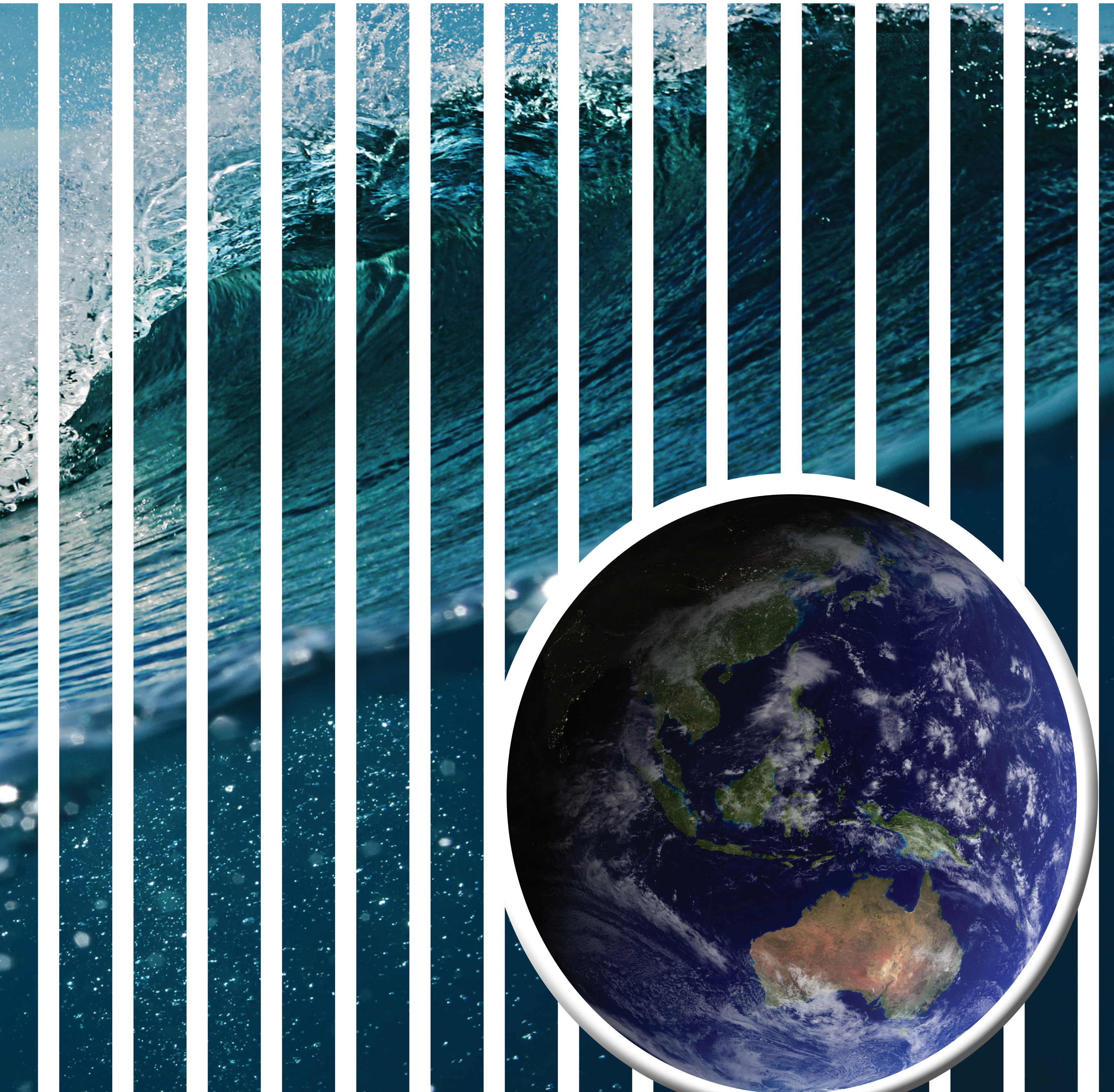
ARC CENTRE OF EXCELLENCE FOR
CLIMATE SYSTEM SCIENCE



2011-2017 Our Legacy

INTRODUCTION

Understanding key climate processes is the foundation for predicting their impact on Australia and the world – today and into the future. A decade ago, the university climate science community competed for sparse resources. A lack of collaboration significantly hindered our progress. However, in 2011 the Australian Research Council established the ARC Centre of Excellence for Climate System Science (ARCCSS) and our journey of innovation and transformation began. We began to tackle tough problems, take risks and deliver world-class solutions.

Over the last seven years we made significant breakthroughs in our comprehension of the climate system, many of which are highlighted in this report. We shed new light on the workings of El Niño and its influence on Australian climate. We discovered a strong connection of tropical cyclones to the north of Australia with heatwaves in the south. By advancing our understanding of tropical clouds, we discovered that the Earth's temperature might be more sensitive to CO_2 in the atmosphere than previously thought.

