Australian Academy of Science

AUSTRALIAN CLIMATE SCIENCE CAPABILITY REVIEW

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Prepared by the Climate Science Capability Review Steering Committee on behalf of the Australian Academy of Science.

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EXECUTIVE SUMMARY

Climate variability and change across seasons and decades has profound consequences for primary industries, coastal and water infrastructure, the generation and delivery of energy, and transport systems in Australia and throughout the world. To the extent that this variability and change is unanticipated and unplanned for, the net impact across sectors will be detrimental. However, research that improves our ability to understand and make projections of climate variability and change has the potential to reduce climate-related impacts and capitalise on potential opportunities associated with these changes. In this way, the impact of climate and weather research in Australia is felt in every corner of society.

Australia's climate is determined by factors that are unique to the southern hemisphere. Because of this, Australia requires a robust national climate science capability to understand and make forecasts and projections of weather, climate variability and climate change. This capability is comprised of infrastructure, and scientific and technical personnel in observations, fundamental climate science, climate systems modelling and application in the provision of climate services. The development of this capability over the past 50 years has ensured that Australia is recognised internationally as a leader and custodian of aspects of southern hemisphere climate science.

The Australian Academy of Science instigated this review in early 2016 to characterise Australia's current climate science capability and identify how well Australia's climate science sector is positioned to meet current and future demands for weather and climate knowledge in the context of increasingly powerful and sophisticated tools and methodologies. The review was overseen by an expert committee chaired by Professor Trevor McDougall FAA FRS, and engaged in broad consultation with climate scientists, relevant government agencies including CSIRO and the Bureau of Meteorology, and other organisations involved in climate and weather research and services in Australia.

On the basis of this consultation, the review committee found that:

1) Australia has developed substantial climate science capability over the past half-century, with particular strengths and achievements in the development of Australian and southern hemisphere climate monitoring, modelling, and services capabilities.
2) Australia has an extensive suite of observational infrastructure, as well as the necessary expertise to maximise the value of this infrastructure. For the most part this infrastructure is well funded and supported.

Coordination arrangements

3) There are weaknesses in coordination and resourcing arrangements for Australian climate science that create avoidable inefficiency. Substantial gains could be realised by measures to improve coordination arrangements, and this review suggests five options for consideration.

Climate science capability

4) There are approximately 420 full time equivalent (FTE) personnel working across the four broad areas of climate observation, understanding, modelling and services. This figure includes the additional 15 FTE in decadal prediction at the CSIRO climate centre in Hobart recently announced by the Minister for Industry, Innovation and Science, as well as additional capability that will be provided from 2017 through the new ARC Centre of Excellence for Climate Extremes which will replace the previous ARC Centre of Excellence for Climate System Science.
5) Many areas of climate science are adequately resourced, particularly those undertaken primarily in the university research sector.
6) A number of specific areas are moderately or critically under-resourced. Critically under-resourced areas include general climate modelling, certain areas of climate understanding (micrometeorology and boundary layer dynamics), and the development of models that take into account two-way interactions between humans and the climate. Because climate science is a highly complex and interconnected field, this under-resourcing presents moderate to significant risks to Australia's ability to deliver necessary climate and weather information to domestic end users and national and international organisations. Climate modelling provides the only tool with which Australia will be able to predict climate variability and change, provide future climate scenarios (for differing emission trajectories), and provide detailed local information. The Australian team developing the Australian Community Climate and Earth System Simulator (ACCESS), a weather and climate modelling system, is a small fraction of the size of groups building equivalent models for their regions in other countries. The current level of resourcing of Australia's climate modelling activity will not allow Australia to keep

pace with world's best practice. This shortfall is brought into sharper focus when considering that Australia is potentially more exposed to the impacts of climate change than most developed nations, and our location means that key climate drivers in our region are not well represented in climate models developed in other countries.

7) To position Australian climate science to deliver necessary knowledge over the coming decade and to ameliorate climate risks to the Australian economy, a staged increase in capability in the under-resourced areas of approximately 77 additional FTE over the next four years is required. This figure (77 additional FTE) is in addition to the 15 FTE in decadal prediction at the CSIRO climate centre in Hobart recently announced by the Minister for Industry, Innovation and Science, as well as the small additional capability that will be provided from 2017 through the new Centre of Excellence for Climate Extremes which will replace the previous Centre of Excellence for Climate System Science. The review has identified a priority order in which the addition of this capability might be staged, starting with 27 FTE that are urgently required.

8) In the medium-term, consideration will also need to be given to maintaining the capability currently resident in the Antarctic Climate and Ecosystems Cooperative Research Centre for which funding will end in 2019.

PRIORITIES FOR INVESTMENT IN CLIMATE SCIENCE CAPABILITY

The review concludes that, over the next four years, 77 additional FTE staff numbers should be added to the current levels of climate science investment: 15 additional FTE in Climate observations; 17 additional FTE in Climate understanding; 33 additional FTE in Climate modelling; and 12 additional FTE in Climate services. The staged hiring of these staff is needed in the following areas.

Capability areas requiring immediate investment (27 FTE in 2017)

- Climate observations—7 FTE out of the total of 15 FTE, especially in atmospheric and ice measurements, land-based flux measurements and ocean hydrography.
- Climate understanding—5 FTE out of the total of 17 FTE, especially in modes of climate variability and radiative forcing.
- Climate modelling—10 FTE out of the total of 33 FTE, especially in ACCESS development, operations and maintenance, CABLE, dynamical downscaling, sea ice modelling and integrated assessment modelling.
- Climate services—5 FTE out of the total of 12 FTE, especially in atmospheric projections, products and services.

Key recommendations:

1) The review recommends implementation of an enduring arrangement for the coordination, facilitation and assessment of climate science and research in Australia, with capacity to assess Australian climate research needs and commission and coordinate research as appropriate. Such a coordinating mechanism will enable the clear identification of those responsible for ensuring the on-going provision of climate research and climate services, and should enable a more streamlined approach to the funding of climate research capabilities. Such a coordinating mechanism could be implemented by the Australian Government in a number of ways, several of which could be cost-neutral. The review suggests five options for consideration (see below).

2) This review recommends that approximately 77 additional FTE staff are needed over the next four years in order to provide adequate capacity to improve understanding and inform advice on strategies for cost-effective mitigation and adaptation to climate change, and to enable Australia to provide regional leadership in aspects of climate science for which Australia bears natural responsibility due to our location on the planet. The review recommends that this extra capacity should be created in a staged approach according to identified priorities.

Supporting recommendations:

3) The review recommends that the Australian Government undertakes a broader assessment of Australia's climate-related research capabilities, including capacity for investigation, analysis and implementation of climate change mitigation and adaptation options.

4) The review recommends that the Australian Government ensures continued capability in the Antarctic Climate and Ecosystems Cooperative Research Centre. Under current CRC funding rules this centre will not continue beyond 2019.

Capability areas requiring investment in 2018 (25 FTE in 2018)

- Climate observations—4 FTE out of the total of 15 FTE.
- Climate understanding—4 FTE out of the total of 17 FTE.
- Climate modelling—14 FTE out of the total of 33 FTE, especially in computer engineering capability.
- Climate services—3 FTE out of the total of 12 FTE.

Capability areas requiring investment in 2019–20 (25 FTE in 2019–2020)

- Climate observations—4 FTE out of the total of 15 FTE.
- Climate understanding—8 FTE out of the total of 17 FTE.
- Climate modelling—9 FTE out of the total of 33 FTE.
- Climate services—4 FTE out of the total of 12 FTE.

POTENTIAL MODELS FOR THE COORDINATION AND RESOURCING OF CLIMATE SCIENCE

The review found that there are significant weaknesses in current arrangements for coordination and resourcing of climate science in Australia that lead to avoidable inefficiency and duplication of effort. Possible models that would improve coordination include:

1) **A new office of climate research**. A small office within or associated with a relevant government department or agency could: assess Australia's needs for climate science and capability to meet those needs; administer a streamlined system of directed resourcing, including commissioned research where necessary; and plan for the development of capabilities and infrastructure.
2) **Transferring responsibility to the Bureau of Meteorology**. Bringing responsibility for coordination of weather and climate science together within the bureau would allow for streamlined coordination of activity, and closer ties between climate research and end users of climate and weather information. This option may require review of the bureau's organisational structure, and would require measures to ensure collaborative and multidisciplinary activity between the bureau and other climate research organisations.
3) **Transferring responsibility to CSIRO**. Bringing responsibility for all weather and climate science together within CSIRO would capitalise on the organisation's current expertise and long experience in the field of climate science, and leverage existing infrastructure. Overarching strategy for climate science would need to be driven by the CSIRO Board. Resources provided to CSIRO for this purpose would need to be quarantined through a Ministerial determination under s9 (1) (a) (iv) of the *Science and Industry Research Act 1949*, or similarly binding mechanism.
4) **A new climate research centre**. A new multi-node, non-governmental national climate research centre could be established to draw together existing capability in research agencies and universities. Such a centre could be given responsibility to coordinate, commission and conduct climate research in Australia, and have control of a substantial portion of the national climate research investment to effect coordination and collaboration.
5) **A new climate research agency**. A new publicly funded research agency could be established, similar to the Australian Institute for Marine Science. The agency could be given responsibility for coordinating, commissioning and conducting climate research in Australia, and have control of a significant portion of the national climate research investment to effect coordination and collaboration. It would further have responsibility for being the principal advisor to government on climate science, and be responsible to a board and one or more ministers through appropriate governance mechanisms.

The strengths and weaknesses of these different coordination and resourcing models require further assessment.

