NATIONAL COMMITTEE FOR
EARTH SYSTEM SCIENCE

Australian Academy of Science

A DECADAL PLAN FOR AUSTRALIAN EARTH SYSTEM SCIENCE

2024–2033

Image: Field of solar panels in the Australian outback

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Acknowledgement of Country

The Australian Academy of Science acknowledges and pays respects to the Ngunnawal people, the Traditional Owners of the lands on which the Academy office is located. The Academy also acknowledges and pays respects to the Traditional Owners and the Elders past, present and emerging of all the lands on which the Academy operates, and its Fellows live and work. They hold the memories, traditions, cultures and hopes of Aboriginal and Torres Strait Islander peoples of Australia.

Australian Academy of Science's National Committee for Earth System Science

This plan was produced by the National Committee for Earth System Science (NCESS), which fosters the development of an active community of Earth system science researchers in Australia. The following contributors formed the National Committee for Earth System Science during the production of this plan:

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Background image: Satellite view of Australia from space

EXECUTIVE SUMMARY

Australia is confronted by a changing climate. Understanding climate risks to the economy, business and environment across Australia requires knowledge founded on Earth system science: a comprehensive scientific understanding of our atmosphere, oceans and land, and the flows of energy, carbon, water and nutrients between these systems. Australia needs a new approach to build this understanding into our predictions and projections using the best available science and ensuring uncertainties and gaps in the science are filled. This new approach must prioritise long-term national coordination, oversight, strategy and implementation.

Australia's Earth system science endeavour is rich with talent. However it is fragmented and operates under various priorities which are often in competition and increasingly focused on short-term outcomes. Excellent investments such as Centres of Excellence, the National Environmental Research Program, the Australian Climate Service and CSIRO initiatives align with the urgent need to solve immediate problems around impacts and adaptation to climate risk. As a result, an unintended vacuum has emerged where no unifying agency or long-term funding initiative is addressing the fundamental understanding of climate to provide the foundations for climate intelligence needs in 10, 20 or 30 years' time. We are, in effect, building climate action and climate policy on foundations developed 10 to 20 years ago.

This plan for Australia by the Australian Academy of Science's National Committee for Earth System Science will, over the next decade, create the scale and ambition of endeavour to generate the scientific understanding needed to answer the critical questions that climate change is demanding of our national and regional security, economic wellbeing, and environmental and social resilience.

This plan makes 14 recommendations. The first, and enabling, recommendation is the **urgent establishment of an Australian Institute for Earth System Science, tasked with developing, coordinating and implementing the national science required to deliver answers to nationally significant questions**. This necessitates long-term investment by the Australian Government.

Other recommendations relate to the urgency of a national strategy for integrated high-performance computing and data via a Tier-1 facility. The national strategy must include a fully integrated strategy for the management and custodianship of data to enable the effective use of new tools, including artificial intelligence and machine learning. We also highlight challenges associated with workforce planning.

With the implementation of Recommendation 1, Australia can establish the science foundations for an evidence-based approach to climate risk, and partner with our allies to provide climate intelligence across our region. Without the establishment of a strong science-based foundation, we risk investments that lead to maladaptation, incorrect disclosure of financial risk by business, and erroneous assessments of national and regional risks associated with climate change.

The recommendations

R1: Urgently establish an Australian Institute for Earth System Science, tasked with developing, coordinating and implementing the national strategies required to deliver answers to nationally significant questions.

R2: Establish an integrated, standardised and curated observational data system, including national and global reanalyses and satellite data, co-located with nationally significant computing facilities to support understanding and modelling, artificial intelligence and machine learning based applications.

R3: Coordinate and prioritise observational programs for research across Australia. Oversight of these observational programs, strategic review of investment in research observations and a strategy to identify emerging needs should be established above the level of individual capabilities.

R4: Develop a strategy and methodology to prioritise process-based studies that build understanding, and leverage that understanding to improve more complex modelling systems.

R5: Establish oversight or coordination of the multiple investments in process-based studies to identify duplication and gaps to maximise the return on investment.

R6: Ensure a sovereign Earth system modelling capability to answer crucial and concerning questions about the interactions in Earth's system via the implementation of a national strategy for exascale capability.

R7: Establish a national solution to manage Earth system science data, including the custodianship of observations and model simulations. This needs to be integrated with data wranglers and technical staff with the required competencies, compute infrastructure to enable analysis, and the implementation of artificial intelligence and machine learning techniques. The establishment of this national data solution is overdue and requires urgent attention.

R8: Maintain strong collaboration with the Australian Community Climate and Earth System Simulator National Research Infrastructure (ACCESS-NRI) to integrate new process-based understanding into ACCESS to enhance national prediction and projection capability.

R9: Universities consider locating disciplines and courses relevant to Earth system science, in particular atmospheric science, oceanography, soil science and ecophysiology, within schools of mathematics or physics where possible.

R10: Provide mentorship or co-supervision, additional to existing institutional supervision, to coordinate and enable world-class postgraduate training aligned with identified priorities and national research needs.

R11: Identify critical areas of model development that are suitable for PhD students, and extend scholarships to recognise the value of, and challenges related to, model development.

R12: Provide a mix of permanent and short-term positions, working in collaboration with external researchers, to target identified areas of process-based understanding and/or model development.

R13: Identify major areas of national need and communicate those needs to funding agencies, and identify and encourage applications from suitable individuals in collaboration with universities and other research agencies.

R14: Provide direct investment in research proposals in the form of cash and in-kind support to highlight those that align with the national strategy.

1. INTRODUCTION

This plan provides a strategic view of Earth system science within Australia, with the ambitious goal of answering crucial questions of fundamental importance to Australia's economic strength, environmental health and human wellbeing. The goal is to enable Earth system science to find solutions to major weather and climate risks that confront Australia. Earth system science brings together the physical, biogeochemical, biological and human systems, including the land, atmosphere, hydrosphere and cryosphere, on timescales that range from hours to a millennium. By leveraging this broad range of science, Earth system science provides the key to unlock how our climate will change, and how extremes including heatwaves, extreme rainfall and drought respond to a changing climate.

Australia faces significant challenges relating to the Earth system.

- How will we achieve net zero emissions?
- Where will water be available in a hotter climate?
- Where might our energy supply lack resilience to weather and climate extremes?
- Where can agriculture be successful in a more varied climate?
- Are there risks of abrupt regional climate change and physical, ecological and social tipping points that will exacerbate natural disasters?

Earth system science provides the mechanism to address these challenges by increasing our understanding of Australia's future weather and climate, as well as the future climate of our trading and strategic partners. Australia's economic success and regional security will be shaped by our ability to respond to these challenges over the coming decades.

Australia has a rich history in ocean science, atmospheric science, ecology, climate science, Antarctic research and climate modelling – research that is necessarily embedded in international research programs[1]. However, our Earth system models omit crucial components, not by choice but due to lack of investment coupled with weak national coordination and no mechanisms to align investment with strategic challenges to answer critical Earth system science questions.

Australian Earth system science has become more fragmented over recent decades. This has undermined the impact of excellent individuals and groups in Australia. In effect, current organisational and funding structures impede rather than enable our ability to answer critical questions. We therefore need to build and implement a strategically well-aligned and integrated national Earth system science plan. Without such a plan and clear direction, our current strategies for observations, process-based understanding and the building of modelling systems will fail to answer the key questions that confront Australia and impede efforts to combat and respond to the risks of climate change.

This strategic plan focuses on what needs to be in place to answer five questions of national significance. This plan constitutes a decadal-scale ambition for Earth system science for Australia and our surrounding region to provide sustained input into the National Science and Research Priorities. Each question requires a multidisciplinary approach, integrating expertise at a scale that cannot be achieved by existing structures. Each might take 10 years to answer, a scale of endeavour that requires a new national structure with a long-term capacity to plan.

1 The World Climate Research Programme is the overarching international organisation Earth system science contributes to, with observations falling under the World Meteorological Organization's Global Climate Observing System (GCOS).

