support the Centre's outreach activities. The Centre reached a broad audience of stakeholders, including governments, industry bodies, businesses, schools, the public and the academic community.

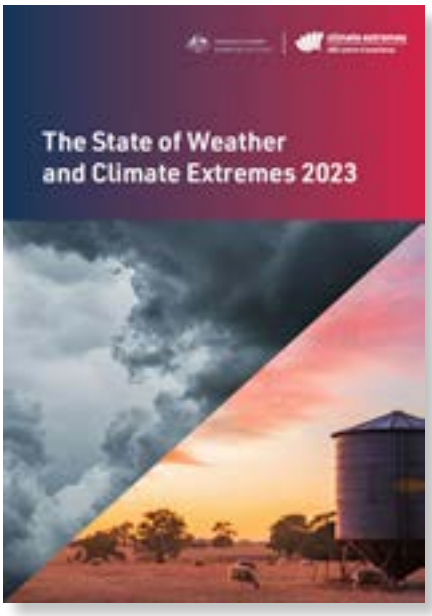
Activities were underpinned by a strong culture of science engagement across the Centre, creating an enduring two-way dialogue between climate scientists and decision makers. Engagement and Impact was a responsibility of all Centre affiliates, with activities supported by the Engagement and Impact team in an inclusive and collaborative process.

From Centre director to students, collaboration and engagement were central to research outcomes, with more experienced researchers mentoring and passing on their experience to early career researchers, facilitated by the team.

Activities were guided by principles that built and maintained the Centre's brand as a leading climate science centre:

Trusted, Respected, Legitimate, Credible, Reputable





There was a focus on delivering research and science information to a wide audience through varied channels, taking advantage of the emergence of new and different mediums.
This was done via the following:

Contributing expert commentary in international and Australian media:

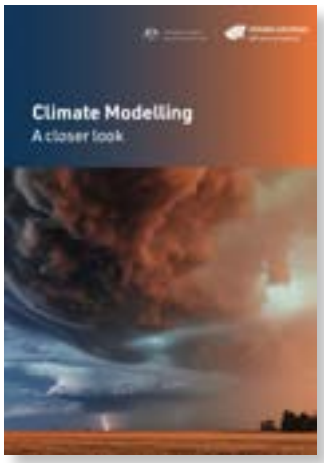
- Radio and TV appearances
- News and magazine articles on new and emerging science.

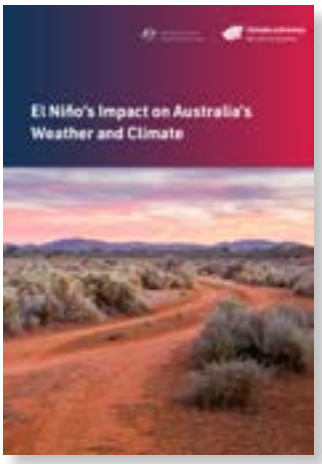
Dr Nicola Maher at the Federal Inquiry into the Climate Change Amendment (Duty of Care and Intergenerational Climate Equity) Bill 2023.

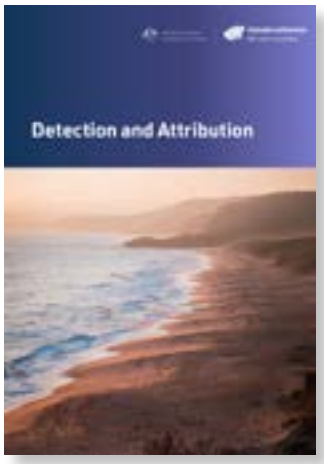
Professor Ailie Galland and Dr Kim Reid at the Victorian state Inquiry into Climate Resilience.