We combined our better understanding with a major investment into a national climate modelling infrastructure, thereby enabling better weather and climate predictions for all Australians. We've developed new land models that demonstrate how vegetation can affect heatwaves. We've built a high-resolution model of the ocean, which captures how ocean eddies influence climate.

While proudly calling Australia home, our reach is far. Our data sets are used worldwide in breakthrough science and even in climate-risk assessments in the finance and insurance industry. It's fair to say that our researchers have shaped the direction of the international climate science community.

Thanks to the substantial funding by the Australian Research Council (ARC), we were able to contribute to a culture of collaboration that stretched well beyond the boundaries of our Centre. Our graduate program has trained more than 100 students and early career researchers - and every single one of them got a job. Our graduates, working in elite laboratories all over the world, now vigorously tackle the challenges of a planet undergoing major changes.

We are thrilled that the generous funding we received from the ARC and our universities revolutionised our Centre's endeavours to undertake world-class research and educate the next generation of climate scientists. Our contribution to smarter weather and climate predictions will provide better information for policymakers, industries and public services. Importantly, our legacy of breakthrough science, better predictions, a culture of collaboration and a new generation of science leaders will shape the Australian community for decades to come.

Andrew Pitman
Founding Director

Christian Jakob
Director

CLIMATE PROCESSES




The foundation for the many ARCCSS triumphs over the past seven years has been a deeper understanding of climate processes. We carried out process-focused studies in all major spheres of the climate system, ranging from tiny cloud droplets to high-pressure systems covering half the Australian continent. This in-depth, fundamental research requires time and persistence, and it could not have been achieved without the long-term funding provided by the Australian Research Council.

ARC funding also meant we could build multi-disciplinary teams. The work of one of those teams, which included plant physiologists and climate scientists, led to an entirely new understanding of how leaves exchange water and carbon with the atmosphere through microscopic openings called stomates. This produced groundbreaking insights into how plants can alter the intensity of heatwaves.

Our work has significantly advanced our understanding of the dynamics of ocean eddies. We discovered that eddies in the Southern Ocean have increased in recent decades. This has direct implications for global warming and the biological productivity of the Southern Ocean.

We also found that wind systems in the atmosphere critically influenced sea ice evolution in the Southern Ocean. This work largely solved the puzzle of why sea ice cover in the northern hemisphere decreased over recent decades but increased in the southern hemisphere.

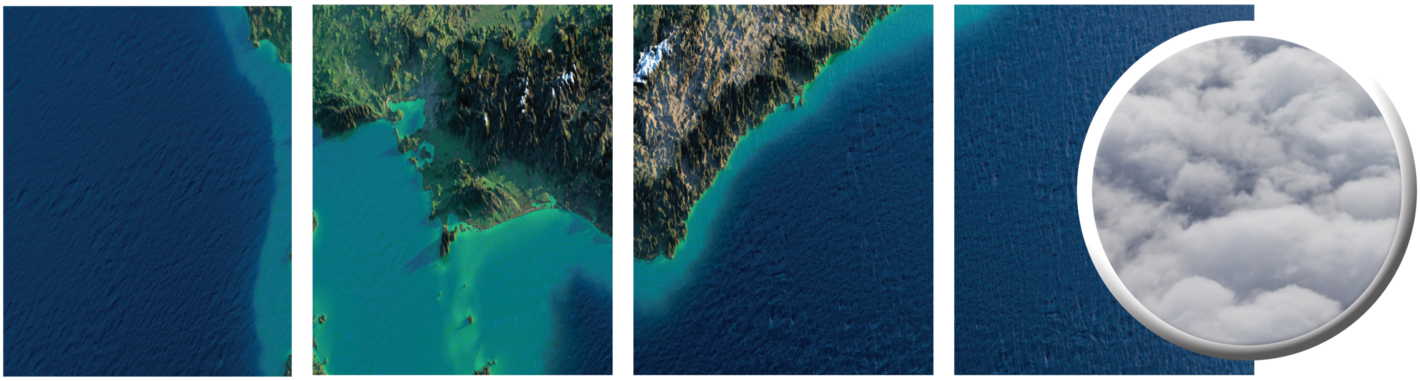
Our foundational research examined the details of the clouds involved in tropical thunderstorms, from their initiation near the Earth surface, through to their growth through the atmosphere and organisation into larger features. This fundamental work revealed new insights into one of the most challenging regions in the world just north of Australia – the Maritime Continent, a region whose climate is particularly important for the economic, mining and agricultural activities in our northern states.

Taking this work and focusing on coastal regions where most population centres are situated, we found about half of the rainfall here is associated with coastally driven convection. We discovered that coastal convection behaves quite differently from its cousins over the open ocean. We used detailed process models of tropical convection to investigate the causes for this behaviour. The pinnacle of this work is a set of 10 years of unique model simulations over the Maritime Continent that will spawn better predictions for climate and weather in this region.

Last but not least, we showed for the first time the overwhelming influence atmospheric dynamical processes have on the strength and duration of recent Australian heatwaves. In doing so, we painted an entirely new picture of the evolution of these extreme events and their impact on our health and infrastructure, enabling improved forecasting of Australian heatwaves.