The Five Questions of National Significance

1. How can terrestrial and marine systems be managed to support net zero ambitions and positive environmental outcomes? This question directly informs National Science and Research Priority 1[2].
2. Where is Australia at risk of abrupt changes in weather and climate, including but not limited to tipping points? (National Science and Research Priorities 2, 4 and 5).
3. Where is freshwater availability in Australia resilient to climate change, and where does it require adaptation strategies to ensure supplies for human consumption, agriculture and natural ecosystems? (National Science and Research Priorities 2, 4 and 5).
4. What exposure do urban areas have to climate change, including climate extremes and air quality interactions? (National Science and Research Priorities 2, 4 and 5).
5. Where will changes in high impact weather events[3] support and/or undermine net zero ambition and where can associated risks be managed effectively? (National Science and Research Priorities 2, 4 and 5, and affects almost every federal and state portfolio).

Each of these ambitions requires:

- sustained and coordinated observations supported by coordinated technical infrastructure
- research to rapidly advance our understanding of critical processes
- computer models that represent important processes critical to understanding climate risk well.

These three requirements call for an integration of capabilities into a 'team Australia' approach.

Above: Strong winds and rain clouds are seen near the Bruce Highway, Far North Queensland

2 The National Science and Research Priorities are (1) transitioning to a net zero future; (2) supporting healthy and thriving communities; (3) elevating Aboriginal and Torres Strait Islanders knowledge systems; (4) protecting and restoring Australia's environment; (5) building a secure and resilient nation. see https://www.industry.gov.au/publications/national-science-and-research-priorities-2024#the-national-science-and-research-priorities-4

3 High-impact weather includes intense rainfall events, heatwaves, storms etc. It includes compound events where the impacts are amplified by the co-occurrence of two extremes either at the same time or in sequence. High impact events also include long periods of low solar radiation coinciding with low winds, or how droughts increase fire risk; in both cases these impact national strategies to achieve net zero emissions.

2. WHY AUSTRALIA NEEDS AN EARTH SYSTEM SCIENCE STRATEGY

Australia lacks coordination across the components of Earth system science and the lack of coordination has worsened over the last decade.

The Australian Climate Change Science Program (ACCSP) ran from 1989 until 2016 and helped coordinate research by CSIRO and the Bureau of Meteorology, underpinned in 2007 by the formation by these agencies of a joint research operation (the Collaboration for Australian Weather and Climate Research) that endured until 2015.

Midway through the ACCSP period a National Strategy for Climate Change Science was also developed by the Australian Government and was adopted in 2009. Over the next three years a coordinated implementation plan involving relevant government agencies and universities was developed under the leadership of the Chief Scientist, and published in 2012. However, a change in government policy after the 2013 federal election saw this initiative lapse. Since 2016 there has been no equivalent initiative or program such as the ACCSP. The successor, the National Environmental Science Program's (NESP) Climate System Hub, has not provided the breadth of coordination and investment in the *science* that was a central objective of the initiatives summarised above (NESP has contributed strongly to the coordination of impacts and adaptation research).

This absence of a national strategy has led to a diversification of scientific approaches, with major science gaps emerging, no mechanism for cross-capability coordination or even effective communication, and multiple reports and reviews that have generally concluded the same things. While the detailed priorities around research have evolved to some degree, the fundamental lack of strategy from the Australian Government, the fundamental differences in the priorities of universities, CSIRO, BoM and the Australian Antarctic Division etc., along with the diversion of significant funding away from the underpinning science towards climate services and products, has left our critical national capacity in Earth system science at a crossroads. Either we establish a national strategy, or we lose our national capability to deliver robust climate intelligence in support of reliable decision-making and effective investment in climate adaptation.

The need to address the lack of cross-institutional leadership, coordination and capacity of research within weather and climate sciences is urgent for many reasons, including:

Key reason 1: Climate projections

There is rapid adoption in the use of climate projections and associated products by government, business and others such as natural disaster managers. This demonstrates the demand for information on our changing climate. Australia needs climate projections to be the best available to avoid maladaptation, ineffective responses and mis-directed investment, so coordinating and aligning activities within a national strategy to ensure projections are as scientifically reliable as possible is essential. This maximises the improvements in public policy outcomes per dollar invested.

Key reason 2: Climate science leader

Australia is the only country in the southern hemisphere that can sustain a leading observational, process-based understanding and modelling capability. Australia should engage with regional neighbours in the Pacific and beyond to confront weaknesses in projections and create models that are customised to our needs by reflecting Australia's unique environment.

Key reason 3: Strategic risk assessments

Climate intelligence and knowledge of climate risk has strategic value to our national security, our regional partners, and to transnational businesses. The better we integrate science into our assessments of risk, the more robust is our capacity to assess and manage risk.

Key reason 4: Coordinated capacity

Answering critical questions requires a 'team Australia' approach with a strong 'made in Australia' strategy. At present, researchers' involvements, contributions and support structures tend to focus on individual institutional interests. Australia is losing national capacity, not because of lack of expertise but because of the lack of a national cross-institutional strategy, organisation and ambition.

Key reason 5: Aligning capability

Australia has invested in essential capabilities including the Integrated Marine Observing System (IMOS), the Terrestrial Ecosystem Research Network (TERN), the Australian Urban Research Infrastructure Network (AURIN), the Australian Community Climate and Earth System Simulator National Research Infrastructure (ACCESS-NRI) and the Australian Climate Service; there is an opportunity now to leverage these investments and coordinate existing capacities to create an integrated and strategically aligned capability.

Key reason 6: Emerging technology

The emergence of artificial intelligence and machine learning in weather and climate science offers an opportunity to accelerate research that leads to better predictions and projections via, for example, model data fusion. Capitalising on this kind of emerging technology requires a scale of national coordination that cannot be achieved by individual institutions and agencies.

Key reason 7: Working together

The complexity of weather and climate science, and the development of tools to predict and project climate, has exceeded the capacity for any one group, institution or country to deliver actionable climate intelligence. Unless Australia establishes a national strategy, our capability to provide answers to critical questions will be lost and our scientific capacity to understand and use advances from overseas and tailor these to Australia's needs will be lost.

The understandable drive for solutions, including adaptation to climate change and an improved ability to predict weather and climate-related natural disasters, underpins the demand for data at high levels of spatial detail that has driven considerable efforts focused on providing climate change products at higher spatial detail. Programs including the Australian Climate Service, state-focused downscaling in NSW, Queensland, Victoria, Tasmania, SA and WA, the NESP Climate Systems hub, and the National Partnership for Climate Projections (NPCP) have been attempting to develop actionable information for stakeholders. However, little coordination – and in the case of the NPCP no dedicated resourcing – has led to limited tangible outcomes.

More fundamentally, all these efforts build on decades of sustained activity on observations, process-based studies, model development and model predictions and projections. Those efforts have become weakened, disconnected and lacking in national coordination over the last decade. Next-generation and actionable climate products, whether via the Australian Climate Service, future NESPs, state-focused initiatives or the NPCP will fail to deliver robust climate intelligence unless the foundations of observations, process-based understanding and modelling is guided by an agreed national strategy and receives significant and long-term federal investment.

A critical challenge is the rapid evolution of, and necessity of integrating, high performance computing and big data (HPCD) in an era of explosive developments in artificial intelligence and machine learning. To capitalise on the burgeoning opportunities for enhanced predictions and projections, our nation will require greatly upscaled HPCD infrastructure investment that can be accommodated by the National Collaborative Research Infrastructure Strategy (NCRIS). In February 2024 the Australian Academy of Science published a considered analysis concluding that without a national strategy to acquire and sustain state-of-the-art high-performance computing and data (HPCD) research, the country's future prosperity and security will be put at risk[4]. The National Committee strongly endorses the Academy's analysis.