LIST OF ABBREVIATIONS

AAD	Australian Antarctic Division
ACCESS	Australian Community Climate and Earth System Simulator
ACCSP	Australian Climate Change Science Program
ACECRC	Antarctic Climate and Ecosystems Cooperative Research Centre
AIMS	Australian Institute of Marine Science
ANSTO	Australian Nuclear Science and Technology Organisation
APS	Australian Public Service
ARCCSS	ARC Centre of Excellence for Climate System Science
BoM	Bureau of Meteorology
CABLE	Community Atmosphere Biosphere Land Exchange (model)
CAWCR	Collaboration (formerly Centre) for Australian Weather and Climate Research
CMIP	Coupled Model Intercomparison Project
CoE	Centre of Excellence
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ENSO	El Niño Southern Oscillation
ESCC	Earth Systems and Climate Change
GA	Geoscience Australia
MNF	Marine National Facility
IMOS	Integrated Marine Observing System
NCRIS	National Collaborative Research Infrastructure Strategy
NESP	National Environmental Science Program
NCI	National Computational Infrastructure
PFRA	Publicly funded research agency
TERN	Terrestrial Ecosystem Research Network

1 INTRODUCTION

Climate and weather sciences are of critical importance to Australia's prosperity, security and well-being. It is difficult to think of a branch of science and research that is used by more Australians on a day-to-day basis, and that is crucial to a wider cross-section of economic activity. Primary producers; utility service providers; sea, air and land transport networks; urban planners; service industries; health; emergency management and many other critical sectors rely directly on the national capability to understand and predict climate and weather, in addition to the indirect exposure of the rest of the economy to climatic events and changes.

1.1 BACKGROUND TO THIS REVIEW

As will be explored in this review, climate and weather science have a direct impact on the national interest. In recognition of this, government has long treated weather and climate science and research as strategic national capabilities, fostering their development through the Bureau of Meteorology (BoM), the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Antarctic Division (AAD). In general, study and prediction of the climate system relating to shorter timescale processes such as weather and seasonal forecasts has been conducted by BoM, whereas CSIRO has been responsible for studying climate on longer timescales.

Over the past five years, Australia's involvement in climate and weather research has changed significantly. In response to changes in government policy, Australia's overall climate science effort has reduced, and structural changes are underway in the conduct of Australian climate science.

Although change has been underway for some time, the impetus for this review came from an internal decision by CSIRO in early 2016 to reprioritise its national research portfolio. The Australian Academy of Science resolved to undertake a review of Australian climate science capability, to investigate whether Australia is retaining appropriate climate science capabilities that are able to deliver research results in the broad national interest. This review will focus on climate science as it relates to longer timescales (inter-annual, decadal and beyond), taking into account the activities of BoM principally where they relate to climate science.

1.1.1 The Australian Academy of Science

The Australian Academy of Science is composed of more than 500 of Australia's most eminent scientists, each elected for his or her outstanding contribution to science. Established by Royal Charter in 1954, the Academy promotes scientific excellence, disseminates scientific knowledge, and provides independent scientific advice for the benefit of Australia and the world. The Academy has undertaken this review to provide the community and government with an independent assessment of Australia's climate science capabilities.

1.1.2 Terms of reference for this review

The terms of reference for this review were to report on:

1) The extent and size of climate science in Australia:
    a. Those aspects of climate science that are critical to the national interest
    b. Those aspects of climate science for which Australia has a unique responsibility or stewardship
    c. Australia's current areas of strength and areas of weakness in climate science including expertise, infrastructure and culture.
2) Current arrangements and characteristics of support of climate science in Australia, and the appropriateness of these arrangements for Australia's future interests in climate science.
3) Australia's potential to sustain its climate science workforce in the future.
4) Australia's ability to respond to new developments in climate science.
5) The means by which Australia's climate science is disseminated to its users, and the appropriateness of the current arrangements for its dissemination.

1.1.3 Steering committee

To undertake this review, the Academy appointed a steering committee, composed of Professor Trevor McDougall FAA FRS (chair), Associate Professor Julie Arblaster, Dr Helen Cleugh, Professor David Griggs FTSE, Professor Rodney Keenan, Emeritus Professor Neville Nicholls FAA and Dr Graeme Pearman AM FAA FTSE. Further information on the committee members is available on the back cover of this report.

1.1.4 Methodology

In preparing this report, the committee gathered information by:

- inviting responses to a questionnaire from members of the climate science community (57 responses—see list of submissions)

- requesting information from relevant organisations (10 responses—see list of submissions)
- holding workshops in Hobart, Sydney and Melbourne (19, 21 and 22 July 2016 respectively), attended by approximately 80 people
- inviting further information from workshop participants (25 further submissions).

The committee considered these inputs, together with its own knowledge of the conduct of climate and the contributions that climate research can and should make to national need. The committee came to an expert consensus, arriving at the extra staffing needs that are listed in the tables in this review. Caution should be used in interpreting these figures; they should be taken as indicative of scale and location of gaps in science capacity rather than a precise requirement.

1.2 WHAT IS CLIMATE SCIENCE?

Climate science seeks to develop an understanding of atmospheric conditions and processes. However, as the land, sea, atmosphere and cryosphere all interact heavily, developing a meaningful understanding of the climate system requires an understanding of each of these components, collectively referred to as the climate system, and how they interact. Although numerical weather prediction and climate prediction are concerned with the same biophysical systems, when studying climate conditions over long time periods, a plethora of processes need to be considered in addition to those that are important at weather timescales.

The climate is a complex, nonlinear system, with many interacting sub-systems. Its study relies on a number of essential components.

Observations and other climate information

The state of the climate is principally investigated through observing key climate variables. These range from variables that are familiar to most people, such as temperature, precipitation, cloud cover and wind speed, through to measurements of atmospheric composition, solar irradiance and insolation, the extent and characteristics of the cryosphere, oceanic composition and circulation, characteristics of terrestrial ecosystems (such as the rate of evapotranspiration and solar reflection from plants and the uptake of carbon dioxide through photosynthesis) and water availability and runoff, to name just a few. In climate science, these observations are most useful when they are continued over an extended period of time, creating datasets across multiple time and space scales which can be used to study climate processes and develop an understanding of the influences on the climate. This information is collected in a number of ways—through measurement networks across the land, air and oceans; through satellite observing systems; from ships, aeroplanes and floats; remote sensing networks and field surveys and experiments. Turning these observations into datasets of use to climate scientists requires specialist climate data expertise.

Significant information and data sets are gained from investigating previous climates. This is commonly referred to as *paleo climate* information. Data on previous climatic conditions can be derived from a number of direct records and proxies—for example, by analysing gases and chemicals trapped in ice cores, or examining the growth of trees or coral, or through analysis of other geological records.

Climate understanding and research

Using information and data gained from observations, climate scientists attempt to develop a detailed understanding of the climate and its processes, requiring the use of the full suite of physical science disciplines, including mathematics, physics, chemistry and earth sciences. Biological systems also have a significant influence on the climate and incorporating their impacts into the understanding of the climate system is an area of significant research activity.

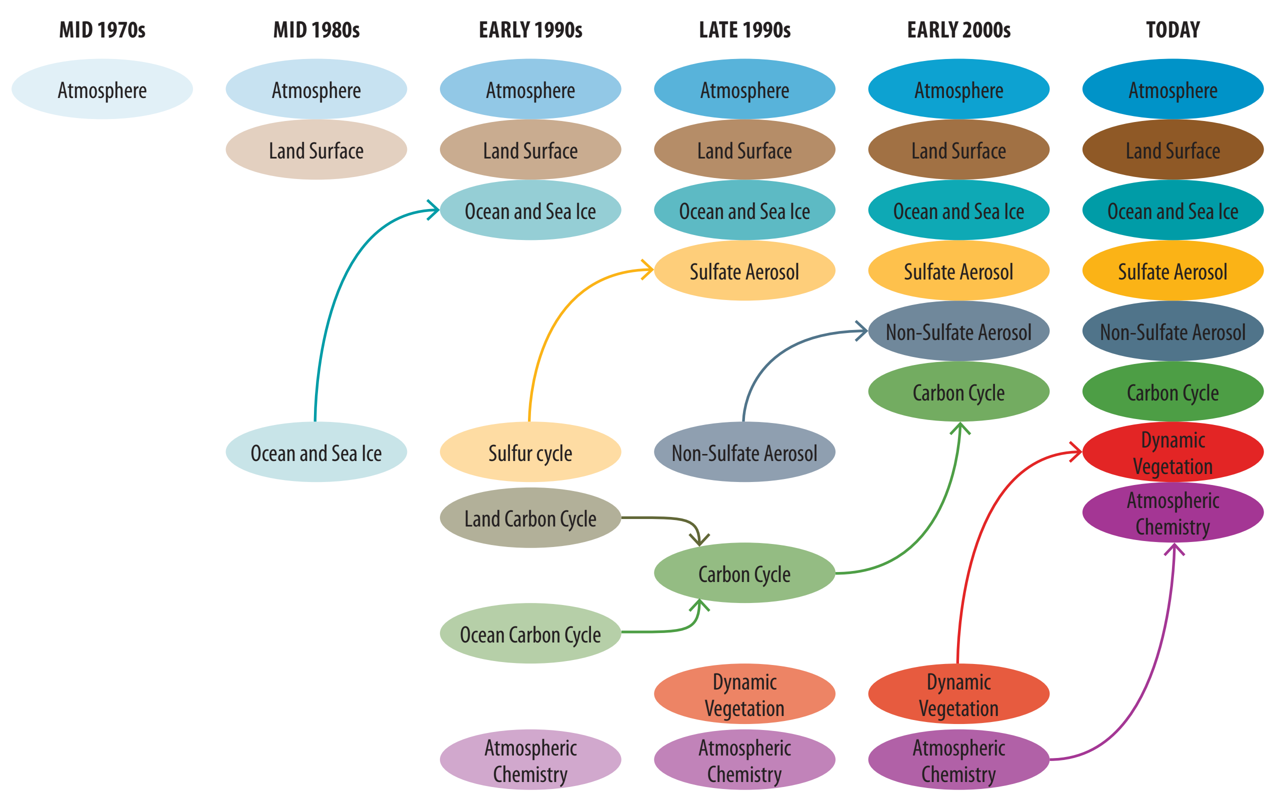
Climatology investigates the mean state of the climate, its variability, its extremes and its changes over time. It seeks to develop this understanding in such a way that it can be used to determine how the climate is currently functioning, how it functioned in the past, and how it might function in the future (making climate predictions).

Climate modelling

The complexity of the climate system means that scientists cannot accurately or usefully describe it in simple terms. A significant branch of climate science seeks to translate the understanding gained through analysis of observations into mathematical models, ranging from simple (but incomplete) models through to more detailed models that represent the elements of the interconnected climate system. These models require the use of high performance computing systems and data, and have progressively incorporated more parts of the climate system as advances in computational technology, process understanding and data streams have allowed (see Figure 1).