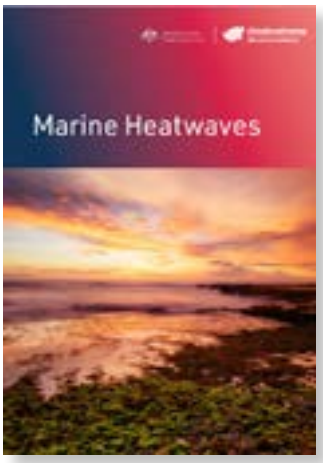
Informing stakeholders:

- Reports on the state of weather and climate extremes in Australia
- Policy submissions to government inquiries and processes
- Briefing notes published to explain important climate science concepts
- Resources created for school teachers to incorporate climate science into the syllabus.



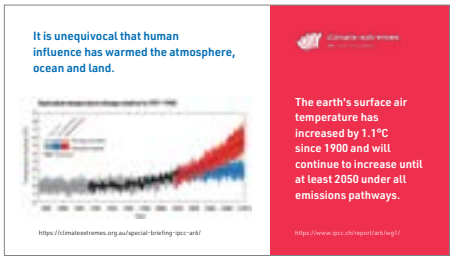


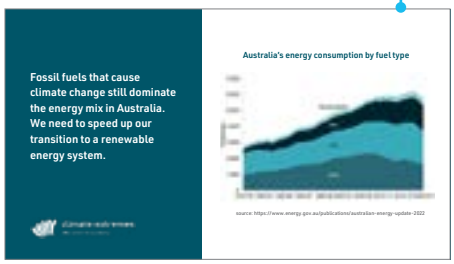


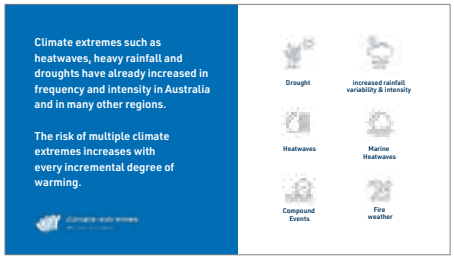


Engaging in a multimedia environment:

- Utilising graphic design to communicate complex concepts
- Producing informative web and social media content
- Creating video content about science topics and researchers
- Speaking to different audiences through tv, webinars and talks at conferences
- Meeting face-to-face.