4 Australian Academy of Science, *The future computing needs of the Australian science sector*, 2024, https://www.science.org.au/supporting-science/science-policy-and-analysis/evidence-briefs/the-future-computing-needs-of-the-australian-science-sector

Background Image: Aerial view of river beds near Kati Thanda-Lake Eyre National Park

Alignment with Australian Government departments

Answers to the key questions posed in this plan have a whole-of-government impact – well beyond the traditional partnership with the Department of Climate Change, Energy, the Environment and Water. The central agencies – Prime Minister and Cabinet, Treasury and Finance – have a whole-of-government overarching interest that sits above the individual portfolio details that follow.

1. **How can terrestrial and marine systems be used to support net zero ambitions and positive environmental outcomes?**
    - Department of Agriculture, Fisheries and Forestry
    - Department of Climate Change, Energy, the Environment and Water
    - Department of Industry, Science and Resources

2. **Where in Australia is at risk of abrupt changes in weather and climate, including but not limited to tipping points?**
    - Department of Climate Change, Energy, the Environment and Water
    - Department of Industry, Science and Resources
    - Department of Infrastructure, Transport, Regional Development, Communications and the Arts
    - Department of Home Affairs
    - Department of Health and Aged Care

3. **Where is fresh water availability in Australia resilient to climate change, and where does it require adaptation strategies to ensure supplies for human consumption, agriculture and natural ecosystems?**
    - Department of Climate Change, Energy, the Environment and Water
    - Department of Industry, Science and Resources
    - Department of Infrastructure, Transport, Regional Development, Communications and the Arts
    - Department of Home Affairs

4. **What exposure do urban areas have to climate change, including climate extremes and air quality interactions?**
    - Department of Climate Change, Energy, the Environment and Water
    - Department of Industry, Science and Resources
    - Department of Infrastructure, Transport, Regional Development, Communications and the Arts
    - Department of Home Affairs
    - Department of Health and Aged Care

5. **Where will changes in high impact weather events support and/or undermine net zero ambition and where can associated risks be managed effectively?**
    - Department of Climate Change, Energy, the Environment and Water
    - Department of Industry, Science and Resources
    - Department of Infrastructure, Transport, Regional Development, Communications and the Arts
    - Department of Home Affairs
    - Department of Health and Aged Care

3. FIXING THE PROBLEM: AN AUSTRALIAN INSTITUTE FOR EARTH SYSTEM SCIENCE

As identified in previous reviews, Australian Earth system science research lacks coordination. Fundamental gaps exist where critical capacity has been lost. This coordination is more complex than other research fields due to the multiple agencies involved, strong university engagement, the rapidly emerging stakeholder needs around climate and hydroclimate risk assessments, and financial risk disclosures that drive the demand for fine resolution regional climate projections. It is infeasible to resolve this lack of coordination without leadership, strategy and investment.

R1 Urgently establish an Australian Institute for Earth System Science, tasked with developing, coordinating and implementing the national strategies required to deliver answers to nationally significant questions.

The challenges that confront Earth system science, and the scale of endeavour required to answer critical questions, cannot be achieved within existing structures. First, the expertise is thinly spread across agencies and institutions, which operate under fundamentally different terms of reference and legal frameworks. This fragmentation makes the national Earth system science enterprise vulnerable to internal strategic decisions within individual agencies that remove critical components of the national capability. There has also been a major shift in Australia towards short-term research. For example, the Bureau of Meteorology has evolved from a strong role in foundational research to prioritise services and product development. CSIRO has similarly moved toward 'solutions-focused' product development and efforts targeting Australia's commitment to the United Nations Framework Convention on Climate Change (UNFCCC) Paris agreement (2015). Programs such as the National Environmental Science Program are end-user driven, and ARC Centres of Excellence which exist in the ARC Linkage program have moved significantly from strategic to end-user driven research.

These changes have left an unintended vacuum with no single organisation tasked with an ambitious and strategic research program to develop understanding and modelling capability that is required to answer critical questions. This sharply contrasts with many other crucial research fields where foundational science is prioritised, lauded and appropriately resourced. While it is important to frame investment in our science on end-user needs, this cannot be at the cost of the science that will provide the understanding and capabilities required 10 to 20 years from now.

For Earth system science to create the understanding and build the prediction tools needed to provide answers to critical questions, strategy, organisation, ambition, scale and a long-term investment that parallels like-minded structures overseas is required. The Max Planck Institutes in Germany, the National Centre for Atmospheric Research in the US, the Hadley Centre in the UK and others are basically permanent research-focused organisations that can embark on long-term research that aligns with national needs. Australia has no equivalent.

A fundamental activity of the institute would be the coordination, management and custodianship of observations, satellite data, reanalyses and data from modelling in a single platform, integrated with computing infrastructure.

R2 Establish an integrated, standardised and curated observational data system, including national and global reanalyses and satellite data, co-located with nationally significant computing facilities to support understanding and modelling, artificial intelligence and machine learning based applications[5].

This institute must:

- be independent and overseen by an independent advisory board
- invest in core capabilities, and establish a decadal-scale research program, to answer nationally significant questions
- provide a core team of permanent researchers to provide a decadal-scale focus on solving major problems of relevance to Australia
- manage significant funding that can only be used externally to the institute, to fund fully coordinated priority research and development within existing government agencies and universities
- support strategic and short-term (e.g. 1-2 year) secondments from other organisations to accelerate solutions to identified priority gaps
- provide a key point of contact to coordinate with international groups to resolve major capability gaps, and contribute Australian capabilities to fill gaps overseas
- coordinate investment in research-focused observations, process-based studies and modelling to maximise the return on investment, and to identify duplication and gaps
- coordinate management and custodianship of research data from observations, satellites, reanalysis and modelling that reflect the national collection of data for enabling research and applications
- provide a focused environment for postgraduate, early career and mid-career researchers to accelerate their capabilities, investing their expertise in research identified by the institute as a key gap or emerging priority
- lead Australia's contribution to World Climate Research Programme (WCRP) activities, including the Coupled Model Intercomparison Project (CMIP) and the Coordinated Regional Climate Downscaling Experiment, and contribute to and leverage other WCRP activities
- provide a focal point for non-Earth system science researchers; an environment for STEM-focused graduates to apply their expertise on emerging priorities and help to bridge the emerging expertise in artificial intelligence and machine learning with relevant problems
- facilitate advanced short courses or summer schools, and provide senior mentorship, to grow the cohort of researchers capable of contributing answers to nationally significant questions.

A clear delineation of responsibilities must be implemented such that the institute would *not*:

- compete with the software and technical infrastructure provided by other entities such as ACCESS-NRI. The institute would be independent of, but complementary to, ACCESS-NRI and infrastructure providers such as IMOS, TERN etc. and Tier-1 HPCD
- provide operational services. The institute would provide research and model development to underpin the climate services of the 2030s and 2040s[6]
- suppress innovation. There is no reason why breakthrough science cannot continue to occur independent of the institute; rather, the institute would provide the pathway to bring those innovations into the heart of next generation prediction systems.

5 This is aligned with the National Digital Research Infrastructure Strategy, Outcome 2.

6 This is not unusual overseas. For example, the National Center for Atmospheric Research in the US has developed new models with a new dynamic core as part of an open competition for the next generation US weather model.

The establishment of an integrated, standardised and curated climate data system

Australia has no centralised repository, stewardship or curation for the multiple types, layers and scales of data in Earth system science. However, the Earth system science community is advanced in managing standards, implementing FAIR principles and building shared tools to enable management and mining of data. It is also well placed to be an exemplar of managing data in a complex world consistent with the National Digital Research Infrastructure Strategy.

Figure 1 provides a proposed pathway to closing the data gaps in Earth system science infrastructure, highlighted in Recommendations 2 and 7. The diverse data sources that Earth system science relies on are curated and maintained in a reference collection, while data storage for simulation data is provisioned according to the strategy of the proposed institute. Data is supported through publication, distribution, cataloguing, archiving and deletion by a clear governance structure and processes that service the institute's strategic goals.