The use of such models allows climate scientists to investigate how the climate functions and to make testable inferences and predictions about how the climate is likely to behave in the future. Since there are numerous and equally valid ways to represent climate processes in models, and it is impossible to verify future predictions now, there are a considerable number of different climate models and sub-models existing in laboratories around the world. Much effort has been dedicated to testing the accuracy of the results of models against real-world observations, and comparing the results of models with each other to determine whether their predictions are consistent and to learn from the modelling work of other groups.

Figure 1: Development of climate models



Development and increasing complexity of climate models. As computing power has increased since the 1970s, so has the complexity of computer models used to simulate Earth's climate. Components are first developed separately and later coupled into comprehensive models. Image source: http://climate.nasa.gov/news/830/climate-modelers-and-the-moth/ NASA (public domain)

Modelling and data sets are critical tools for developing understanding and predictions related to the climate system—study of the climate without models is essentially impossible. Climate scientists therefore place a great deal of importance on the development and improvement of models and devote significant resources to this task.

Applying climate science to real-world problems

Although climate observations and understanding support the development of robust knowledge on the climate, the direct results of climate science are not usually able to be used in the same form by stakeholders. An important part of climate science is to translate the results into relevant information in appropriate forms for other researchers, government, businesses and individuals to use.

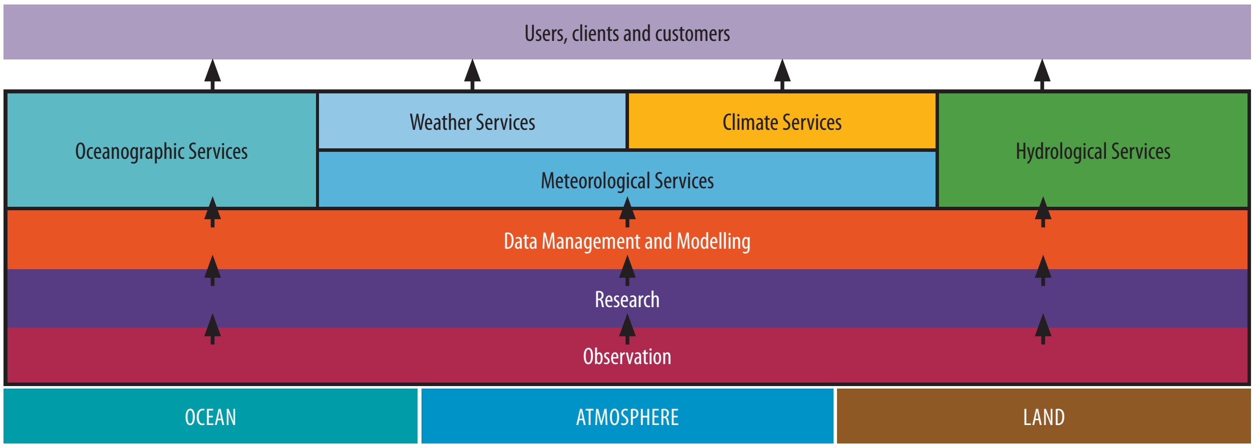
This translation can take a variety of forms—for example, an important output of climate science is the construction of models and datasets that other researchers can use. These could be used by other climate scientists to study different parts of the climate, or by researchers in other fields to investigate how the climate interacts with other parts of the earth system. Similarly, the results of fundamental climate science are of considerable importance to government, for example in planning for infrastructure and community services, but the raw knowledge from understanding the climate must be applied to specific problems and/or packaged in such a way as it can be employed by an end user.

This work is often referred to as climate services, and its relation to other parts of climate and meteorological sciences are shown in Figure 2.

1.2.1 Climate science vs climate change science

In common usage, the terms *climate science* and *climate change science* are frequently used interchangeably. However, climate change science refers to the study of the natural and human-caused long-term changes to the climate, including those changes that result from the addition of greenhouse gases to the atmosphere. Climate science studies the climate more broadly, including fundamental climate processes that are not linked to climate change. For example, one of the most significant natural drivers of variability in the Australian climate is the El Niño – Southern Oscillation (ENSO). No clear effect of global warming on this natural phenomenon has been identified yet (Cai et al, 2015). Climate science also studies how the ENSO operates, and a significant scientific challenge remains in extended prediction of ENSO events. This would be a significant scientific challenge even in the absence of climate change.

Figure 2: Climate and meteorological science from fundamental science to end use



Adapted from 'Weather and climate information delivery within national and international frameworks' by John Zillman, presented at the First International Conference on Energy and Meteorology: Weather and Climate for the Energy Industry, 8-11 November 2011, Gold Coast, Australia. Reproduced with permission. **https://www.wmo.int/pages/prog/dra/eguides/index.php/en/2-legal-and-institutional-form-of-an-nms/2-2-institutional-form-scope-and-structure**

Climate change science is a subset of broader climate science—without a fundamental understanding of the climate, it is not possible to detect or understand climate change. Whilst climate change science is a significant endeavour in and of itself, it can't be successfully studied in the absence of knowledge about the broader climate.

A specific use of climate change science is in the evaluation of likely futures related to energy use and carbon emissions. This science enables jurisdictions to assess their potential exposure and risk, which they can use to underpin their commitment to international negotiations concerning emissions reduction targets. In this regard, no two nations are likely to bear the same risks, and national assessment is essential.

1.2.2 Scope of this review

Due to resource limitations, this review has limited itself to considering the biophysical scientific basis of climate research—that is, the capability of Australia in observing, understanding and modelling the climate system. As a rough approximation, this includes those areas of climate science that would be covered in the Working Group I portion of the Intergovernmental Panel on Climate Change's *Assessment Reports*. However, the review examines all of climate science, not only climate change science. In particular, the areas on which this review focuses include:

- climate observations—capability in capturing and analysing key climate data
- climate understanding—capability in studying the processes and interactions in the climate system
- climate modelling—capability in developing, adapting, running and analysing models to describe and predict the climate
- climate services—capability in taking the results of climate understanding and modelling and translating them into forms that can be used for further research or end use in decision making in a range of economic, social and environmental sectors.

It is critical to note that climate and climate change research encompass a much wider sphere than the focus of this report. It is hoped that this review will be followed by a much larger exercise which takes into account all of climate research. There are a number of important areas, particularly relating to climate change research, which have fallen outside the scope of this review:

- *Climate change mitigation and policy*: Although the results of climate science and climate change science inform climate change mitigation and policy, the actual study and practice of climate change mitigation is not covered by this review beyond the scientific inputs into those processes.
- *Climate change impacts science and research*: Although climate services does include research and science related to predicting the impacts of climate change, there is a considerable area of research in understanding how the outputs of climate understanding and modelling will affect the natural, built and social environments.
- *Climate change adaptation research*: Climate change adaptation is a critically important sphere of research that looks at how society can adapt and be resilient to climate change. Adaptation research is highly inter- and multi-disciplinary. It was not possible to treat climate change adaptation research satisfactorily in this review. We do note that current investment in climate adaptation research has declined significantly; for example, the National Climate Change Adaptation Research Facility is now operating on 30% of its former annual budget.

Like the fundamental basis of climate science, these areas of science and research are critical to an effective response to climate change, and capabilities in these areas are also in need of review.

1.3 WHY IS CLIMATE SCIENCE IMPORTANT?

It is difficult to think of a branch of science and research that has a closer relationship to the national interest than climate science. Understanding the climate and providing accurate information about future climatic conditions, as well as helping to craft a response to climate change, is of critical importance to Australia's economic prosperity, security and sovereignty, and community wellbeing. Examples of this importance include:

- **Defence and sovereignty**: In the 2016 *Defence White Paper*, climate change was identified as a key risk, making states more fragile and posing increased risk of extreme weather events. Climate science provides the means to understand when and how extreme weather is likely to be a threat to people and property, on timescales from short-term forecasts to longer-term projections of regional risk, and also helps inform the ability of the defence force to operate effectively.
- **Primary production**: Accurate climate information is of critical importance to the agricultural sector. Improving the accuracy of seasonal forecasting has been estimated to be worth over $1.5 billion per annum to the agricultural sector (CIE, 2014). At longer time scales, improvements to climate projections (for example, 10–30 year predictions of drought frequency) could represent a distinct competitive advantage for Australian farmers and primary producers.
- **Informing adaptation policy**: As the 2015 *National Climate Resilience and Adaptation Strategy* makes clear, climate science is at the heart of decision-making to create a climate-resilient society. As a predominantly coastal society, Australia remains highly vulnerable to changes in the oceans, such as sea level rise and ocean acidification. The Australian Government and local and state governments all share responsibility for planning for the future of the populated coastal zone, and use the outputs of climate science to help map for future infrastructure and plan for future emergencies. Adaptation also needs to extend well beyond the coastal zone, with the health, prosperity and well-being of people, cities and rural areas, and terrestrial ecosystems and biodiversity subject to considerable future impacts that can potentially be anticipated, avoided and managed.

These are only a few examples of the importance of climate science throughout society. Combined, numerical weather prediction and climate forecasts are a vital community service—they provide the community with the information it needs to plan for the future, whether that future is measured in hours or decades.

It is important to recognise that climate science, which underpins the ability to provide this information, is a **strategic, national capability**, which is intrinsically linked to the national interest. Because of this strong link the Academy considers that capability in climate science must be maintained, in the interests of the continued welfare of the Australian community.

As the World Meteorological Organization points out, '….we know that—where they exist—needs-based climate services are extremely effective in helping communities, businesses, organizations and governments to manage the risks and take advantage of the opportunities associated with the climate' (WMO, 2011). The World Bank Group estimates that globally improved weather, climate and water observation and forecasting could lead to up to a US$30 billion per annum increase in global productivity and up to US$2 billion per annum in reduced asset losses (WMO, 2015). A benefit-to-cost ratio of between 4:1 and 36:1 has been estimated for the economic value of improved meteorological/hydrological services in national weather and climate sensitive sectors within developing countries (Hallegate, 2012).