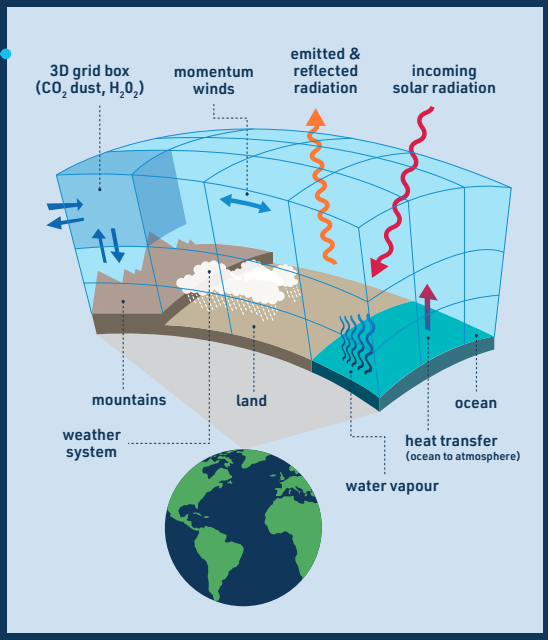


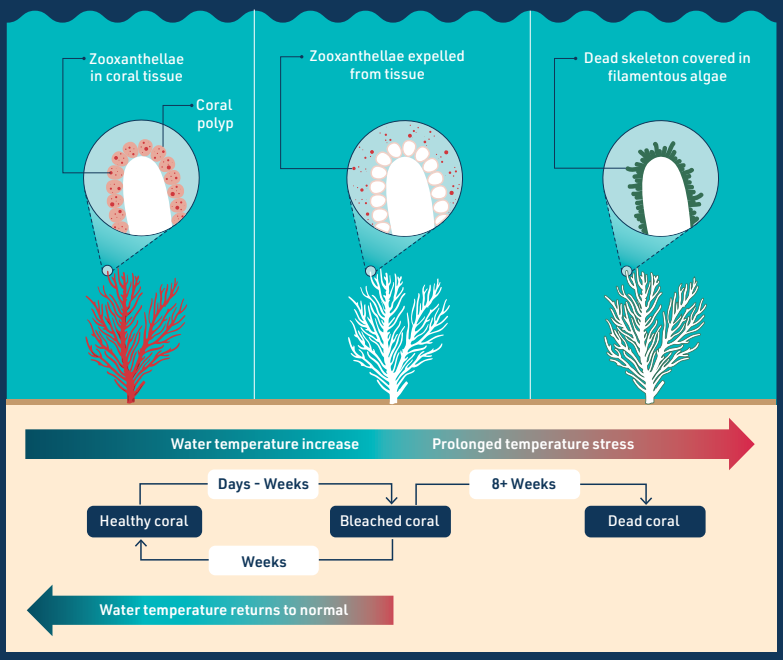


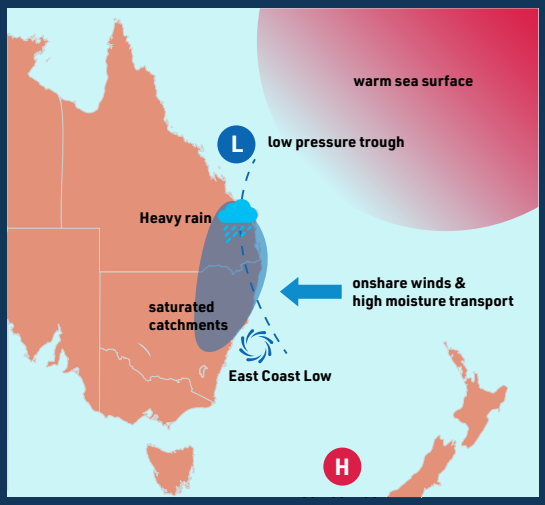


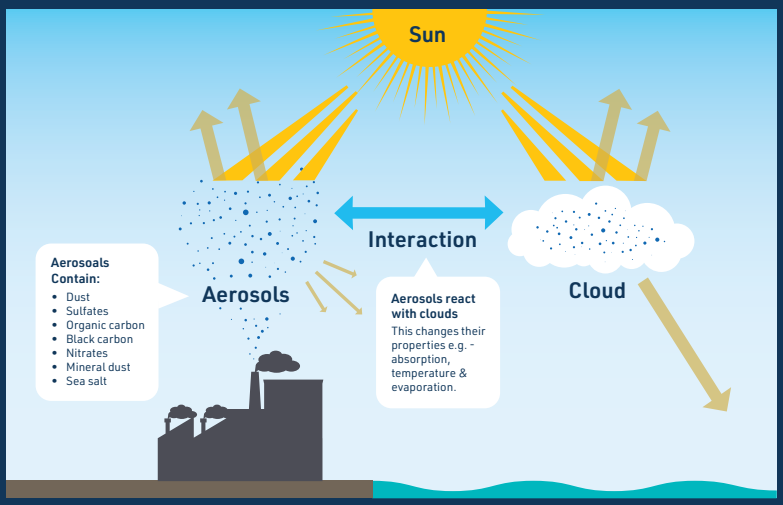
Professor Ben Newell, Professor Lisa Alexander, Angela Kaplish, Hon Tanya Plibersek MP, Professor Attila Brungs.

Ruby Lieber joined Channel 7's Weekend Sunrise to explain the likely declaration of an El Niño.