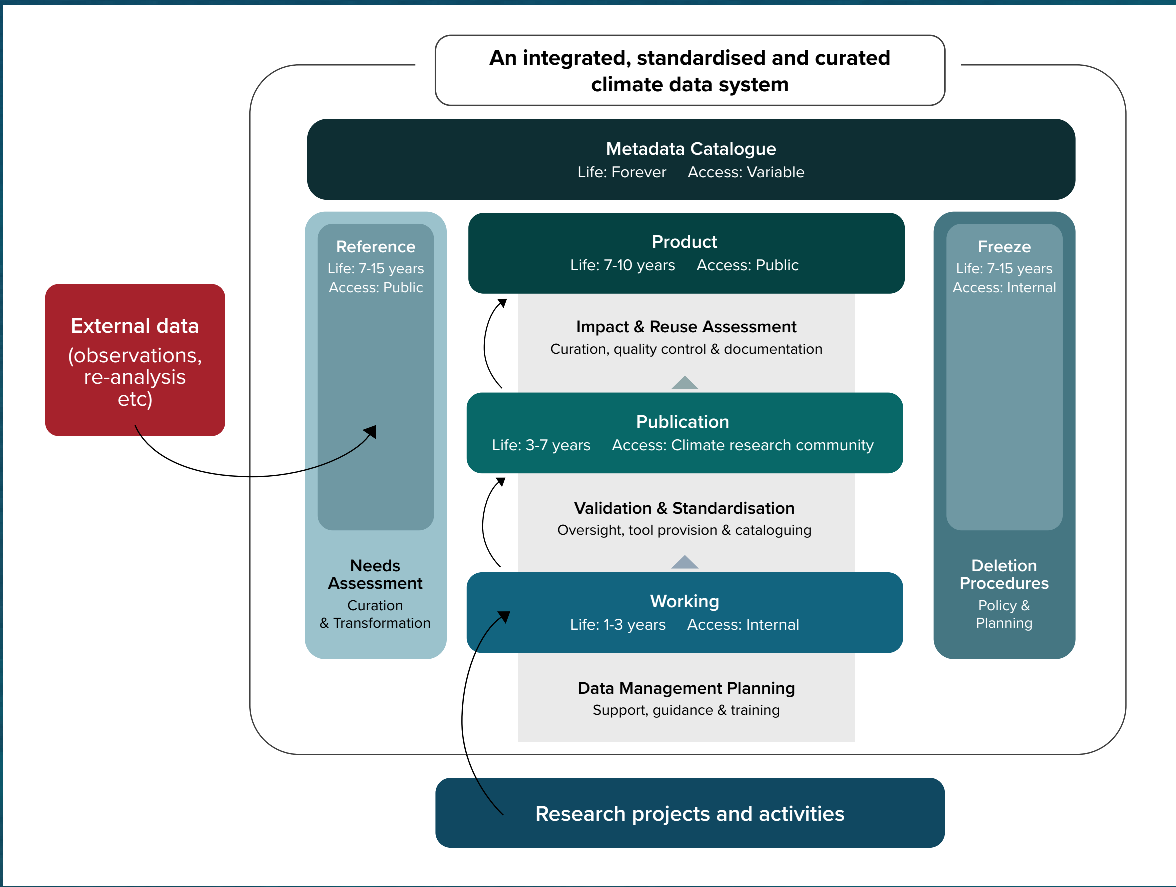


Figure 1: A proposed pathway to closing the data gaps in Earth system science infrastructure.

This figure highlights the complexity of data management – this is beyond the capacity of generic data stores, individual research groups or even current institutions to implement. The institute would manage data, balancing the types and value of different forms and the need for internal versus external data provision.

Some of these data are already petascale (millions of gigabytes) and require high-performance data systems to be managed and accessible. In turn, this necessitates that these data be co-located with high-performance computing systems for traditional analysis and for artificial intelligence and machine learning applications. In addition, some modelling absorbs some of these data; if these data are not co-located with high-performance computing systems many applications of climate prediction and projection cannot be optimised.

The required fundamentals of Earth system science

Answering critical questions aligned with the National Science and Research Priorities requires ongoing and sustained investment in three broad areas: *observations, process-based understanding* and *prediction and projections*. With these in place, supported by a strategy for essential research infrastructure such as HPCD, Earth system science can provide increasingly robust answers to critical questions using global and regional climate models that provide predictive skill at policy-relevant and decision-relevant scales.

Observations

Observations, ranging from long-term monitoring to short-term site-focused contributions, are sourced via the NCRIS facilities, investment by the Bureau of Meteorology, CSIRO, the Australian Antarctic Division, Geoscience Australia, the Australian Research Council, and via our access to international programs of observations including satellite data. National programs, including the NCRIS-funded IMOS, the RV Investigator, TERN, and AURIN provide observations essential to our understanding of the Earth system. Each provides critical information about our climate, such as the nature of the land surface, the atmosphere and the hydrosphere, and fundamental processes, such as the movement of energy, water and carbon between the atmosphere, ocean and terrestrial biosphere[7]. They underpin model development by providing the data against which models are tested. This leads directly to better models, and better and more actionable projections.

The Australian Antarctic Division and university-based centres provide coordinated activities that deliver important data and process-based understanding of the Antarctic environment.

Infrastructure needs for observations

Earth system science builds on national programs including the NCRIS-funded Integrated Marine Observing System (IMOS), the RV Investigator, the Terrestrial Ecosystem Research Network (TERN) and the Australian Urban Research Infrastructure Network (AURIN). These infrastructure projects are indispensable for process-based understanding and modelling of our weather and climate.

CSIRO, the Bureau of Meteorology, the Australian Antarctic Division and programs within states and territories add both systematic monitoring and specific observational programs of very high value.

Sources of observations are therefore diverse and complex and can be blended with satellite data and national and international reanalyses to create a wealth of opportunity.

Critically, however, these multiple lines of observation are not coordinated and lack strategy, standards and custodianship. Fundamentally, Australia has failed to create a modern data capability to support observations that has scale, transparency and custodianship with agreed standards and that adheres to the FAIR (findable, accessible, interoperable and reusable) principles.

This means Australia cannot utilise artificial intelligence and machine learning techniques to their full potential – a fundamental impediment to utilising data to solve important economic, societal and environmental problems.

7 The need for fundamental research in Earth system science is further necessitated by the risks that a changing climate pose to many relevant sectors including, but not limited to, health, financial resilience, economic well-being, agriculture, biodiversity and so on.

Atmospheric observations, such as the background monitoring measurements at Kennaook/Cape Grim, are central to many research projects. Atmospheric observations by the Bureau of Meteorology are also central, including observations of temperature, precipitation (combined into the Australian Gridded Climate Data) and streamflow. Radar and radiosonde (weather balloon) observations are critical to our understanding of the atmosphere. Sea level measurements are taken by the Bureau of Meteorology and Geoscience Australia. The Bureau of Meteorology provides a national reanalysis, which provides an important sovereign capability.

For urban environments, observations are sparse or of short duration, and often come from state government initiatives. Available observation networks are not always accessible or utilising the same standards as national data. However, urban observations provide crucial foundations for understanding our environment, identifying critical processes that are lacking from our models, and benchmarking models.

Australia has lost a great deal of capability in measuring atmospheric processes including via aircraft. Opportunities exist to replace some of these with autonomous drones (UAVs) at low cost. Australia has failed to explore or exploit the opportunities these offer in a strategic or coordinated way.

Australia does not host its own meteorological satellites but is a beneficiary of geostationary and polar-orbiting satellites hosted by nearby countries, and of satellites with global coverage. This data is only useful when so-called retrieval algorithms are applied to translate raw satellite radiances into products. Currently, there are uncoordinated efforts to process and store various satellite products. A coordinated satellite database will give Australia an unprecedented supply of high-quality data about the atmosphere, land surface and ocean.

However, while these observations and reanalyses are individually critical, they are often stored in institutional repositories with no oversight or coordination of activities, and these data are not systematically co-located in accessible, standardised and curated data systems. This severely limits the effectiveness with which these invaluable resources can be used. The rapid development of artificial intelligence and machine learning requires enormous volumes of data to be interrogated on nationally significant HPCD systems. Further, the value of additional data shared within a common repository and accessible to artificial intelligence and machine learning techniques can be enormous and in ways never anticipated when the data were collected. Fundamentally, Australia has failed to create a modern weather and climate data capability that has scale, transparency and custodianship with agreed standards that adheres to the FAIR (findable, accessible, interoperable and reusable) principles.