1.4 WHY SHOULD AUSTRALIA DO CLIMATE SCIENCE?

The climate is a complex, global system, and its study is necessarily an interdisciplinary and worldwide endeavour. Atmospheric conditions and events seemingly distant from our continent can have considerable impact on Australia. For example, the changes in atmospheric composition over Antarctica that resulted in a loss of ozone in the stratosphere has direct consequences for Australia today, with the resultant increased irradiance of ultraviolet radiation causing elevated levels of skin cancer amongst the Australian population. The discovery of the ozone hole above Antarctica (and its causes) demonstrates the interdisciplinary nature of climate science—changes in the concentration of ozone above Antarctica (atmospheric composition observations) are caused by reactions in the stratosphere between ozone and ozone-depleting substances (atmospheric chemistry), concentrated over Antarctica by the spring polar vortex (atmospheric dynamics), allowing additional ultraviolet light to reach the surface of the earth (terrestrial irradiance observations) impacting plants and animals (biological science) and humans (health).

Similarly, as climate events and processes in one region affect or are influenced by climate conditions elsewhere in the globe, national climate science efforts are necessarily interdependent on climate science efforts in other regions and countries. This also means that climate science is also highly collaborative. Climate scientists in one region rely on data, models and expertise from scientists in other regions, and vice versa, making climate science a truly global endeavour.

In light of the fact that the study of the climate is increasingly a global enterprise, it could be argued that it is not necessary for Australia to maintain its own climate science capability, and necessary knowledge and information could be acquired from other nations whose climate science effort dwarfs Australia's. However, there are a number of reasons why Australia must maintain its own climate science capability.

Regional expertise for regional conditions

The Australian climate and environment is unique. Australian landscapes and vegetation are very different to those encountered in other countries, particularly vegetation and other terrestrial factors. In fact, it has been necessary to develop a unique Australian model (the Community Atmosphere Biosphere Land Exchange model—CABLE), to adequately describe Australian terrestrial influences on climate. CABLE has been developed with a view to satisfying requirements for accurate information in six key areas, some well beyond the sphere of climate: weather forecasting, climate change projections, water resources management, carbon management and accounting, environmental information and accounting, and integrated assessment modelling (Law et al, 2012). The development of the CABLE land surface model allows for very detailed information about Australian climate and ecosystems to be obtained, which directly supports government and community needs in climate research and in other areas of environmental science. It is highly unlikely that a similar level of detailed information could be obtained through other countries' research programs. The same Australia-specific point applies to the regional fine-resolution modelling that is undertaken to better represent atmospheric convection at the scale of individual states of Australia.

Regional responsibility and stewardship

The southern hemisphere is also very different to the northern hemisphere (where much of the scientific activity is focused) in climatic, social, and ecological respects. Its ocean-dominated climate has different drivers, greater inter-annual and inter-decadal climatic variation, and stronger droughts, floods and other extreme events. Its climate record is sparser and shorter than that of the north. This places an important responsibility on Australia, as one of the few developed countries in the southern hemisphere with strong science capacity, to maintain and develop observation, climate science and modelling capacity that can support better global understanding of the climate system.

The Southern Ocean plays a very important role in global climate processes, and a large portion of it falls between the Australian mainland and the Australian Antarctic Territory. Australia is both best-resourced and best-placed to conduct research in the Southern Ocean, making Australia the steward of Southern Ocean science.

It is also incumbent on Australia to assist less-developed neighbours in the Asia–Pacific region to develop climate understanding necessary to maintain regional stability and prosperity. Other countries undertaking climate research, which are principally in the northern hemisphere, understandably focus more closely on their own regions. Without Australia's contribution to climate science, global knowledge of southern hemisphere climate processes and conditions would be considerably poorer, which could influence economic and political decisions of other nations that relate to our region.

Capturing the best of global science in a timely manner

Despite Australia's significant investment in climate science, it will, as in other fields of scientific research, be relatively small compared with that of many other countries. Ongoing collaboration in the global community ensures that Australian scientists are aware of the best science as it happens, which is to Australia's benefit.

Relationship to strategic government policy

The ability of the Australian Government to call upon climate science expertise is a strategic national capability. Climate information will remain an important input in a number of areas of government activity:

- **Representing Australia's interests in international negotiations**: To ensure that Australia is able to prosecute a credible case in international negotiations on climate change and other environmental issues, the Australian Government needs trusted, credible and informed scientific advisors. Australia has been able to argue for its national interests in previous negotiations, with its arguments being supported by credible scientific positions.
- **Australia's Antarctic interests**: Australia's claim to sovereignty over 42% of the Antarctic continent is supported by Australia's commitment to maintaining a presence in Antarctica, which is primarily scientific in nature. Australia's ability to maintain that presence is supported by the important climate science work carried out by Australian scientists in Antarctica.
- **Responding to climate change**: Mitigation and adaptation efforts are underpinned by scientific assessments of the extent and type of mitigation and adaptation policies required. Without an understanding of how Australia may be affected by climate change, it is impossible to make rational policy to deal with climate change. Similarly, Australia will need the advice of its own climate scientists should other countries decide to proceed with climate engineering (geoengineering), which could affect Australia.
- **Maintaining a scientific quid pro quo**: Australia relies heavily on the scientific resources of other countries for critical data and tools. For example, Australia has no observational satellites of its own, and relies on other countries such as Japan and the United States to provide a steady stream of data to Australia for a variety of purposes including weather prediction and environmental science. As part of a general quid pro quo in international science, Australia contributes knowledge, data and resources in its areas of expertise and ability, such as through the maintenance of the Cape Grim Air Pollution Station, providing expertise and data on the Australian landscape, and through collaborative Antarctic

research, among many others. Australia must make its own contribution to the global scientific effort (and be seen to be doing so) to safeguard the many valuable sources of information and expertise provided to Australia essentially through scientific goodwill.

- **Maintaining a strategic and competitive advantage**: Should Australia fail to maintain an appropriate level of climate science capability, Australia may lose competitive and strategic advantages that it currently enjoys in a number of areas. Inadequate climate services could jeopardise the ability of Australian primary producers to compete effectively on world markets, or hamper the ability of Australia's defence forces to deploy effectively in order to maintain regional security. Similarly, an inability to predict or plan for future circumstances that have a climatic element (for example, urban water and food security, increased mobility of refugees away from areas of adverse climatic conditions like drought, public health issues associated with climate change) will have a considerable detriment to Australian community welfare and impair the ability of the government to focus on policy priorities.

It is clear that without a local climate science capability, the national interest will be put at risk. Climate science capability is important to maintain Australia's economic prosperity, community welfare, and security and sovereignty. It is the purpose of this review to determine whether Australia's national climate science capability remains fit-for-purpose, to serve the national interest.

1.5 WHAT IS THE CLIMATE SCIENCE TASK?

There are two separate but linked national tasks for climate science. The first is to provide the community with information and predictions on climatic conditions and events, and the second is to inform the national policy response to climate change.

Information and predictions on climatic conditions and events

The national capability to provide the community with information about current and future climates and extreme weather events is distributed amongst a range of institutions, although principally led by the Bureau of Meteorology, CSIRO and the universities. Research into a more accurate understanding of the local and regional climates has provided Australia with significant national benefit in the past, including the development of the Australian Community Climate and Earth System Simulator (ACCESS), which has enabled considerably improved weather and climate forecasts in Australia (CAWCR, 2014).

Information on current and future climatic conditions and events is used both by *next-users*, who use the information to conduct further research, and end users such as government and primary industry.

Informing the response to climate change

The national capability to respond to climate change relies heavily on the national climate science capability. Climate science provides the physical basis of climate change science, and provides information about the likely future climate. National policy responses to climate change needs climate science to answer several important questions, such as:

- How and why is the climate changing (past and present)?
- What is the likely nature and extent of future climate changes?
- What are the likely impacts of future changes in the climate of Australia (impacting the natural, built and human environments) and internationally (impacting Australia's foreign and humanitarian aid, and international relationships)?
- What level of mitigation of greenhouse gas emission is needed to reduce the likelihood of dangerous climate change?

By having credible and accurate answers to these questions, other researchers, governments and the community can attempt to build resilience to climate change, and plan to adapt to future climatic conditions (see the 2015 *National Climate Resilience and Adaptation Strategy*).

Australia's response to climate change is a community-wide effort, of which climate science is an important part. Understanding the physical science basis of climate change is the task of climate scientists, with many other researchers doing important work in linking that fundamental understanding with social, economic and other environmental systems. Together, this information helps governments to craft evidence-based and effective responses to climate change.

1.6 REVIEWING AUSTRALIA'S NATIONAL CLIMATE SCIENCE CAPABILITY

Cognisant of the importance to Australia's national interest of an effective national climate science capability, this review seeks to investigate the following questions:

- Is the current level of climate science capability in Australia appropriate to the task?
- Is the level of climate science capability in Australia sustainable on current trends?
- Are there areas of climate science in which Australia has either a surplus or a deficit of capacity, relative to the national interest?
- Is the way that climate science is currently conducted in Australia appropriate?
- Is the current mode of administration of climate science optimal?
- Can efficiencies in the conduct of climate science be achieved?

2 THE AUSTRALIAN CLIMATE SCIENCE EFFORT

Climate science and research in Australia is a distributed and collaborative effort involving governments, government research agencies, universities, stakeholders and end users. Over the past 50 years, Australia has developed substantial national capability in climate science to serve the requirements of the nation. This climate science capability is underpinned by a combination of people, institutions, infrastructure, policy and resources.

2.1 PEOPLE

The focus of this report is Australia's capability in climate science. People are the most important component of any science and research capability—people to design and run observation networks, to develop an understanding of the climate system, and to develop ways to apply that understanding to current and future situations. Australia's climate science workforce is principally employed in universities and research agencies, as shown in the following table:

Institution	Climate science workforce (FTE)
CSIRO	95[a]
Bureau of Meteorology	85 (approx.)[b]
Australian Nuclear Science and Technology Organisation	17
Australian Antarctic Division	14 (approx.)
Australian Institute of Marine Science	12
Geoscience Australia	2.7
Collaborative research infrastructure networks (TERN, IMOS)	5 (not counted separately)
University staff associated with ARC Centre of Excellence for Climate System Science	72
University staff not associated with Centre of Excellence	95 (est.)[c]
Antarctic Climate and Ecosystems Cooperative Research Centre	26[d]
Total	**419 (approx.)**

a Estimated after 2016 restructure **b** Includes only those BoM staff working on climate rather than weather. This number is an estimate, as BoM does not officially distinguish between those working on weather and climate science **c** Estimate only, based on responses received **d** Includes only those employed directly by ACECRC. Source: Institutional and individual submissions.