Together, this process-based understanding provided the foundation for all our research programs. It provided invaluable insights into the development of new algorithms that improved the representation of processes in climate models, which are at the heart of predictions of future climate and remain some of our major research tools.

NEW TOOLS AND SYSTEMS



Climate science relies on the use of complex climate models which in turn rely on world-class research infrastructure, including supercomputers and big data systems. Our models capture current knowledge of climate processes and produce new insights into how the climate works.

Our research has improved Australian and international climate models, leading to new discoveries and better prediction of weather and climate. Our improvement of models of the Southern Ocean is vital to Australia because of its influence on our weather and future climate. Our ocean modelling legacy includes

- development of Australia's first free-running "eddy-rich" global ocean-sea ice model at 0.25° resolution;
- the creation of a fully coupled ocean-atmosphere-sea ice high-resolution version of our national climate model, the Australian Community Climate and Earth System Simulator (ACCESS); and
- development of an ultra-fine regional model of the Southern Ocean – the first model in the world to resolve sub-mesoscale processes in this region.

These models underpinned much of our research on the role ocean eddies play in Southern Ocean circulation.

Australia's land models are also much improved thanks to our fundamental research. Our research on stomates, soil evaporation, soil hydrology and vegetation led to a better representation of important processes in Australia's Community Atmosphere Biosphere Land Exchange (CABLE) model, which is part of ACCESS. We revealed the strong influence of stomates on the intensity of heatwaves, complemented by an improvement in CABLE's treatment of soil

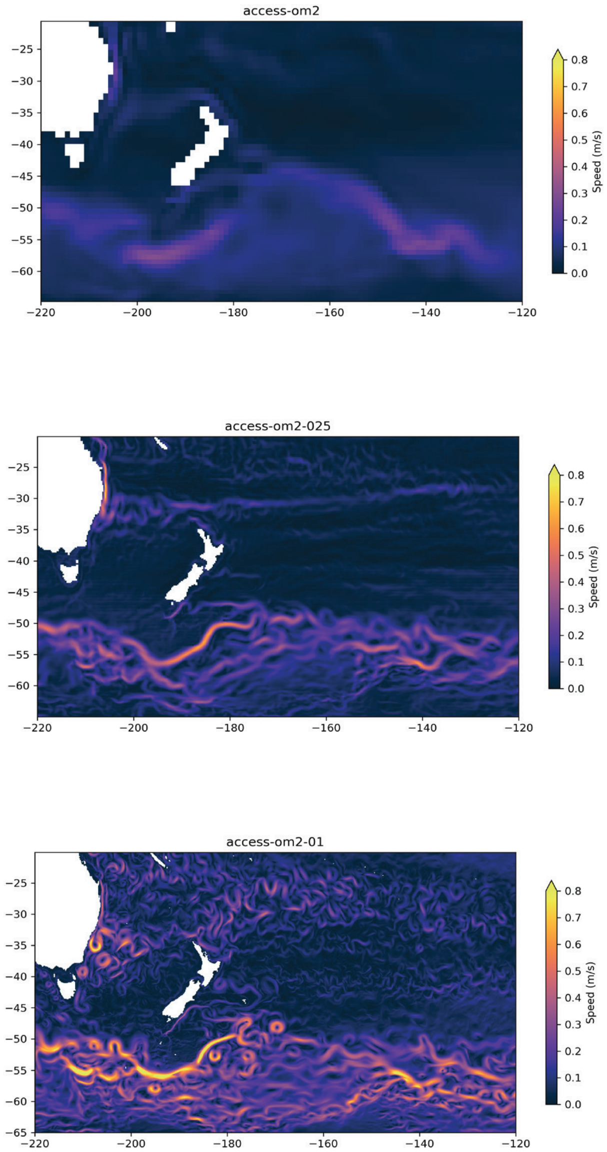


Figure 1: Surface current speed in 1, 0.25 and 0.1-degree ACCESS-OM2 ocean model configurations

hydrological processes. This work improved ACCESS and our understanding of Australia's water cycle.

Our world-leading research into thunderstorms allowed us to develop an entirely new representation of convection for global models. Some of the innovations included stochastic approaches and clouds with 'memory' that can co-exist in their various forms in a single model grid cell. Tests of these model innovations have shown significant improvements in representing tropical climate – a weak spot in contemporary climate models.

We also took our climate tools to the public, building one of the simplest climate models possible – the Monash Simple Climate Model. Using this interactive, web-based model, every Australian can explore the current climate, the processes that control its behaviour, and what might lie ahead. We held training workshops on the model for teachers and ran classes in schools. As a result, the Monash Simple Climate Model has been successfully used in high school and university classrooms.

Beyond climate models, we developed new data sets for climate research, in particular in the area of climate extremes. This extremes data showed total and extreme precipitation intensifying in the world's wettest and driest regions. A comparison of our new data sets to others showed large-scale warming and wetting signals in observations over the 20th century were consistent across all of them. These data and others now underpin risk assessment across parts of the globe by groups such as the American Society of Actuaries.