We note that there is no oversight or coordination of observations. Some Earth system observations require continuous and consistent measurements over an extended period, such as temperature, sea level, rainfall and streamflow measurements by the Bureau of Meteorology; soil moisture and air chemistry measurements taken at Kennaook/Cape Grim; carbon fluxes by TERN; and ocean observations by IMOS. Gaps in these types of observations compromise efforts to understand, monitor and predict our weather and climate. Some measurements of critical systems barely exist, or only exist for a few years (such as energy, water and carbon exchanges within urban environments). Many short-duration observations are collected via often short-lived university initiatives and are not integrated into national data collections. Finally, not all observations need to be continuous; some short-duration but intensive observations often collected in dedicated field studies can create vital information that accelerates understanding and model improvements, provided these data adhere to FAIR principles. Critically, an observation program can be terminated without consultation, or consideration of the whole, which weakens the national capability to answer the overarching questions posed in this plan.

A role for the institute would be to design and implement, in collaboration with NCRIS capabilities, solutions to the following recommendation.

R3 Coordinate and prioritise observational programs for research across Australia. Oversight of these observational programs, strategic review of investment in research observations and a strategy to identify emerging needs should be established above the level of individual capabilities.

Process-based understanding

Earth system science unlocks awareness of processes that help mitigate or adapt to climate change. A growing awareness of the risks associated with vegetation and soil carbon sinks and stocks, ice sheet collapse, stratospheric dynamics, high-impact weather events, hydroclimate and hydrological changes, and vegetation responses to carbon dioxide has led to changes in how Australia perceives and manages the associated risks of climate change. The series of weather and climate extremes impacting settlements and infrastructure, and the need to build more resilient communities, have accelerated demands for better predictions, which build from better process-based understanding.

Infrastructure needs for process-based understanding

Process-based understanding is a bridge that connects observations with prediction and projection. Infrastructure must:

- allow multiple lines of observation and reanalysis to be combined and used transparently to build better understanding
- enable this better understanding to flow into prediction and projection capabilities efficiently and robustly
- provide a means to develop, test and benchmark process-based models reliably and reproducibly.

Process-based infrastructure therefore cannot be isolated from either observations or prediction and projection infrastructure.

The infrastructure must include a Tier-1 HPCD facility hosting both models and the fully curated, readily accessible and routinely updated observational, satellite, and reanalysis and modelling data that forms the national and international data collections that underpin Earth system simulation.

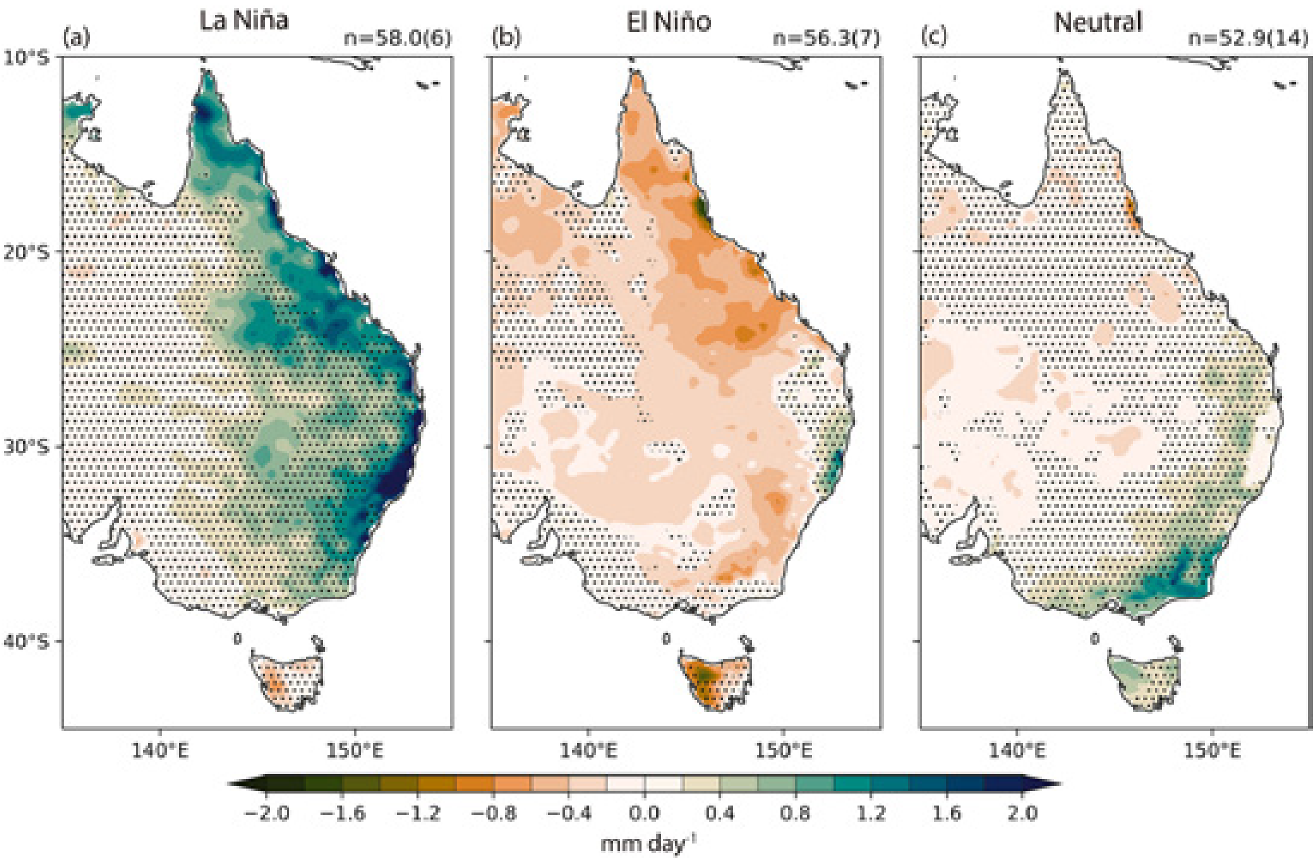
Discoveries at the process level often profoundly change what requires urgent attention in our observations and modelling systems (e.g. ocean deoxygenation, risks of tree mortality). Some major challenges have been explored for decades – whether we will see a more El Niño or La Niña state in the future, or whether vegetation will help or hinder net zero ambition. These are not easily solvable but offer profoundly different futures for Australia. Process-based understanding exists as a bridge between observations and predictions, but there is no coordination, organisation or prioritisation of which processes need to be built into our prediction systems. The scale of the challenges will not be managed by piecemeal or uncoordinated investment, nor will they be resolved by short-term funding.

Process-based understanding is also important for ensuring that we have a workforce in Earth system science who can understand the reasons behind trends in observations and models. Without this understanding, there is a vulnerability to misinterpretation of trends, overlooking model errors or over-simplifying the science. This workforce is also central to interrogating overseas models, many of which show large biases in our region or fail to represent the nature of our endemic landscapes.

Oversight, coordination, strategy, prioritisation and long-term targeted investment are largely missing from the Australian research ecosystem, leaving it to chance whether an emerging problem is neglected. To meet this challenge, we make the following recommendations.

R4 Develop a strategy and methodology to prioritise process-based studies that build understanding, and leverage that understanding to improve more complex modelling systems.

R5 Establish oversight or coordination of the multiple investments in process-based studies to identify duplication and gaps to maximise the return on investment.



Above: Composite precipitation anomalies on austral spring cyclone days during (a) La Niña, (b) El Niño and (c) neutral El Niño-Southern Oscillation years. (credit: Zoe Gillett)

Simulations, prediction and projections

Prediction and projection on all timescales, from weather forecasting through to millennial-scale projections, require numerical models.