The climate science effort in Australia currently consists of approximately 419 full-time-equivalent scientists (not including students). To place this number in context, the public research sector in Australia consists of approximately 50,000 researchers, which consists of 42,000 university researchers and 8,000 researchers across the Australian Government and state governments (ABS, 2016; Department of Education, 2015). It does not appear that there is significant fundamental climate science activity in the private sector.

It is important to recognise that Australia's climate science capability rests entirely in these people. Climate scientists are employed in a number of ways, at different levels of seniority and in a variety of roles (such as postdoctoral fellows, research fellows, research group leaders and technical specialists).

An issue raised by a number of survey respondents is the increasing reliance on short-term insecure employment in both research agencies and universities. Although data representative of this phenomenon across the field is not available, approximately 55% of university researchers associated with the Centre of Excellence for Climate System Science are on short term contracts. At BoM, approximately 12% of all employees are non-ongoing and we estimate that approximately 25% of CSIRO employees are non-ongoing, with researchers more likely than general staff to be employed on funding-contingent fixed-term employment arrangements.

This issue is of most concern to junior scientists who currently face significant career uncertainty. It is not appropriate for this review to make extensive comment on individual employment arrangements, noting that it is common practice in science and research more generally for there to be a mix of employment modes.

However, workforce planning to sustain an enduring capability is certainly an important element of any national capacity, and climate science is no different. It is likely that a mix of ongoing and short-term employment will remain the norm for the foreseeable future, and it is important for the nation to ensure that sufficient local expertise is retained through retention of an appropriate cohort of climate scientists that can make their expertise available to the nation on a continuing basis.

In particular, it appears that in the current set of structural changes occurring in the climate science community insufficient consideration is being given to succession planning. Australia has invested a considerable amount of money over the last 25 years in Australian climate science, and failure to properly plan for orderly capability succession risks greatly damaging the present and future value of that investment.

2.2 INSTITUTIONS

There are a number of institutions involved in climate science in Australia. To date, climate science has been undertaken on a collaborative basis between different institutions that work in different areas of climate science (see Figure 3).

2.2.1 Australian Government organisations

Commonwealth Scientific and Industrial Research Organisation

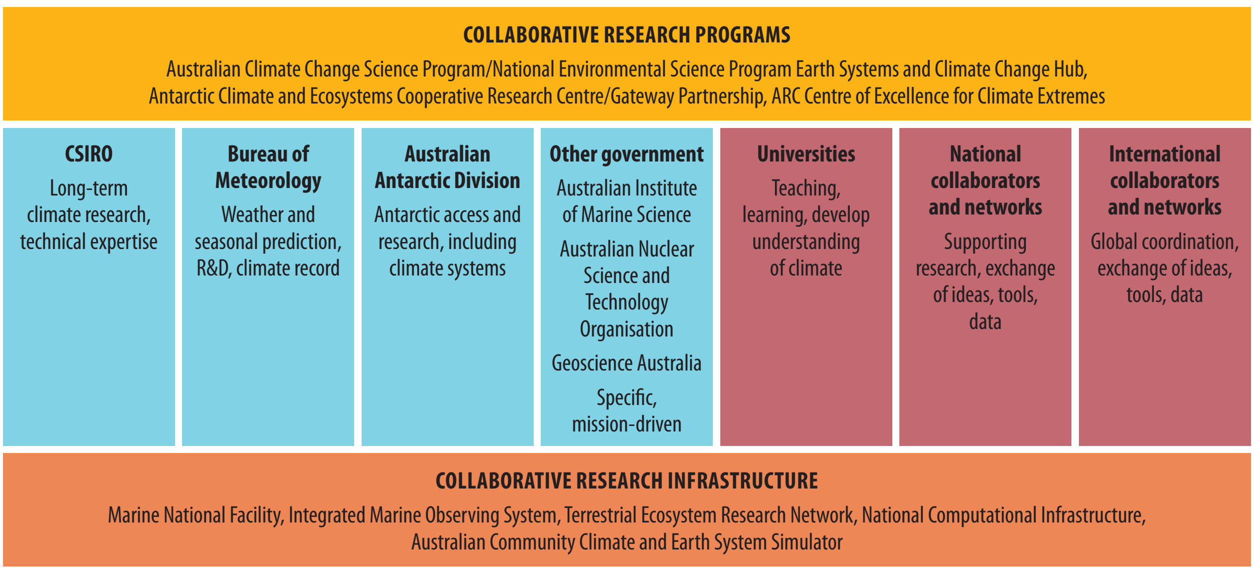
The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has been undertaking climate research in Australia for nearly 70 years, with the establishment in 1949 of the Meteorological Physics Research Section. CSIRO's climate research efforts have evolved considerably throughout the decades, working collaboratively in various forms with the national meteorological service. Today, fundamental climate research is principally carried out through CSIRO's Oceans and Atmosphere division which incorporates previous atmospheric and marine research divisions, with researchers located principally in Hobart, Melbourne and Canberra. CSIRO's other divisions (most notably Land and Water) also contribute to climate research, particularly in the application of climate science to the natural, built and human environments. In August 2016 CSIRO grouped its climate activities into a new CSIRO Climate Centre.

CSIRO has a unique place in the Australian research and innovation system as a publicly funded multidisciplinary research organisation. CSIRO conducts research not only into fundamental climate science, but also into climate change impacts, mitigation and adaptation. CSIRO operates the Marine National Facility, which consists of Australia's ocean-going research vessel, the RV *Investigator*, as well as scientific equipment, expertise and data which supports marine research. CSIRO is also responsible for developing and operating a significant portion of Australia's climate observation capability, under arrangement with the collaborative research networks (the Integrated Marine Observing System—IMOS—and the Terrestrial Ecosystem Research Network—TERN). CSIRO is deeply involved in the development and maintenance of the Australian Community Climate and Earth System Simulator (ACCESS), and has previously developed its own climate models.

In 2014–15, CSIRO's total staff numbered 5,269 (4,836 full time equivalents), of whom approximately 77% were research scientists, project staff and technical services, with the remaining 23% involved in administrative support, communications/ICT and management (CSIRO, 2015). CSIRO receives a direct appropriation from the Australian Government, and is expected to gain revenue from sale of products and services to support its work.

The CSIRO is a statutory Commonwealth entity, established by the *Science and Industry Research Act 1949*, and exists within the Industry, Innovation and Science portfolio. Although a Commonwealth entity, CSIRO exists outside the framework of the *Australian Public Service Act 1999*, and enjoys some

Figure 3: Institutions and organisations involved in climate science



Adapted from IMOS submission

autonomy from the government. An agreed relationship between CSIRO and government is set out in the CSIRO *Public Research Agency Charter*, which emphasises the independence of CSIRO in its research activities, and the ability of CSIRO researchers to contribute as experts to the public debate within certain guidelines. However, the relationship between CSIRO's research freedom and the interests of the executive government continues to evolve, and the responsible minister retains broad power under Section 13 of the Science and Industry Research Act to give directions to the CSIRO Board without restriction.

Bureau of Meteorology

The Bureau of Meteorology (BoM) is a Commonwealth agency established by the *Meteorology Act 1955*, with national responsibility for meteorological observations and weather forecasting which are to be carried out in the public interest. Compared with CSIRO, the BoM has a lesser emphasis on research, and a greater emphasis on delivering meteorological information (most visibly weather information and forecasts) to the public.

BoM plays a key role in the Australian climate science effort, as the operator of the national network of meteorological observation stations that provide key climate observations land, upper atmosphere, oceans and cryosphere. BoM contributes heavily to the development and operation of the ACCESS model, most strongly with shorter weather and seasonal timescales, but also contributing to longer timescales. The organisation works closely with stakeholders to operationalise weather and climate information, and has strong relationships with end users of meteorological information. As Australia's national meteorological service, BoM has primary responsibility for working with the World Meteorological Organization which facilitates global meteorological cooperation.

BoM is a statutory organisation, but unlike the CSIRO, BoM is an executive agency under the direction of the Minister for Environment and Energy and its staff are employed under the *Australian Public Service Act 1999*. BoM employed 1,654 staff in 2014–15, of whom approximately 64% were professional officers, technical officers or research scientists, with the remainder comprising administrative support officers, management or information technology officers. BoM is funded through direct government appropriation and also receives income from external contracts and the sale of products and services (BoM, 2015).

Australian Antarctic Division

The Australian Antarctic Division (AAD) is Australia's lead agency for operations and science in the Australian Antarctic Territory. AAD is particularly involved in climate science activities relating to Antarctica, such as the acquisition and analysis of ice core records, investigations of the extent and characteristics of ice sheets and their interactions with ocean and atmosphere, sea ice processes and atmospheric science. AAD works in partnership with a wide range of other research organisations to facilitate Antarctic research through its Antarctic logistics capability.

AAD's science and research covers all facets of Antarctic research, not just climate science, but climate research remains an important area of research for AAD. The government's Australian *Antarctic Strategy* released in 2016 included a commitment to build a capability to traverse the continent and drill for ancient ('million year') ice cores. AAD also works with other climate research institutions in the sector, including BoM and CSIRO, on helping to include the cryosphere in Australian and global climate modelling efforts.

Although operationally distinct, AAD is an integral part of the Department of Environment and Energy, and its staff are employed under the *Australian Public Service Act 1999*. AAD is funded through direct appropriation from the Commonwealth budget. Approximately 370 departmental FTE were assigned to the Australian Antarctic Program in 2014–15.

Australian Institute of Marine Sciences

The Australian Institute of Marine Sciences (AIMS) is a publicly funded research agency charged with conducting research in tropical marine environments. A significant portion of its research involves oceanographic sciences and coral reef research. AIMS contributes to national marine observing networks, maintains an archive of coral cores, and contributes to oceanographic modelling, particularly around the Great Barrier Reef. Additionally, AIMS has a significant area of research activity in the impacts of climate change on the Great Barrier Reef.