Computational Modelling Support

The secret to the success of the ARC Centre of Excellence for Climate System Science in developing new tools was our Computational Modelling Support (CMS) team. Building a dedicated team of modelling and data infrastructure experts was a game changer and, again, it was only possible through the long-term funding from the Australian Research Council that allowed this multi-institution collaboration.

Training provided by the CMS team enabled staff and students to employ models and data sets rapidly. What once took months could now be done in days. The team established new workflows and supported the multiple modelling systems we use.

In collaboration with the Bureau of Meteorology, the CSIRO and the National Computational Infrastructure, the team built the infrastructure needed to carry out research with the ACCESS model and its components. It brought together in one location the international climate model data sets collected by the Coupled Model Intercomparison Project (CMIP). When we look back on our research successes, without doubt, we can say many would not have been achieved without the CMS team.

GLOBAL AND AUSTRALIAN CLIMATE

Our fundamental research, new tools and an international network of collaborators opened the door to major discoveries about global and Australian climate. The reach of these findings goes beyond science, affecting major policy decisions at all levels here and abroad.

We played a major role in solving a conundrum – why greenhouses gases continued to rise but the rate of surface warming slowed briefly in the early 21st century. The key was an unprecedented rise in the strength of Pacific trade winds. Our investigation showed the stronger winds increased the rate at which heat from the atmosphere was transferred into the ocean. With more heat in the ocean, there was less in the atmosphere. It also told us that when the trade winds returned to normal we would see a strong increase in warming and quite likely a strong El Niño. Both events occurred following those findings. Understanding these decadal variations on the surface temperature has profound implications for policy and it increases our confidence in projections of future climate.

Bringing together meteorologists and oceanographers, we made major new discoveries about the world's oceans. The deep circulation of oceans, known as the overturning circulation, brings carbon-rich waters to the surface of the Southern Ocean to power ecosystems in this region. Researchers suspect the circulation process is driven by strong westerly winds in this area. It was thought the increase in these winds in recent decades may have enhanced the rate of upwelling and this would continue into the future. However, using our new high-resolution global ocean model, Centre researchers found it was not so simple. While increasing winds dragged more deep water to the surface, this effect was offset by the winds shifting closer to the poles as the climate changed. This result implies future climate trajectories may not be associated with enhanced upwelling, which has profound implications for life in the ocean.

Collaboration between our Oceans and Extremes research program teams opened an entirely new area of research – that of marine heatwaves. We built a new framework for studying marine heatwaves and assessing their trends around the globe. This framework was applied to the first major study of the record marine heatwave in 2015-16 off Tasmania's east coast. The heatwave lasted more than 250 days and at its greatest extent was seven times the size of Tasmania. It reduced the productivity of Tasmanian salmon fisheries, led to a rise in blacklip abalone mortality and sparked an outbreak of Pacific Oyster Mortality Syndrome. At its peak intensity, waters off Tasmania were almost 3°C above normal. We showed that human-caused climate change was a significant contributor to the intensity of this heatwave.

Our Extremes and Variability research program teams joined forces to discover a previously unknown connection between tropical cyclones off the northwest coast of Western Australia to heatwaves over south-eastern Australia. This work showed that dynamic interactions of the cyclones with the extra-tropical atmosphere could strengthen and prolong heatwaves over south-east Australia. As a result, we can now predict that heatwaves in Victoria are more likely during active convection over the Australian tropics. This leads to more reliable forecasts and improves planning decisions for these high-impact events.

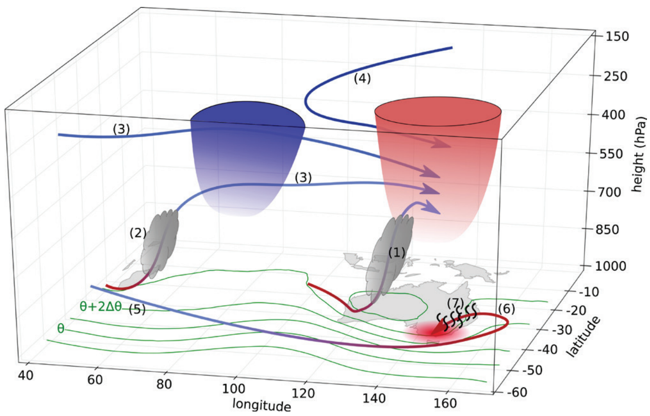


Figure 2: A schematic of the ingredients of a heatwave over south-eastern Australia, the most important being: the upper-level anticyclone (red inverted cone); air rising into the upper anticyclone with cloud and precipitation over Western Australia (labelled 4); and air subsiding (labelled 6 and 7) into the surface high (red disk).

Our work on prolonged heat extended to research on drought through our Land research program. The prevailing view, when our Centre started, was that rising global temperatures increased aridity and drought worldwide. We showed this was not true and there had been little change in global drought over the past 60 years. We traced this finding to complex interactions between vegetations, water and CO_2.