Infrastructure needs for prediction and projections

Predictions and projections require models. The modelling software for predictions and projections is provided by the Australian Community Climate and Earth System Simulator (ACCESS) hosted and supported by the ACCESS National Research Infrastructure facility (ACCESS-NRI). This NCRIS-resourced capability does not undertake, provide or resolve science questions, rather it provides the software infrastructure that integrates science from Australia and overseas into professionally maintained, documented and published software.

ACCESS requires a Tier-1 peak high-performance computing (HPC) system; this is currently provided by the National Computational Infrastructure facility (NCI). ACCESS also requires a Tier-1 peak high-performance data (HPD) system, something that is lacking in Australia.

To enable predictions and projections using the ACCESS system, the HPCD infrastructure must be seamlessly integrated. A concrete pathway to exascale computing integrated with exascale data is vital but remains lacking as a national strategy.[8]

To maintain a sovereign capability, it is essential that a prediction and projection system, configured for Australia's needs, is available and focused on our societal, commercial and environmental problems. Such a system would comprise all the ACCESS-NRI, a Tier-1 peak HPCD facility, and a pathway for this facility to expand to exascale.

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8 Australian Academy of Science, *The future computing needs of the Australian science sector*, 2024, https://www.science.org.au/supporting-science/science-policy-and-analysis/evidence-briefs/the-future-computing-needs-of-the-australian-science-sector

The ACCESS-NRI is re-engineering the ACCESS model to enable modularisation, reproducibility, computational efficiency and so on. Any Earth system science strategic plan must be consistent with the objectives and goals of the ACCESS-NRI. A critical concept in the ACCESS-NRI is that differentiating between physical climate models and Earth system models is no longer appropriate. Rather, a library of modules, representing key processes, needs to be available to be chosen when building a model based on the specific research needs of the problem being addressed. This should mean that Earth system processes such as fire will be represented via modules of varying complexity and be available to any model on an as-needs basis.

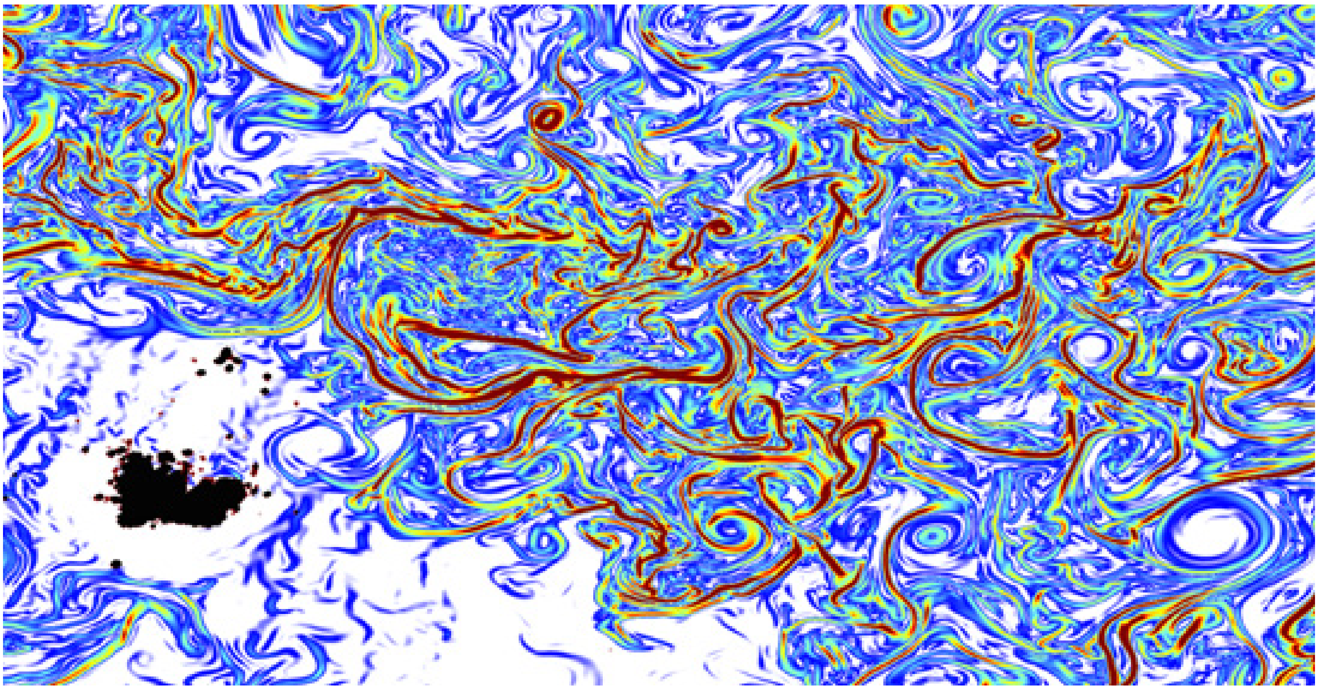
The scale of the data and modelling efforts required to underpin Earth system science in the future means that researchers cannot work in a fragmented way. The only way to efficiently and productively progress the scientific advancement of our understanding of the future Earth system is to provide researchers with suitable exascale supercomputing, data, and people with the required technical skills to ensure effective use of these resources.

We recommend that the institute be tasked with working collaboratively with ACCESS-NRI and with national Tier-1 HPCD facilities[9] to achieve the following.

R6 Ensure a sovereign Earth system modelling capability to answer crucial and concerning questions about the interactions in Earth's system via the implementation of a national strategy for exascale[10] capability.

R7 Establish a national solution to manage Earth system science data, including the custodianship of observations and model simulations. This needs to be integrated with data wranglers and technical staff with the required competencies, compute infrastructure to enable analysis, and the implementation of artificial intelligence and machine learning techniques. The establishment of this national data solution is overdue and requires urgent attention[11].

R8 Maintain strong collaboration with the Australian Community Climate and Earth System Simulator National Research Infrastructure (ACCESS-NRI) to integrate new process-based understanding into ACCESS to enhance national prediction and projection capability.



Above: Small-scale ocean eddies found downstream of the Kerguelen Plateau in the Southern Indian Ocean. (credit: Isa Rosso)

9 Tier-1 faculties are those run at a national scale and funded via the Australian Government. Current examples are the National Computational Initiative (NCI) and Pawsey.

10 A strategy for high-performance computing and high-performance data, leading to an exascale capability, was called for by the Australian Academy of Science in February 2024. https://www.science.org.au/supporting-science/science-policy-and-analysis/evidence-briefs/the-future-computing-needs-of-the-australian-science-sector

11 How to enable access to weather, climate and oceanographic data across institutions has been explored – see https://doi.org/10.5281/zenodo.11254868 (report) and https://doi.org/10.5281/zenodo.11254528 (synthesis). This recommendation is consistent with the National Digital Research Infrastructure Strategy.

Background Image: Drone photograph of ocean swell

Very high-resolution coupled modelling

Global climate models use spatial resolutions of about 100 kilometres, leading to an inability to resolve key processes in all spheres of the climate system. An important strategy to overcome those limitations is to build models operating at resolutions closer to 1 kilometre. At such resolution many processes and phenomena of critical importance can be directly simulated, overcoming a long-recognised Achilles heel in climate modelling[12]. The importance of kilometre-scale climate modelling has been recognised as a priority around the world[13].

As a result of their poor resolution, current climate models do not faithfully represent critical weather systems, and it is the amplification of extremes by weather system processes that cause the extreme events and consequential disasters we observe. For example, the Lismore (NSW) floods in 2022 were associated with multiple weather processes, initiated over the Southern Ocean and interacting with synoptic-scale processes and moist tropical air that led to a sequence of extreme weather events and catastrophic flooding. Global climate models cannot resolve these processes, and therefore cannot tell us if such events will become more common in the future. As the weather that produces extreme events is connected globally, downscaling using high-resolution regional climate models cannot overcome the limitations introduced in the global models, as downscaling relies on the global models for information at its boundaries.