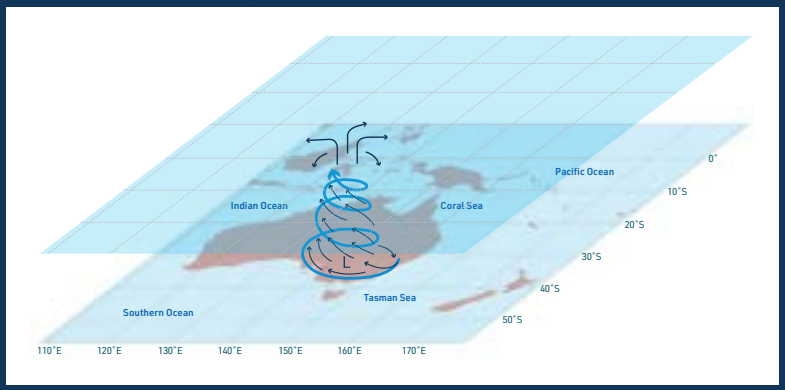








Top left: Illustration of the three-dimensional grid of a climate model. From the Climate Modelling - An Overview briefing note. Bottom left: Schematic of the conditions that led to the devastating floods in QLD and northern NSW in 2022. From the High impact compound events in Australia briefing note. Top right: Diagram showing the effects of water temperature changes on corals. From the Climatic factors affecting the Great Barrier Reef briefing note. Middle right: Schematic from the ARC Centre of Excellence for Climate Extremes website describing how aerosols affect atmospheric processes. Adapted from Wang Hao. Bottom right: Low pressure rotation graphic. Used in conference presentations and posters to explain scientific concepts.



Training the climate scientists of the future in strong science communication skills:

- Media training in real TV studios, with tips from experts (allowing researchers to gain realistic experience)
- Training on presentations, media communications and the writing of policy submissions and briefing notes.