We also demonstrated that climate models generally projected vegetation greening because of increasing CO_2. This was consistent with paleoclimate and modern observations. By combining process-level knowledge with satellite data we showed that over arid regions the magnitude of observed vegetation greening was broadly as expected, due to increasing CO_2.

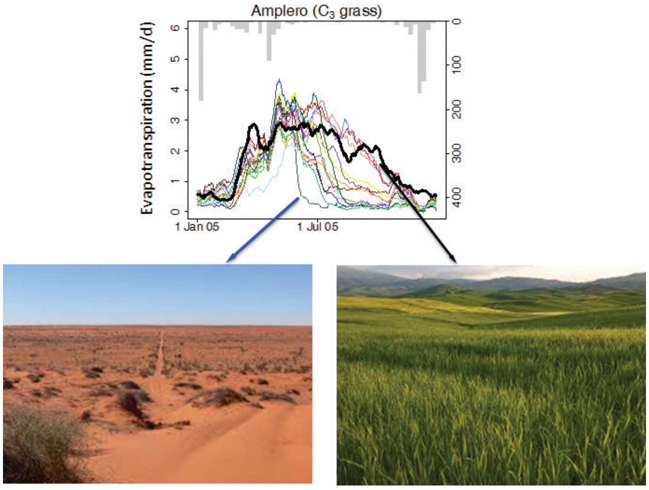


Figure 3 Land models respond very differently to drought. Here, after a week one model simulates a desert like landscape with almost no evaporation. Others sustain evaporation for months and reflect conditions more like a productive grassland. Work by ARCCSS has understood and resolved this profoundly different response leading to better predictions of drought.

Given the key role of tropical cyclones and thunderstorms, we examined how these connect to and influence the atmospheric circulation. Tropical atmospheric processes have a powerful effect on our climate, but they are poorly represented in climate models. To improve their understanding, Centre researchers used satellite observations of different cloud types. We discovered that recent trends in tropical rainfall could be traced to changes in the occurrence of organised convection. We also found that climate models treated this convection and interaction differently to the way it occurred in the real world. This was a crucial discovery because tropical clouds play a major role in determining how sensitive our climate is to CO_2 concentrations.

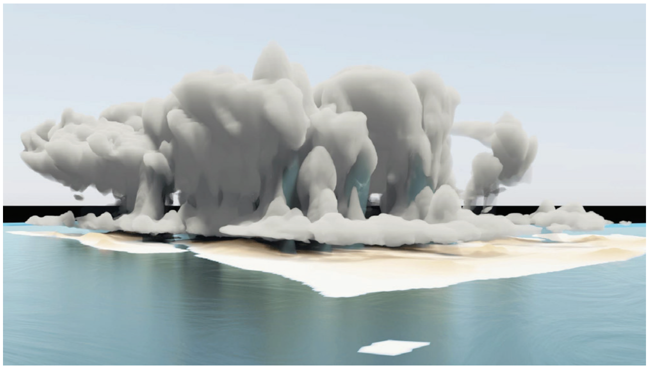


Figure 4: A high-resolution (~400 m) simulation of the Hector storm over the Tiwi Islands, Australia. Clouds in white-grey, rain in blue.)

The Centre of Excellence was also a world leader in the new research field of the attribution of climate events. This research revealed clear signatures of human-induced climate change in many recently observed temperature extremes. Our team led the first-ever investigation into how humans contributed to the record hot 2013 Australian summer. They found human influences increased the odds of the extreme heat 2.5 to 5 times.