Ocean processes operate across many scales, and eddies in the Southern Ocean transfer considerable heat and nutrients[14]. These eddies are also crucial to the uptake, transport and storage of carbon[15]. Operating at scales of order 10 km, they are too fine to be resolved in ocean models used for climate projections. This means the role that oceans play in influencing climate are poorly resolved.

Further, there is evidence that high-resolution coupled models simulate fundamentally different historical trends in tropical and Southern Ocean sea surface temperatures[16], reproducing recent observed changes which coarser models cannot. They also exhibit greater low-frequency variability in midlatitude regions[17], compared with Coupled Model Intercomparison Project (CMIP)-class models. Using current CMIP models, or indeed the regional models that rely on them, therefore risks fundamentally wrong projections of future climate and its variability.

As information is required at increasingly fine spatial detail, some elements of the land surface become extremely important. Land management, lateral flows of soil moisture, coupling of water and carbon with vegetation and vegetation mortality, urban systems and so on become important enough to change the projections of important climate extremes including rainfall, temperature, streamflow, drought risk, human health etc. Using coarse resolution models, and omitting these crucial elements, can change how the land influences water availability, urban liveability and carbon futures.

Fundamentally, when a climate model brings together the atmosphere, ocean, land and ice systems, the projections by the model are strongly influenced by the resolution[18]. Building very high-resolution models are a critical tool in the armoury of Earth system science and its applications and are not an academic luxury. Instead, its local granularity, globally, is essential to provide more reliable trajectories of our projected climate and the information urgently needed to define our response strategies and support our decisions for managing emerging risks.

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Education

Earth system science is built from mathematics, physics, biology, chemistry, software engineering, data science and high-performance computing. A coordinated and ambitious strategy building on undergraduate STEM, through PhDs and into career paths linking universities, government agencies and business would help address the need for STEM-literate graduates. This is not specific to Earth system science – the profound challenges that confront Australia in terms of STEM training at all levels of the education system require solutions for many areas of national priority.

The institute will serve as a beacon for the application of STEM disciplines to some of the most pressing issues for humanity, and in doing so attract students at all levels to STEM education initiatives.

Many issues relating to workforce planning are beyond the scope of this plan and could not be resolved by the institute. For example, the teaching of STEM-related subjects in schools is often provided by non-STEM trained teachers[19]. Further, weather and climate science, and Earth system science more generally, is not widely understood to be fundamentally founded in STEM.

The institute could not resolve this, but would support the National Committee for Earth System Science, the Australian Meteorological and Oceanographic Society, leading universities and so on in the further development of teaching plans[20], whereby specific elements of the existing curriculum in maths, physics and chemistry are supported with materials relevant to Earth system science.

The institute would also not be the appropriate structure to resolve problems in the teaching of Earth system science at individual universities. However, recognising that the Earth system science community needs to create opportunities within maths, physics, quantitative biology and computer science departments does point to the following specific strategy.

R9 Universities consider locating disciplines and courses relevant to Earth system science, in particular atmospheric science, oceanography, soil science and ecophysiology, within schools of mathematics or physics where possible.

The institute would play a role in postgraduate teaching. The PhD system in Australia, in key areas of Earth system science, has been very effective due to three ARC Centres of Excellence, two Antarctic-focused Centres of Excellence and the Australian Antarctic Program Partnership (AAPP). Training programs, including in software engineering and data science, supported by ACCESS-NRI and the National Computational Infrastructure (NCI) have led to very significant improvements in the quality of graduates. The institute would reinforce this progress in the following way.

R12 Provide a mix of permanent and short-term positions, working in collaboration with external researchers, to target identified areas of process-based understanding and/or model development.

19 See for example https://ideas.repec.org/p/zbw/glodps/511.html

20 Examples already exist led by the ARC Centre of Excellence for Climate Extremes (CLEX) and the Monash Climate Change Communication Research Hub (MCCCRH). See https://www.monash.edu/mcccrh/projects/climate-classrooms

Finally, there is little alignment between ARC funding of early career researchers (e.g. DECRA), Future Fellowships or Laureates and a national strategy. The institute achieve the following.

R13 Identify major areas of national need and communicate those needs to funding agencies, and identify and encourage applications from suitable individuals in collaboration with universities and other research agencies[21].

R14 Provide direct investment in research proposals in the form of cash and in-kind to highlight those that align with the national strategy.

Above: Boranup Karri forest in Western Australia

21 Note that in the UK, the NERC offers research grants specifically targeted at improving the parameterisations in the UKMO's unified model and in its successor, MOMENTUM. The UM forms the atmospheric module in ACCESS.

Image: The city of Lismore, NSW experienced extreme flooding in February 2022.

Image credit: Lannon Harley, ANU


Image credit: Lannon Harley, ANU

Key Earth system science modelling applications in Australia

Climate resilience and adaptation requires an understanding of how multiple physical and biophysical climate risks emerge on different timescales at high spatial detail. Some risks, such as tipping points, emerge on long timescales; some, such as major changes in some extremes like trends in aridity, on 30-to-50-year timescales; while some might be predictable on multi-annual to decadal timescales.

Ultimately, the purpose of observations, process-based studies, model development, model predictions and model projections are to provide guidance on emerging risks, and to guide investment in adaptation and mitigation strategies. This means that a hierarchy of model prediction and projection systems is required which reflects how climate change influences risk. Model prediction and projection systems necessarily vary across scales and include:

- initialised weather prediction on scales from hours to seasons (known as weather forecasting and seasonal prediction). This is the domain of the Bureau of Meteorology
- initialised prediction on timescales of years to a decade (known as decadal prediction). This was being developed by CSIRO but that development has ceased. Initialised prediction can be used with any type of climate model and has the potential to impact many sectors of the Australian economy. The computational cost makes high-resolution simulations challenging, and the degree to which decadal prediction can provide useful climate intelligence in our region remains uncertain. Nevertheless, the timescales of decadal prediction cover some of the most sought-after planning timescales for many sectors, making it a potentially important ingredient in the modelling and prediction ecosystem
- projections on timescales of decades to centuries at high spatial detail. The high spatial detail is balanced by undertaking relatively low numbers of simulations. The computational cost leads to many processes being omitted, or highly parameterised. However, it is possible to run global models at kilometre scales meaning weather phenomena are resolved. The ability to run kilometre-resolving models for climate simulations including many Earth system components is under development in the US and Europe and is a central focus of the ARC Centre of Excellence for 21st Century Weather
- projections on timescales of decades to centuries at low spatial detail using Earth system models. The low spatial detail is balanced by large numbers of simulations. The lower computational cost means that more components can be included (e.g. chemistry, fire, nutrients) but some processes which may be extremely important are difficult to resolve (e.g. sea ice, topographic forcing of clouds and storms, cloud processes, some ice sheet dynamics, vegetation demography, urban landscapes, agricultural areas). The low resolution used is not by choice and may profoundly impact the robustness of projections using these models
- assessment and projections of biogeochemical flows using Earth system models and other biogeochemical and atmospheric models to constrain greenhouse gas budgets and trends of terrestrial and ocean carbon sinks and sources.

All of these could be supported via a common modelling infrastructure supported by the ACCESS-NRI in partnership with an integrated Tier-1 high-performance computing and high-performance data system.

Australian Earth system science community: its strengths and opportunities

Strengths

+ **Australia is in a strategic location to provide national and internationally significant expertise on climate signals of global significance,** including but not limited to:
  - a pivotal location between the globally influential sea surface temperature oscillations in the Indian and Pacific oceans
  - uninterrupted flow from Antarctica and the Southern Ocean
  - influence from the Maritime Continent region to Australia's north, which is the rainiest area of the globe
  - globally significant trends and variability of terrestrial carbon sources and sinks.

+ **Australia could be the regional strategic partner of choice** for understanding and managing climate risk across our region, including the Pacific Island states, Indonesia, Papua New Guinea and Southeast Asia.