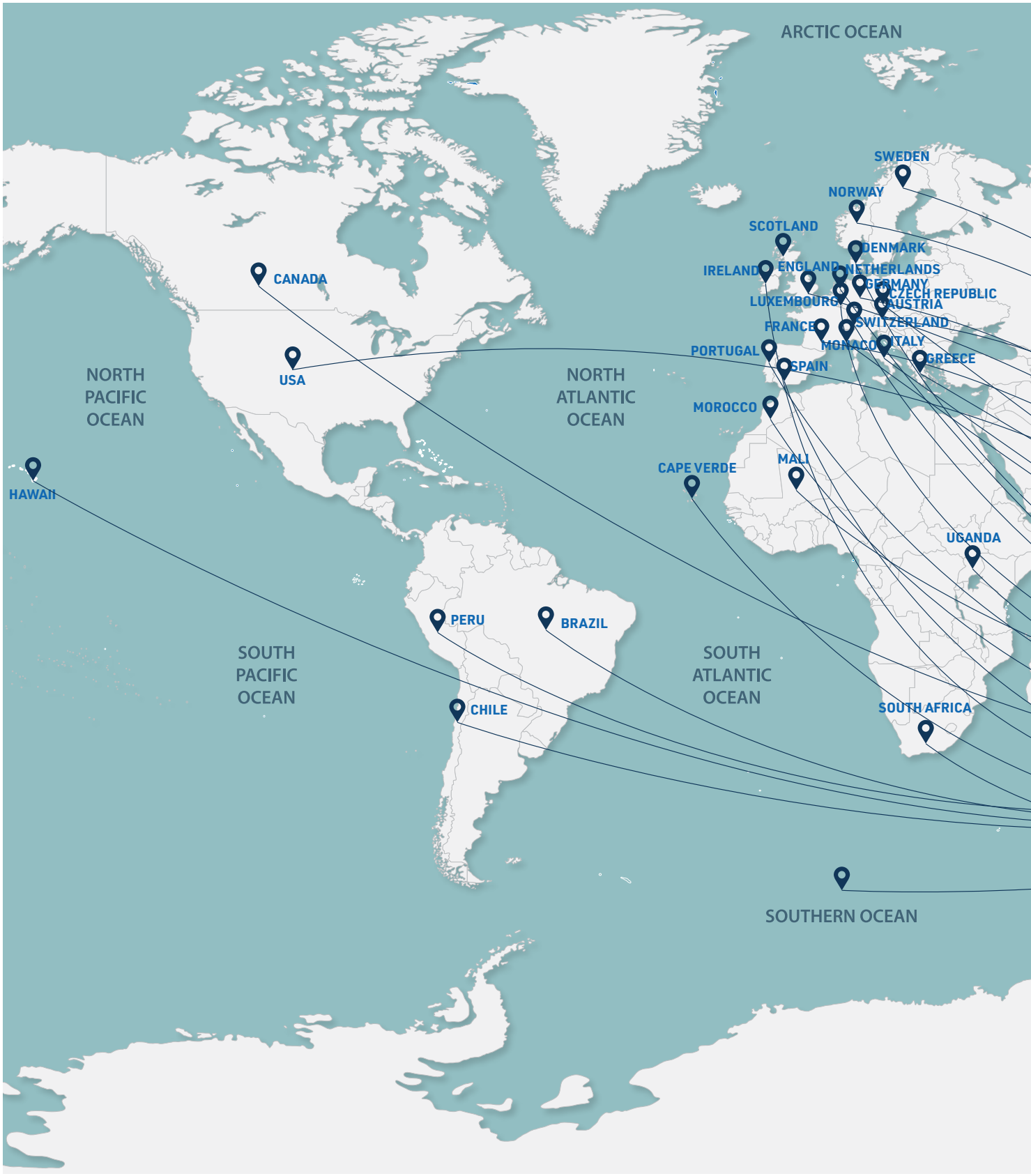


The Centre promoted a person-centred positive approach to Engagement and Impact activities, giving our early career researchers the opportunity to contribute. They were provided with media training and writing opportunities – in the form of government submissions and briefing notes – which also contributed to building the Centre's profile. The Engagement and Impact team focused on producing quality, regular publications, distributed effectively to the right audiences to enhance and maintain the Centre's reputation.

Through investing time in building the science communication skills of researchers, the Centre's efforts in Engagement and Impact will have a lasting legacy in the next generation of climate scientists. These science communication skills and linkages with stakeholders pave the way for a new generation of climate leaders to contribute their impactful science and inspire solutions to adapt to our changing climate. The Centre leaves a lasting legacy of enduring quality and expertise in the form of its researchers.

Collaboration at the Centre

The ARC Centre of Excellence brought together researchers from across Australia and internationally. Of our publications, 65% involved international collaborators, demonstrating the global collaboration in our research output. The Centre built cross institutional partnerships, engaging in a two way exchange of knowledge, with researchers travelling to overseas institutions and international collaborators visiting our Centre's university nodes.



This international engagement enhanced scientific discovery by leveraging diverse knowledge, methodologies and resources by engaging with subject matter experts from various fields of climate science. This allowed for innovative approaches to complex problems, producing scientific discoveries that may not have been achievable without a collaborative approach.

Centre researchers travelled to 44 different countries throughout the duration of the Centre, attending conferences, workshops and field trips, building their skills and continuing to strengthen an international research network. Through our efforts at the ARC Centre of Excellence, we have demonstrated the power of collective inquiry and the profound impact of shared knowledge on advancing science.

Our alumni

Estefania Montoya Duque
at the University of Melbourne in 2022.

Dr Estefania Montoya Duque was affiliated with the Centre from 2020 to 2024, completing her PhD at the University of Melbourne. Her research focused on understanding cloud microphysics and how they relate to different weather patterns over the Australian sector of the Southern Ocean.

Dr Duque participated in the workshops and winter schools organised by the Centre and is grateful for both the soft and technical skills she learned during those events. She found the workshops a good opportunity to make connections and participate in conferences. Dr Duque highlights the uniqueness of this Centre in enabling collaboration with other institutions (even internationally) to promote career development. By interacting with students outside the Centre, she realised how lucky she was to have had these opportunities. Dr Duque is now working as a risk analyst at Risk Frontiers in Sydney.

Sugata Narsey
climate scientist at the Bureau of Meteorology.