AIMS is a statutory research organisation established by the *Australian Institute of Marine Science Act 1972*, and is similar to CSIRO in having some autonomy in its operations. AIMS consisted of 210 staff in 2014–15, with approximately 55% of staff classified as research scientists or research support, with the remainder classed as technical or administrative support. AIMS is funded through a mix of government appropriation and external funding.

Australian Nuclear Science and Technology Organisation

The Australian Nuclear Science and Technology Organisation (ANSTO) houses Australia's nuclear science and research capability, and participates in climate science through its Environment theme. ANSTO has particular expertise in radioisotope studies and works in climate science through studying the movement of radioisotopes through the atmosphere and in helping to analyse ice cores. ANSTO staff work on climate modelling in areas including atmospheric circulation and transport.

ANSTO is structured and funded in a similar way to CSIRO and AIMS as a publicly funded research agency, operating under the *Australian Nuclear Science and Technology Organisation Act 1987*.

Geoscience Australia

Geoscience Australia (GA) is responsible for maintaining information in Australia's geology and geography, and plays a role in climate science. In particular, GA has a role in monitoring sea level and conducts research into extreme weather events. Climate science is a relatively minor part of GA's activities, and somewhat peripheral to its core business. However, GA is an important part of the overall climate science effort, proving geographical and geodetic information used in observing systems, models and other earth system science.

2.2.2 Universities

University research plays an increasingly important role in fundamental climate science, particularly in the development of knowledge of climate processes, although universities also play a significant role in climate observations and modelling. Universities also conduct considerable research in other areas of climate and environmental science, and work with a wide range of stakeholders. In contrast to the publicly funded research agencies (PFRAs), universities focus more heavily on investigator-led research, and have lesser capability to support mission-driven science.

The university climate research effort is widely distributed and obtaining a complete inventory of climate science research undertaken has proven difficult. However, centres of particular emphasis on fundamental climate science are the Australian National University and Monash University, and the universities of Tasmania, New South Wales, Melbourne, Sydney, Wollongong and Western Australia. Many more universities have research activities in climate change impacts, mitigation and adaptation.

University researchers may occupy a variety of roles, from academic group leaders to postdoctoral fellows, but as universities have a considerable role in undergraduate education and research training, the university research effort also encompasses a considerable number of research students. For the purposes of this review, research students have not been considered either at universities or where they work at PFRAs, as their contribution to the national capability rests substantially with their supervising academic. Universities also play a significant role in knowledge transfer to both the public and future generations of climate scientists.

University research is resourced in a number of ways. University academics are supported through university research block grants, project funding from the Australian Research Council, infrastructure access through facilities supported by the National Collaborative Research Infrastructure Strategy (NCRIS), research fellowships supported through a variety of individual schemes, and income from a wide range of other Australian Government and state government grant schemes, as well as contract and private sector income. The review estimates that approximately 167 university researchers are involved in fundamental climate science.

2.2.3 Private sector organisations

There are a number of private sector organisations involved in climate science modelling activities, primarily in a climate services role (that is, to provide tailored information to end users). Although private sector firms contribute to a national climate services capability, their activities have not been canvassed to a large extent by this review.

2.2.4 Collaborative institutions

As noted previously, the scale and complexity of climate science necessitates strong collaboration, both nationally and internationally. Within Australia, there are a number of institutions designed to support collaboration in climate science, including:

ARC Centre of Excellence for Climate System Science

The ARC Centre of Excellence for Climate System Science (ARCCSS), renewed in September 2016 as the ARC Centre of Excellence for Climate Extremes, is a collaborative research network headquartered at UNSW Australia. The centre's focus is to conduct 'blue sky' climate science, and it facilitates collaboration between university researchers working on the quantitative study of climate system science, including the universities of NSW, Tasmania and Melbourne, and Monash University and the Australian National University. The ARCCSS also has links to researchers in both CSIRO and BoM, and partnerships with the Commonwealth Department of Environment and Energy, the National Computational Infrastructure and the Australian National Data Service, and collaborations with important international climate science research institutions in the United Kingdom, United States, France and Germany. Members of the centre undertake fundamental research into one or more of five research themes, relating to tropical convection in Australia's climate, examination of changes in Australia's climate extremes, surface forcing and feedbacks in regional climates, Australian climate variability over space and time, and changes in ocean circulation. (ARC ARCCSS, 2015).

The centre provides significant financial and in-kind support to investigators associated with it. It sponsors around 15 post-doctoral research fellowships, and provides very valuable in-kind support through training, outreach, conferences/workshops and skilled technical support for researchers. This is particularly notable in its computational modelling support activities, where computational experts assist researchers to contribute their expertise in climate system processes to computer climate models. The centre's activities complement those of individual researchers, allowing for efficient shared use of resources and expertise that would otherwise be unavailable to university researchers.

Some 72 university researchers are associated with the centre, as well as more than 80 research students. A small number of technical and professional staff are employed through the centre.

Antarctic Climate and Ecosystems Cooperative Research Centre

The Antarctic Climate and Ecosystems Cooperative Research Centre (ACECRC) is a collaborative research program headquartered in Hobart at the University of Tasmania. It is a partnership between the University of Tasmania, CSIRO, BoM, AAD, the Department of Environment and Energy, and 16 other national and international partner institutions. ACECRC's mission is to help understand the role of the Antarctic region in the global climate system, and the implications for marine ecosystems. The CRC acts both as a collaborative research network and a driver of research, focusing on seven research areas: the Southern Ocean in a changing climate; ocean-forced evolution of the Antarctic ice sheet; sea ice processes and change; Antarctic climate variability of the past 2000 years; uptake of carbon dioxide in the Southern Ocean; biological responses to climate change; and status and trends in habitats, key species and ecosystems. The CRC's climate science activities revolve around climate understanding and modelling, focusing on the Antarctic region and the Southern Ocean.

The CRC sponsors or employs 26 research staff directly, and is associated with a further 100 staff employed at partner institutions. It has been funded through the Cooperative Research Centres Programme since 1991 and is currently funded until 2019.

The Collaboration for Australian Weather and Climate Research

The Collaboration for Australian Weather and Climate Research (CAWCR) is a formal collaboration between CSIRO and BoM, described as a partnership to extend the research capability of both organisations in earth system science. The partnership boasts a long list of achievements, including the development of the Australian Community Climate and Earth System Simulator (ACCESS), climate change projections for natural resource management regions, and the virtual Climate and Weather Science Laboratory, used by many researchers to harness the data and computing power available through ACCESS and the National Computational Infrastructure (CAWCR, 2015). CAWCR also published a series of technical reports and research letters that provided an avenue for technical discussion around earth system science and climate system science in Australia.

CAWCR staff are employed by either CSIRO or BoM, and assigned to CAWCR. CAWCR does not have any staff in its own right, beyond a notional director of the collaboration, employed by CSIRO. The future of CAWCR is currently uncertain due to the uncertainty regarding CSIRO's future climate research activities.

Earth Systems and Climate Change Hub

The Earth Systems and Climate Change Hub is a consortium of research organisations that undertake research under the National Environmental Science Program (see later section on Policy and Resources) relating to national research priorities.

The hub's current research priorities are improving our understanding of past and current climate; improving our understanding of how the climate may change in the future; and building the utility of climate change information. Members of the hub are CSIRO, BoM, UNSW, the Australian National University, Monash University, University of Melbourne and University of Tasmania (ESCC, 2015).

The hub does not employ researchers directly, but engages and funds its member organisations to conduct research under the direction of the hub's steering committee.

2.3 INFRASTRUCTURE

The study of the climate is undeniably big science—it relies heavily on research infrastructure on a global scale, and transfer of vast data sets around the globe. To avoid duplication with the current National Research Infrastructure Roadmap process, this review will not consider infrastructure in great detail.

2.3.1 Observing networks

Climate science is heavily reliant on distributed observing networks that record key climate variables. These observational networks are land, sea, air and space-based, and Australia's contribution comprises a key part of the global earth observing system.

BoM weather and climate observing systems

BoM is responsible for operation of a network of observing systems that monitor key weather and climate variables across Australia and its territories including Antarctica. This network includes automatic weather stations, radiosondes and ozonesondes, baseline surface radiation networks, and a range of other observing networks that form the core climate record and represent some of the most readily available longitudinal climate observations. Operation of the observing network system is a core function of BoM.

Integrated Marine Observing System

The Integrated Marine Observing System (IMOS) is a collaborative network of ten different marine observing systems that provide important data about the oceans and environs. These include a fleet of thousands of Argo floats, which autonomously measure ocean temperature and salinity at a range of depths up to 2000 m. Australia is responsible for around 800 of the world's Argo fleet. IMOS also deploys deep-water and Australian coastal moorings that provide information about oceanic currents and circulation, ocean acidification and a number of other physical and biological oceanic parameters. IMOS operates an oceanic data network in partnership with other organisations, and coordinates access to satellite remote sensing facilities.

IMOS is funded through the National Collaborative Research Infrastructure Strategy (NCRIS) and attracts co-funding to cover its expenses.

Terrestrial Ecosystem Research Network

The land-based cousin of IMOS, the Terrestrial Ecosystem Research Network (TERN) is a collaborative network of 12 different terrestrial research facilities. Of relevance to climate science is the OzFlux network, which, using instruments mounted on meteorological towers, monitors the movement of carbon, energy and water between the land and atmosphere. The OzFlux network is of particular importance to modelling of the land surface – atmosphere system. Globally, there are around 400 flux towers, although there are few in the southern hemisphere. OzFlux currently maintains 24 towers, with an additional 11 towers decommissioned. OzFlux is partially funded by TERN through NCRIS, and partially by other stakeholders.

Satellite observing networks

Although Australia does not operate any satellites, satellite observations are of critical importance to Australia's climate science effort. Satellites are able to sense variables over a massive spatial area and provide consistent time-series observations. Satellites are critical in making observations including land and sea surface temperatures, insolation and albedo measurements, vegetation cover and other terrestrial characteristics, atmospheric composition, cryosphere extent and variation. Australia's access to these important satellite measurements are gained by agreement with other countries, which often involve an element of quid pro quo—such as providing calibration and validation data and providing access to other data not available in other countries.