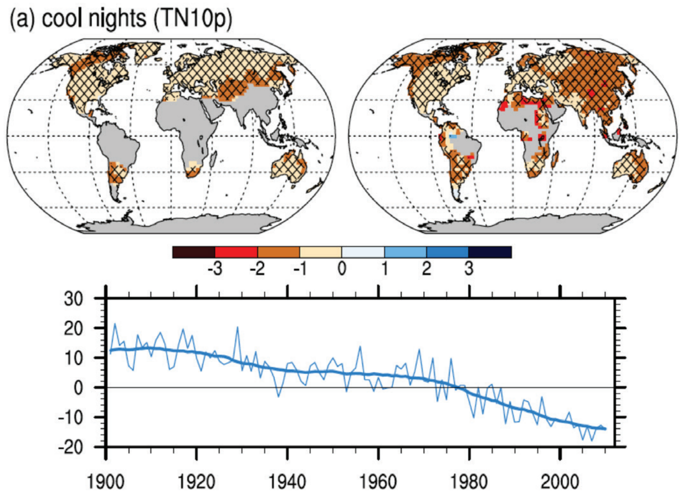
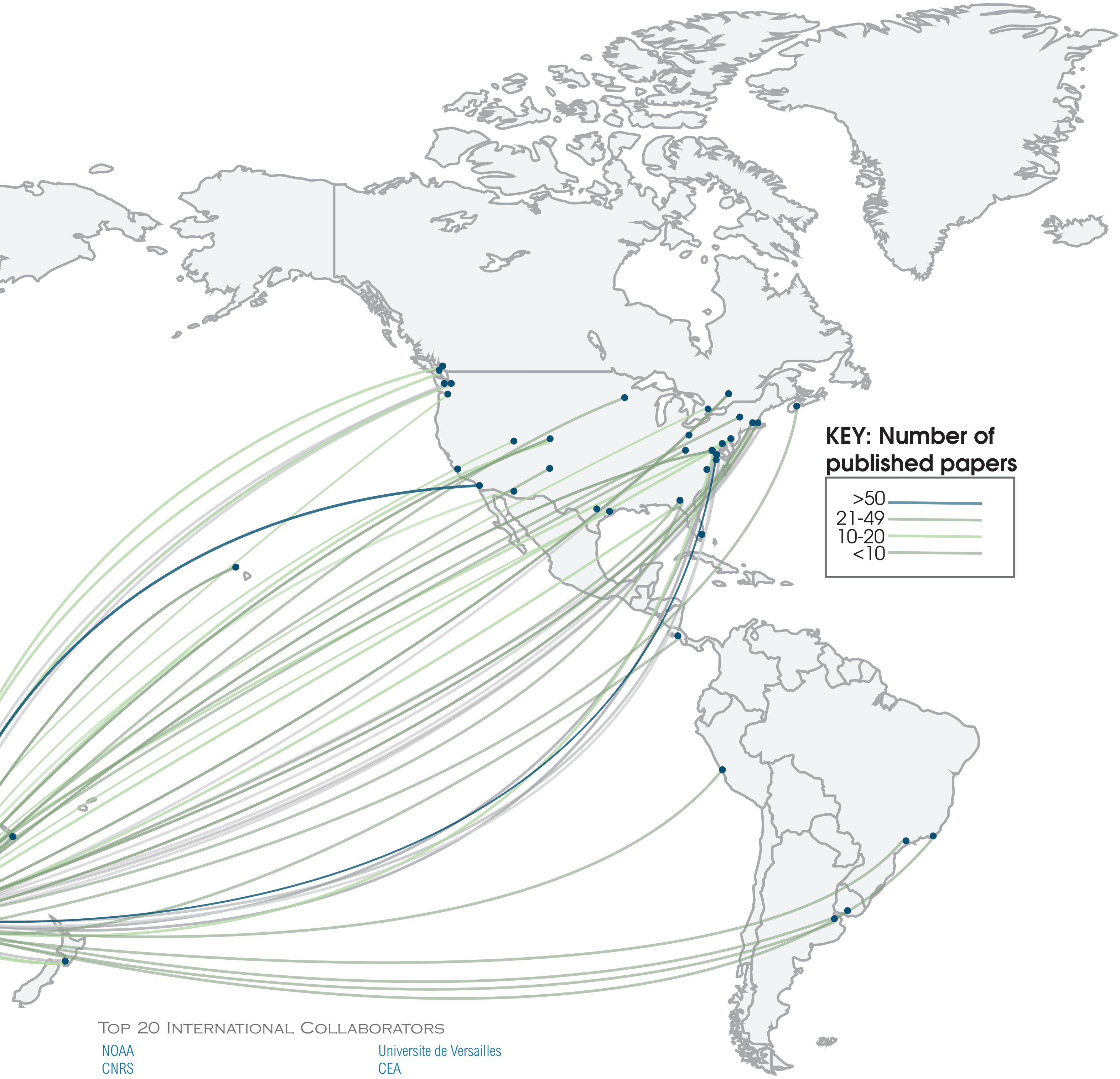


Figure 5: Trends (in annual days per decade, shown as maps) for cool nights for (left) 1901–2010 and (right) 1951–2010. Hatching indicates regions where trends are significant at the 5% level. The time series show the global average annual values (in days per year) for cool nights as anomalies relative to 1961–1990 mean values (thin blue line) and multi-decadal smoothing (thick blue line).

These examples are just some of our key discoveries about global and Australian climate. What they all have in common is that none of them would have been possible when tackled as a set of small, isolated projects. This research required deep collaboration by experts from various disciplines and institutions, equipped with new shared tools, which was enabled by the existence of the ARCCSS.

ARCCSS GLOBAL COLLABORATION

This map shows the enormous reach and interconnectedness of our research. We published **over 1000** peer reviewed articles, with **over 2,500** authors from **463** institutions in **108** countries.