Dr Sugata Narsey was a PhD student at Monash University from 2014 to 2018 before working as a postdoctoral researcher with the Centre from 2018-2019. He researched the dynamics of Australian monsoon rainfall bursts in reanalyses and climate models. Since leaving Monash University, Dr Narsey has worked as a climate scientist at the Bureau of Meteorology, where he develops the next generation of climate change projections for Australia. During his time at the Centre he benefited enormously from the generous mentorship, education, and support of great scientists and professional staff at every career stage. Aside from helping him advance in his studies, this provided Dr Narsey with a great network of professional and personal relationships that continues today.

Annette Hirsch
climate risk expert at Deloitte.

Dr Annette Hirsch was a UNSW postdoctoral researcher in the Centre from 2018 to 2021. Her research focused on how antecedent land surface conditions and atmospheric dynamics can amplify surface temperatures during heatwave events. She went on to become a director at Deloitte, where she is now a climate risk expert, translating climate science into applications to support decision makers as they manage the risks and opportunities associated with climate change. Her most memorable experience at the Centre was the opportunity to learn about the science-policy interface through an internship facilitated by Centre leadership.

Josué Martínez Moreno
postdoctoral researcher at IFREMER, France.

Dr Josué Martínez Moreno completed a PhD from 2017 to 2021 at the Centre's Australian National University node, where he investigated the response of mesoscale currents to our changing climate over the last 30 years. After his time at the Centre, Dr Moreno began a postdoctoral position at the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) in France, where he currently works, focusing on the interaction between ocean currents and ice in the Arctic. He particularly appreciated the nurturing culture of the Centre, which fostered enriching discussions and collaboration among peers, all within an inclusive and encouraging environment.

Margot Bador
a research fellow at the CNRS in Toulouse, specialising in extreme weather phenomena.

Dr Margot Bador was a research fellow at the University of New South Wales from 2018 to 2021. She studied how extreme precipitation is affected by climate variability and change in Australia and globally, as well as other types of climate extremes. During her time at the Centre she experienced quite a few extremes in real life: heavy rainfall, heatwaves, droughts, bushfires. These were a lot of extremes for someone coming from a more moderate European climate, compared to the south of France. Dr Bador is now a climate scientist at the Centre National de la Recherche Scientifique (CNRS), France.

Highlighted publications

Drought research program

1. Holgate, C. M., J. P. Evans, A. I. J. M. van Dijk, A. J. Pitman, and G. Di Virgilio, 2020: Australian Precipitation Recycling and Evaporative Source Regions. J. Climate, 33, 8721–8735, https://doi.org/10.1175/JCLI-D-19-0926.1.
2. Taschetto, Andréa & Stojanovic, Milica & Holgate, Chiara & Drumond, Anita & Evans, Jason & Gimeno, Luis & Nieto, Raquel. (2024). Changes in moisture sources contributed to the onset and development of the 2017-2019 southeast Australian drought. Weather and Climate Extremes. 44. 100672. 10.1016/j.wace.2024.100672.
3. Falster, G., Wright, N., Abram, N., Ukkola, A., & Henley, B. (2024), Potential for historically unprecedented drought from natural variability and climate change, Hydrology and Earth System Sciences.
4. Mu, M., De Kauwe, M. G., Ukkola, A. M., Pitman, A. J., Guo, W., Hobeichi, S., and Briggs, P. R.: Exploring how groundwater buffers the influence of heatwaves on vegetation function during multi-year droughts, Earth Syst. Dynam., 12, 919–938, https://doi.org/10.5194/esd-12-919-2021, 2021.
5. Devanand, A., Falster, G.M., Gillett, Z.E., Hobeichi, S., Holgate, C.M., Jin, C., Mu, M., Parker, T., Rifai, S.W., Rome, K.S., Stojanovic, M., Vogel, E., Abram, N.J., Abramowitz, G., Coats, S., Evans, J.P., Gallant, A.J.E., Pitman, A.J., Power, S.B., Rauniyar, S.P., Taschetto, A.S., Ukkola, A.M., 2024. Australia's Tinderbox Drought: An extreme natural event likely worsened by human-caused climate change. Science Advances 10, eadj3460. https://doi.org/10.1126/sciadv.adj3460
6. Jin, C., Reeder, M.J., Gallant, A.J.E., Parker, T., Sprenger, M., 2023. Changes in weather systems during anomalously wet and dry years in southeastern Australia. Journal of Climate. https://doi.org/10.1175/JCLI-D-23-0305.1
7. C.M. Holgate, A.S. Pepler, I. Rudeva, N.J. Abram, Anthropogenic warming reduces the likelihood of drought-breaking extreme rainfall events in southeast Australia, Weather and Climate Extremes, https://doi.org/10.1016/j.wace.2023.100607.
8. King, A. D., Pitman, A. J., Henley, B. J., Ukkola, A. M., & Brown, J. R. (2020). The role of climate variability in Australian drought. Nature Climate Change, 10(3), 177–179. https://doi.org/10.1038/s41558-020-0718-z
9. 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
10. Yang, Y., Roderick, M.L., Zhang, S., McVicar, T.R., Donohue, R.J., 2019. Hydrologic implications of vegetation response to elevated CO2 in climate projections. Nature Climate Change 9, 44. https://doi.org/10.1038/s41558-018-0361-0
11. Ukkola, A. M., De Kauwe, M. G.,Roderick, M. L., Abramowitz, G., & Pitman, A. J. (2020). Robust future changes in meteorological drought in CMIP6 projections despite uncertainty in precipitation. Geophysical ResearchLetters, 46, e2020GL087820. https://doi.org/10.1029/2020GL087820