Terrestrial and marine research stations

A number of organisations operate discrete research stations dedicated to different tasks, such as Australia's Antarctic bases, tropical marine research stations and other experimental and recording stations. Many of these stations conduct climate and weather observations in addition to their primary purpose, including measurements of atmospheric and marine characteristics and composition. These other stations form an important part of the overall climate picture.

A particular example of this is the Cape Grim Baseline Air Pollution Station recording facility in Tasmania, which is operated by BoM. CSIRO collaborates with BoM to undertake the science and research on the data collected, and is responsible for data curation and quality assurance and control. Cape Grim is one of only three premier baseline greenhouse gas monitoring stations in the world, but also does a number of other significant measurements relating to atmospheric composition and circulation. The samples taken at Cape Grim are analysed by CSIRO's Gaslab and provide critical data not only for Australia, but for global climate research as part of key global networks such as the Advanced Global Atmospheric Gases Experiment and the World Meteorological Organization's Global Atmosphere Watch.

2.3.2 Oceangoing infrastructure

A significant part of Australia's research capacity in the marine and Antarctic spheres rests with two vessels: the research vessel RV *Investigator* and the icebreaker *Aurora Australis*. These vessels provide a platform for Australia to maintain scientific research capabilities in Antarctica and on southern oceans.

The RV *Investigator* is operated through the Marine National Facility, which provides the ship, equipment and instrumentation, technical expertise and a collection of research data. The RV *Investigator* is funded to go to sea for 180 days per year, and scientific access to sea time is provided on the basis of scientific merit, in a similar way to access to other landmark research infrastructure. However, submissions to this review indicated that on-board capability to support scientists coming on voyages was diminishing in response to tightening resourcing constraints and arrangements. The RV *Investigator* is capable of a total annual sea time of 300 days, subject to resourcing (MNF, 2016).

The *Aurora Australis* provides logistical and scientific support to Australia's presence in Antarctica, making three or four voyages each summer to resupply Antarctic bases and conduct marine science. The icebreaker is the means by which Australia's Antarctic program is deployed, and it is managed by the Australian Antarctic Division. AAD provides funding and logistical support to scientists from other institutions to access Antarctica or otherwise conduct Antarctic research, with logistical support depending on availability.

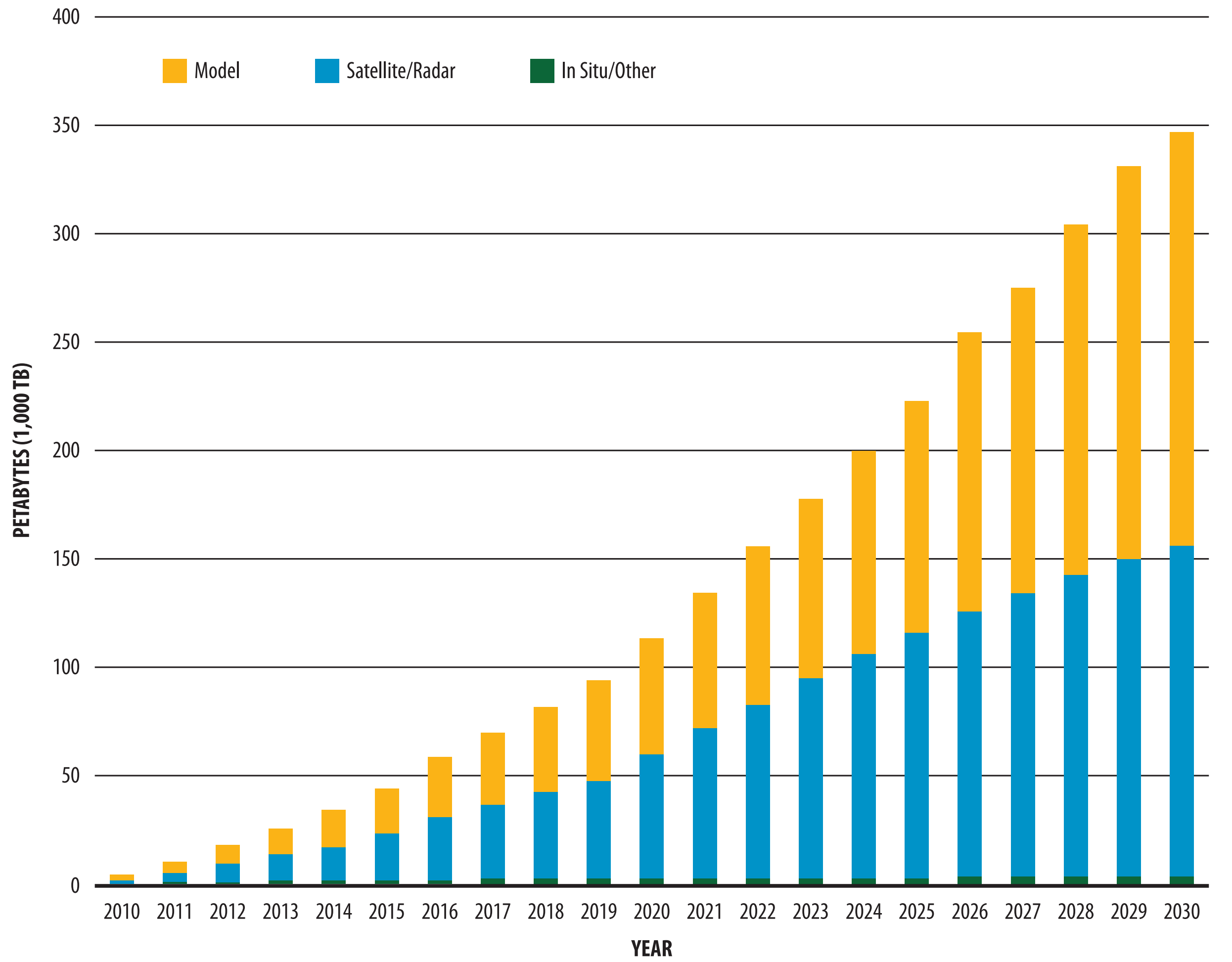
A diverse range of institutions operate smaller research vessels, complementing the deep ocean and Antarctic capability with coastal research capability.

2.3.3 Computing and data infrastructure

High-performance computing and high-performance data infrastructure are a key component of climate science. As models become more and more complex, ever greater amounts of data are required in their development and operation. For most researchers, current computational needs are generally met by the National Computational Infrastructure facility and the Australian National Data Service. These facilities are funded by NCRIS and partners, including CSIRO, BoM, other agencies and universities. BoM maintains its own, separate computational and data facility for its operational forecasting activities.

Although computational and data infrastructure is to be examined closely in the National Research Infrastructure Roadmap, it is clear that significant investment in this infrastructure will be required in the future to keep pace with the complexity of climate models and data sets. As Figure 4 suggests, the amount of data that climate models will produce will continue to increase exponentially.

Figure 4: Projected increase in global data holdings for climate models, remotely sensed data, and in situ instrumental and proxy data



From: Overpeck, J. et al. (2011). Climate Data Challenges in the 21st Century, *Science*, vol 33., pp 700–702.
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Computational expertise

A recurring theme raised throughout this review is that in addition to the need for powerful computational infrastructure, there is an unmet need for computer science expertise to properly utilise that infrastructure. Several respondents mentioned that utilising specialist computer scientists and software engineers helps climate scientists produce computer code that most effectively makes use of large data sets and computational resources.

ACCESS

The Australian Community Climate and Earth System Simulator (ACCESS) model has been developed over the past decade to create a uniquely Australian model. ACCESS brings together the Unified Model for atmospheric studies, the Modular Ocean Model for oceanographic modelling, the Community Atmosphere Biosphere Land Exchange (CABLE) model and the Los Alamos sea ice model (CICE) into an integrated global weather and climate model, with a focus on the Australasian region. ACCESS provides weather, climate and earth system scientists with the ability to model Australian climatic conditions on a variety of different timescales. It should be noted that the majority of the components of ACCESS are produced by overseas institutions, and Australia relies on those collaborators to maintain their components of the model. Australia contributes to the global model development effort by jointly developing expertise and model components with overseas collaborators on Australian conditions.

ACCESS has been developed jointly by BoM and CSIRO through CAWCR and includes input from the university sector. It enables collaborative research and is a substantial national asset that requires ongoing maintenance and development to remain relevant and up to date. Therefore, it should be considered as a nationally important piece of research infrastructure with significant value, and the nation must plan for its future in this way.

2.3.4 Access to international infrastructure, data and expertise

Australia relies heavily on access to international research infrastructure (such as satellites), data (such as from world-wide oceanic observing networks and from the outputs of models), and expertise (such as the climate modelling efforts that form part of our own modelling systems). Access to these facilities is often provided at minimal or no cost, in recognition of a global scientific effort in climate research. Without these facilities provided by other nations, Australia would have no weather forecasts, no climate outlooks, no idea of the potential impacts of climate change and no realistic expectation of being able to develop a domestic climate science capability. Access to these facilities are provided in many cases on the basis of an international scientific quid pro quo, to which Australia must contribute its part.

Australia does participate in global networks, such as the Global Climate Observing System, internationally coordinated research programs, and international climate and weather research coordinating bodies. It is essential that Australia continues this participation, and is seen to be doing its fair share, in the interests of ongoing cooperation with other nations. Climate science is an increasingly global endeavour, and Australia must keep a global focus in its climate research to maximise insight into regional and local processes.

2.4 POLICY AND RESOURCES

Climate science in Australia is conducted as strategic basic research, as well as applied research and experimental development. Basic research in climate science is enabled through investigator-driven university research and mission- and investigator-driven science and research in PFRAs. Government policy recognises the relationship of climate science to the national interest, and through directed funding permits focus on mission-driven climate science that would generally not be possible through the ARC's National Competitive Grants Programme.

Overall policy responsibility for climate science currently lies with the Department of Environment and Energy. As well as being the parent department to BoM and AAD, the department is tasked with designing and implementing Australia's policies to respond to climate change. The department currently sponsors climate and other environmental research through the National Environmental Science Programme, through six research hubs. Climate research is undertaken through the Earth Science and Climate Change Hub.