Top 20 International Collaborators

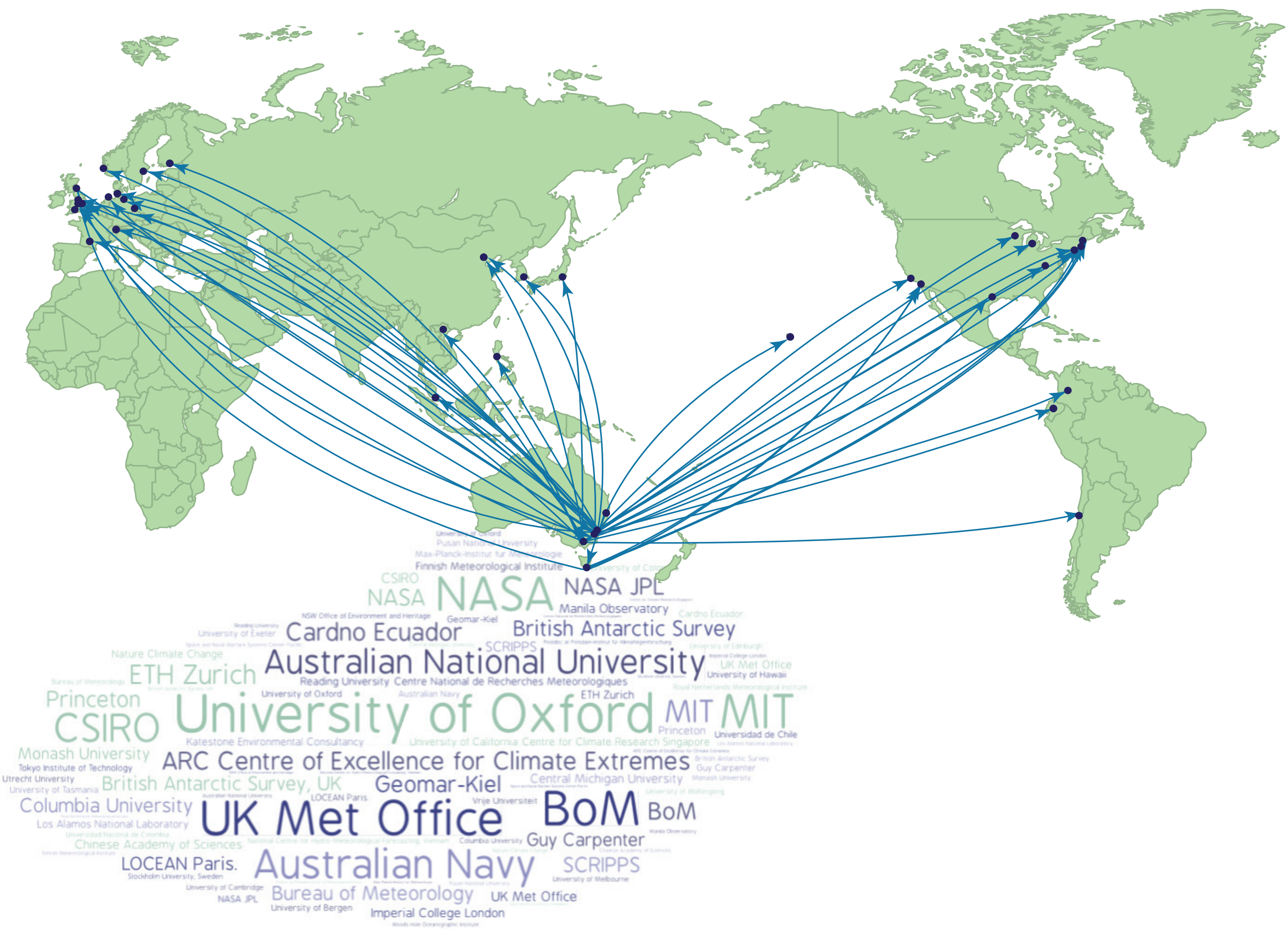
NOAA
CNRS
University of California
National Aeronautics and Space Administration
UK Met Office
Universite Paris 7
IRD
National Center for Atmospheric Research
Universite Paris Saclay
University of Hawaii at Manoa
Universite de Versailles
CEA
Universite Pierre et Marie Curie
CNES Centre National d'Etudes Spatiales
ETH Zurich
Chinese Academy of Sciences
Woods Hole Oceanographic Institution
Columbia University
PSL Research University
Environment Canada

OUR GRADUATE PROGRAM

Our great success in graduate and early career researcher (ECR) education is a direct result of the ARC Centre of Excellence for Climate System Science dedicated graduate program. The program was led by a full-time director, who liaised with centre researchers and graduate research schools at each of our universities and acted as a point of contact, mentor, and advocate for all our students.

Our graduates have achieved a 100% employment rate within six months of graduation. This map shows the global reach of our ever-growing network of in-demand alumni, spread across leading universities and research institutes around the world.

Alumni Destinations



Graduate Training Cornerstones

Under the leadership of our Graduate Director, the centre designed and implemented a dedicated program for all our graduate students.
This program provided breadth, depth, support and collaboration.
It ensured our students and early career researchers received tailored, individual support that greatly enhanced their experience.