+ **The ACCESS system enables predictions and projections that ultimately answer the questions posed in this plan.** The ACCESS developer and user community requires that the ACCESS-NRI is maintained long term to provide the necessary research infrastructure. Independent evaluation of the ACCESS model indicates it is a model that captures many key elements of our weather and climate well. ACCESS is the only physical climate model or Earth system model with bespoke development for the Southern Hemisphere and is the only model that Australian scientists can improve in a coordinated strategy to meet national priorities and goals. Australia requires the long-term maintenance of infrastructure support for the ACCESS modelling suite to achieve recommendations 6 and 8.

+ **Australia has engaged with and contributed strongly over many decades to multiple international programs using its climate model capability**. Most recently, these include the Coupled Model Intercomparison Project (CMIP) Phases 5, 6 and 7. These are critical to developing improved understanding of our climate and how our weather and climate will change in the future. The opportunity to maintain a role in future phases of CMIP, and other similar international projects, should be seen as a nationally significant obligation.

+ **The National Computational Infrastructure (NCI) hosts most weather and climate research in Australia.** This plan builds on the assumption that Australia will maintain a Tier-1 facility with an agreed national pathway to exascale compute and exascale data, integrated seamlessly and available to the national research community. See recommendations 2, 4, 6, 7 and 8.

+ **Elements of Earth system science are reflected in coordinated world-class research, at scale, in Australia.** Examples include Southern Ocean science, elements of Antarctic science, research into ocean science and modes of variability, reactive atmospheric and aerosol (air quality) chemistry and physics, and the development of national and global greenhouse gas budgets. Australia must maintain world-class research, at scale, in key areas. Identifying those priorities that can be maintained at scale requires a strategic assessment of the priority areas and should be part of a national coordination process.

+ **An ambitious Australian Earth system science strategy focused on our national needs that sustains world-class research,** feeding directly into enhanced modelling capability supported by coordinated observations, would lead directly to better mitigation and adaptation decisions in critical areas. See Recommendation 1.

+ **A coordinated Earth system science program in Australia would identify weaknesses and gaps in major international observation and modelling programs,** leading to international investment to improve those systems with direct benefit to decision-making in Australia. See Recommendation 1.

Opportunities to improve

- **Workforce planning in STEM, and in Earth system science, is failing to keep up with demand as business recognises climate risk.** Resolving this is beyond the scope of this plan in isolation but can be helped via recommendations 9 to 14.

- **The lack of strategy, vision, ambition and coordination in Earth system science represents an existential threat to sovereign capability.** The need for coordination and organisation of Earth system science has been identified in previous reports (e.g. NCSAC in 2019) but not resolved. This requires an urgent response from the Australian Government. See Recommendation 1.

- **A loss of sovereign capability in Earth system science undermines our capacity to develop tools that reflect the peculiarities of Australia's biophysical systems and region.** This includes, but is not restricted to, our:

  - extraordinary hydroclimatic variability
  - native vegetation
  - phosphorous-poor soils
  - exposure to sea ice and ice variability around Antarctica
  - fire regimes
  - urban landscapes
  - exposure to cascading/compounding natural disasters.

  This threat can be minimised by a strategic approach to observations, process-based understanding and modelling. See recommendations 1 to 8.

- **A loss of sovereign capability in Earth system science undermines our capacity to support the climate risk and climate intelligence needs of our partners in the Pacific and elsewhere in our region,** and opens opportunities for other countries to become the science provider of choice.

- **Process-based studies are often of strong scientific merit but not part of a strategy leading to better predictions or projections.** There is no funded mechanism to evaluate models or identify flaws; such a mechanism could lead to targeted research to resolve these issues and enhance the national capability to answer critical questions. The ACCESS-NRI can provide technical solutions, but is not resourced to provide research solutions. The establishment of the institute would enable priority areas for process-based research to be identified and resourced. See Recommendation 1.

- **Australia has lost its ambition to excel in Earth system science.** This is unacceptable in an area of critical national need where climate intelligence has major implications for our economy, national security, society and environment. A national strategy is required to align observations, process-based understanding and modelling strategies with national priorities. See Recommendation 1.

- **Australia is investing to increase resilience to climate change. Decisions are based on climate projections that are far more uncertain than they need to be, particularly for our cities.** Australia risks investing in ineffective adaptation strategies because of limited modelling capacity.

- **Scientific model development of ACCESS has fallen behind due to lack of research investment and strategy.** This directly threatens our ability to respond to climate change. A vision to accelerate scientific development of the ACCESS model, including goals for reaching kilometre-scale resolution as well as improved use of climate projections, is needed – a vision that the institute could implement.

- **Rapid developments in artificial intelligence and machine learning might lead to better predictions and projections at high levels of spatial detail.** This could lead to tools and data that will help Australia manage climate change, direct mitigation and adaptation strategies, underpin financial disclosures and so on. Australia's economic wellbeing and our resilience to climate change will be sub-par without a strong and coordinated Earth system science program. A fundamental requirement to leverage this opportunity is a strategic approach to data systems (with implementation of FAIR principles and including a system of curation) co-located with compute. See Recommendation 7.

Background image: View of Antarctica from space

The challenge of spatial detail: an Antarctic example

In March 2022, a series of extreme events occurred in Antarctica. A widespread heatwave centred over East Antarctica led to temperatures up to 38.5°C higher than the mean, representing the most intense heatwave ever recorded on Earth[22]. On 15 March, the Conger Ice Shelf broke up becoming the first observed evidence of ice shelf disintegration in East Antarctica[23]. Finally, between 16-18 March, almost 70 billion tonnes of snowfall accumulated across East Antarctica[24] contributing to a net *gain of mass* in Antarctica - that is, a reversal in the mass loss trend over the preceeding 20 years[25].

This series of extremes was the result of strong teleconnections between the tropics and Antarctic via the most intense "atmospheric river" (AR) ever observed in Antarctica[26]. Measurements of this AR-generated integrated water vapour transport along the East Antarctic coastline were over eight standard deviations from the mean of all AR events between 1980 and 2022. A consequent increase in longwave radiation during the AR event led to the extreme temperatures, as well as to widespread rain and surface melt along coastal regions of Antarctica.

While ARs are relatively rare in Antarctica (occurring approximately three times per year within any region), they are a primary contributor to Antarctic surface mass balance variability, accounting for 10–20% of total snowfall in East Antarctica. ARs also account for the most extreme Antarctic precipitation events[27 28] and high impact weather extremes[29] that induce breakup of both sea ice and ice shelves through changes in the ocean state[30] (e.g. sea surface height and swells)[31], Accurately simulating these events and their impacts is crucial to predicting changes in the Antarctic mass budget and the future contribution of Antarctica to sea level rise.

There have been no systematic studies of the impact of resolution on the accuracy and reliability of model projections of ARs. A recent study[32] indicates that a minimum model resolution of 1° x 1° is required to detect ARs around Antarctica. However, higher resolutions may be required to accurately capture convective cells and orographic effects that occur on much finer scales and can change the local distribution and magnitude of accumulation associated with ARs.

A future with more ARs, leading to larger accumulations of snow on the Antarctic continent, would be experienced very differently in Australia to a future with fewer ARs. Specifically, projections of sea level rise depend, in part, on how synoptic scale processes such as ARs change using models too coarse to properly represent these processes.

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6. THE WAY FORWARD

The foundational requirement to advance Earth system science to enable answers to major questions for Australia and the region is the establishment of the Australian Institute for Earth System Science (Recommendation 1).

Recommendations 2-14 can be implemented by the institute in partnership with the many agencies, research groups and individuals that make up the Earth system science research community in Australia.

Many major decisions by governments at all levels now depend on climate intelligence that is founded on robust and reliable science. Strategies for net zero, investment in risk mitigation, adaptation policy, and the requirements for financial disclosure of climate risk by business all depend now on knowledge of our weather and climate. Our knowledge is incomplete, and major gaps mean we cannot answer the questions posed at the beginning of this plan. However, by implementing the recommendations in this plan, the foundations for far more robust and actionable climate intelligence would be put in place and management of emerging climate risks in Australia and across our region would become evidence based.

Above: Flooding in the Brisbane CBD during February 2022