Attribution and Risk research program

1. Reid, K, Michael A. Barnes; Zoe E. Gillett; Danielle G. Udy; Hooman Ayat; Ghyslaine Boschat; Annabel Bowden; Nicholas H. Grosfeld; Andrew D. King; Tess Parker; Doug Richardson; Yawen Shao; Lina Teckentrup; Blair Trewin; Pandora Hope; Linjing Zhou; Alexander R. Borowiak; Chiara M. Holgate; Rachael Isphording. 2024., A Multiscale Evaluation of the Wet 2022 in Eastern Australia", Journal of Climate, accepted
2. Shao, Y., Bishop, C.H., Hobeichi, S., Nishant, N., Abramowitz, G., Sherwood, S., 2024. Time Variability Correction of CMIP6 Climate Change Projections. Journal of Advances in Modeling Earth Systems 16, e2023MS003640. https://doi.org/10.1029/2023MS003640
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5. Lane, T.P., King, A.D., Perkins-Kirkpatrick, S.E., Pitman, A.J., Alexander, L.V., Arblaster, J.M., Bindoff, N.L., Bishop, C.H., Black, M.T., Bradstock, R.A., Clarke, H.G., Gallant, A.J.E., Grose, M.R., Holbrook, N.J., Holland, G.J., Hope, P.K., Karoly, D.J., Raupach, T.H., Ukkola, A.M., 2023. Attribution of extreme events to climate change in the Australian region – A review. Weather and Climate Extremes 42, 100622. https://doi.org/10.1016/j.wace.2023.100622

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9. Nguyen, PL., Bador, M., Alexander, L.V. et al. Selecting regional climate models based on their skill could give more credible precipitation projections over the complex South-east Asia region. Climate Dynamics 61, 3431–3452 (2023). https://doi.org/10.1007/ s00382-023-06751-5

10. 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

Ocean Extremes research program

1. Holbrook NJ, HA Scannell, A Sen Gupta, JA Benthuysen, M Feng, ECJ Oliver, LV Alexander, MT Burrows, MG Donat, AJ Hobday, PJ Moore, SE Perkins-Kirkpatrick, DA Smale, SC Straub and T Wernberg, 2019: A global assessment of marine heatwaves and their drivers. Nature Communications, 10, Article number 2624, https://doi.org/10.1038/s41467-019-10206-z.

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