The Cornerstones of this program were:

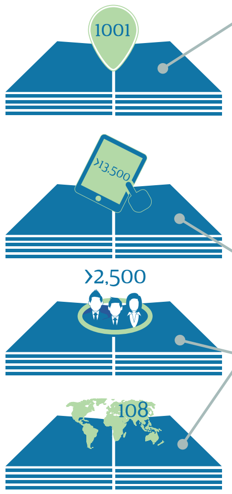
- **Collaboration**. While enrolled at one university, each student was considered a cross-institutional student.
- **Leadership.** Students and ECRs self-organised through an ECR Committee.
- **Professional development.** Students and ECRs had access to annual professional training opportunities, including writing and career advice workshops.
- **Scientific training.** We trained almost 500 students from 34 institutions at our annual scientific winter schools.
- **Technical training.** Students and ECRs had continuous access to our CMS team, which provided regular training in modelling and data systems.

As a result of the dedicated work in the graduate program, our students have been able to carry out world-class research. All are continuing their scientific careers, in top national and international laboratories, in Federal and State governments or in industry.

NATIONAL & INTERNATIONAL IMPACT

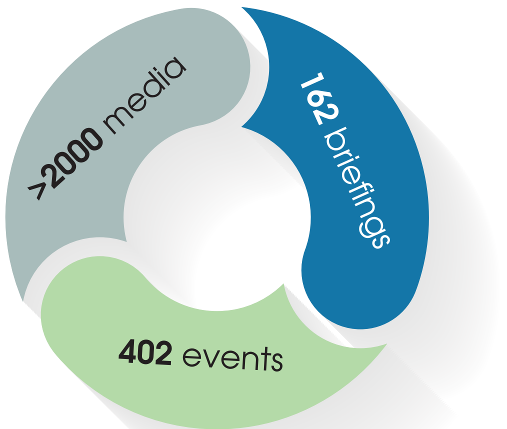
Our work has had a profound impact; both nationally and internationally. This ranges from the traditional measures of success, such as publications and citations, to community-wide influence, such as a transformation of the collaborative culture in Australia.

Publications and Citations



- We published **1001** studies in the international literature; of these, **90.4%** in the discipline's highest-impact journals, including **76** papers appearing in Nature and Science.
- Our research has been cited **over 13,500** times.
- We have collaborated with **over 2,500** colleagues outside of the five university groups from **108** countries (centre spread map)

The deep collaborative network established by ARCCSS has strongly increased Australia's climate science reach and will serve the community for de-cades to come.



Media and Communications

- We had over **2000** media mentions, including in very high-profile publications, such as ***The New York Times, BBC, CNN, Al Jazeera*** and ***The Wall St Journal.***
- We gave **162** expert briefings to government and industry and participated in **402** public events.
- We developed new **tools for teachers**, such as our simple climate model, so that they can engage in more meaningful ways with the next generation of Australians.

Awards and Leadership

- Centre researchers and students have won **132 prizes** and awards, amongst them **20 fellowships to learned societies and every Priestley Medal awarded by the Australian Meteorological and Oceanographic Society since the Centre's inception.**
- **Nine** of our staff participated in the assessments carried out by the Intergovernmental Panel on Climate Change, including its 5th Assessment Report and recent special reports.
- Centre researchers have held major international leadership positions on initiatives such as the **World Climate Research Programme and its associated activities.**

Enrolments and Employment

We believe our biggest legacy is human: the people we have worked with and trained throughout the life of our Centre, none more so than our **128** doctoral researchers and **10** masters students. We provided employment, training and mentoring to **50** young scientists. We are extremely proud to report that **100%** of our graduates found employment in research, government or industry in Australia and abroad.

OUR LEGACY

ARCCSS fundamentally transformed collaboration in the wider Australian climate science community. We have partnered with the Bureau of Meteorology, the CSIRO, and the NCI on a number of major projects. Together, we built a new national modelling framework for the ACCESS system, enabling deeper collaboration and more rapid translation of scientific discoveries into better climate predictions for all Australians.

Jointly, we were also successful in establishing the National Environmental Science Program's Earth System and Climate Change Hub, which provides yet another avenue for our scientific discoveries to directly influence climate-related decision making and policy.

Over seven years we have fundamentally changed the culture of collaboration in climate science across Australia and created new pathways and linkages to our colleagues overseas. ARCCSS is now recognised as an international research leader and has been at the forefront of climate research here and internationally.

Our legacy includes important, world-first improvements to climate models; multiple data sets that are used internationally; a new system for bringing together tools to make the process of climate research easier; and the establishment of new research networks. However, our most important legacy will be the young scientists who now have the tools, skills and networks to become science leaders. ARCCSS has produced some impressive results over the past seven years, but it is the decades of work to come from our alumni as they make their name in climate science that will be our lasting legacy.

All this work was made possible thanks to generous funding from the ARC; the commitment of our participating institutions to form a robust partnership; and a strong national commitment to research infrastructure, such as the NCI facility in Canberra. And of course, none of our success would have been possible without the incredible staff and students whose hard work and dedication made ARCCSS the remarkable success it has been.

PUBLICATION HIGHLIGHTS

ARCCSS published over 1000 papers in the science literature. Here are a few key examples (a full list is available at www.climatescience.org.au).

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