2.4.1 National Environmental Science Programme

In the 2014–15 Budget, the Australian Government consolidated the National Environmental Research Program and the Australian Climate Change Science Program into a new National Environmental Science Programme (NESP). Under this new arrangement, research hubs are a consortium of Australian research institutions that conduct research in response to research priorities.

Funding for the ESCC Hub is $24 million over six years, or approximately $4 million per annum, with matching co-funding from participants (Department of the Environment, 2014).

Australian Climate Change Science Program (ACCSP)

The NESP has replaced the ACCSP, which was a directed funding program that had funded climate change science and most of Australia's climate capability since 1989. In contrast to the hub model of the NESP that uses consortia which includes PFRAs and universities, the ACCSP was run jointly by the responsible Commonwealth department, CSIRO and BoM, meaning a close relationship between the activities of CAWCR and the resourcing provided by the ACCSP.

Between 2006–07 and 2013–14, budgetary appropriation for the ACCSP was $7.8 million (on average, per annum, for this period), and once this funding was matched by BoM and CSIRO, the total spent on this ACCSP research was about $15 million per annum. The current level of NESP funding devoted to Earth systems and climate science at BoM and CSIRO is $4 million per annum, which is also matched by the two organisations. This is a real reduction of 56% since 2013–14. The long-term, stable nature of the former ACCSP funding not only enabled the steady development of an Australian climate change science capability over several decades, it was also the foundation for a suite of regional climate change science programs including IOCI, SEACI and PACCSAP, and the regular production of regional climate projections for Australia (the latest being done via the NRM Regional Projections project). These are described in more detail below.

The ACCSP was considered to be a significant success, as it supported greater collaboration between CSIRO and BoM on weather and climate research, adding significant value to the investment made (Solomon and Steffen, 2007). The NESP takes a similar approach in aiming to foster collaboration in its consortium model, but necessarily spreads resources more thinly among a greater number of institutions than under the former ACCSP.

2.4.2 Other previous initiatives

There have also been a significant number of previous initiatives that led to the development of Australia's climate science capability. These included:

- The Pacific Climate Change Science Program, which provided $20 million between 2008–11 to allow BoM and CSIRO to provide technical assistance to Pacific Island nations to understand how climate change might impact them. This work was continued by the Pacific–Australia Climate Change Science and Adaptation Planning Programme (2011–15, $32 million).
- The South East Australian Climate Initiative (2006–12, $16.5 million) that examined causes and impacts of climate change and variability in southeastern Australia, as a partnership between BoM and CSIRO, with other state and federal government stakeholders.
- The Indian Ocean Climate Initiative (1997–2012), which examined the causes of the changing climate in southwest Western Australia, as a partnership between BoM, CSIRO and the Western Australian Government.

- The Victorian Climate Initiative (2013–16), tasked with examining climate change and variability with an emphasis on water availability, as a partnership between BoM, CSIRO and the Victorian Government.

Each of these programs included CSIRO and BoM as partners, strengthening their collaboration and providing spill-over benefits of increasing climate science capacity at each organisation. The cessation of these programs over the past five years has removed a significant amount of funding available to climate research in general, contributing to a winding-down of climate science capacity at CSIRO and BoM.

2.4.3 Co-contributions

The current regime for funding climate science activities involves significant emphasis on co-contributions in funding (often referred to as co-funding or leveraging). This can take a variety of forms, but the general principle is of matching government funding from one source with funding from another source, which might be from a stakeholder, private interests or another government program. Particular examples include: CSIRO and BoM internal co-funding, where external research funding is matched with a contribution from within the CSIRO or BoM budgetary appropriation; infrastructure co-funding, where funds from NCRIS are matched with user or stakeholder funding; or collaborative co-funding, where members of a collaborative institution (like the NESP hubs or cooperative research centres) make cash or in-kind contributions, to which the funding body adds its own funding.

Co-contributions are a widespread practice in science and research generally and have advantages and disadvantages. Co-contributions enable motivated stakeholders to contribute to the direction of research and can facilitate collaboration. Co-contributions can also improve the diversity of resources (including funding, expertise and infrastructure) available to a project.

However, co-contributions can also lead to inefficiency and waste where multiple sets of funding and co-contributions support single activities, particularly where operational scientists are responsible for securing or coordinating that funding. It is also important to recognise that in almost all cases, the original source of the majority of funds for climate science is the Commonwealth Government (see figure 5). It is highly likely that there is a considerable amount of wasted time and resources in granting and cross-granting between institutions, including satisfying application, contractual and reporting requirements. As front-line research staff are usually responsible for securing and maintaining funding, streamlining funding processes would free up significant amounts of time and money, maximising the value of finite resources.

2.5 PLANNING AND COORDINATION

Climate science has some characteristics that make planning and coordination essential to its success:

- **Scale of the problem**: Climate science relies on extensive collaboration and cooperation between institutions (and countries), because the questions being investigated are simply too big for any one institution.
- **Large infrastructure requirements**: Climate science relies on extensive, distributed observational and research infrastructure that require high levels of resourcing.
- **Spatial and temporal scope**: The data from the observational infrastructure only have significant value when acquired over a sustained period of time and over a wide, representative area.
- **Direct community need**: The community has a direct reliance on the outputs of climate science, both as end users of climate information and to inform other research.
- **Relationship to the national interest**: Climate observations and understanding are critical to Australia's strategic interests including national security, and its areas of competitive economic advantage.

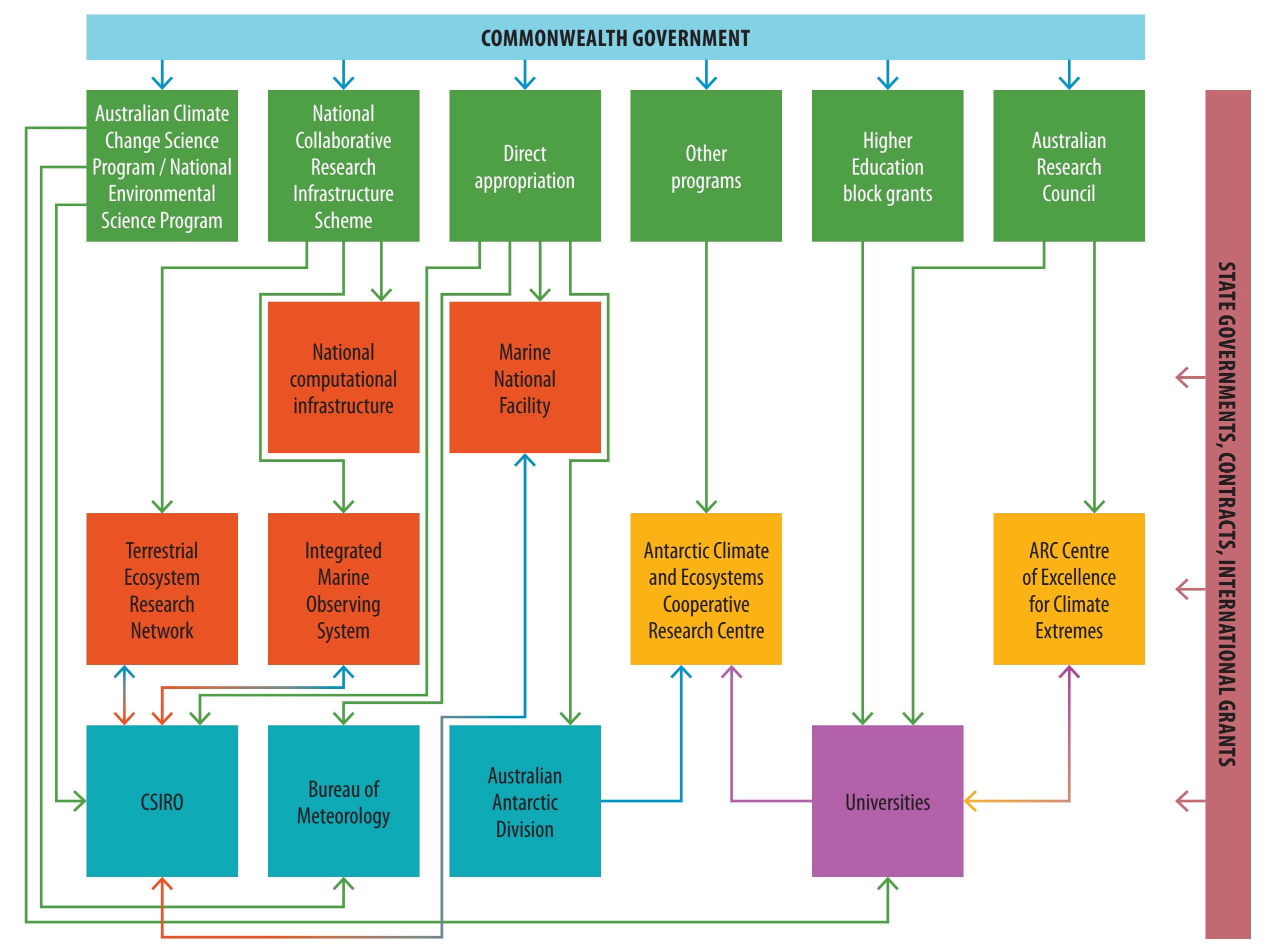
With these considerations in mind, it is clear that climate science must be coordinated to ensure optimal use of resources. In the obvious extreme, this means ensuring that wasteful duplication is avoided (such as only operating one set of observational infrastructure), but also requires a degree of connectedness throughout the climate science community, allowing for optimal and timely collaboration and knowledge transfer between researchers, and between researchers and stakeholders.

Particularly over the last 30 years, coordination and leadership of climate and weather science has resulted from ever-increasing collaboration between the principal organisations, BoM and CSIRO. Collaboration has existed in various forms, most recently with the formal introduction of CAWCR. With the increasing participation of the universities in climate research, efforts have been made to improve coordination between the academic and government research sectors and create cohesive planning structures and frameworks.

These efforts were formalised in three documents:

- *Australian climate change science: a national framework* (2009, Department of Climate Change)
- *To live within Earth's limits: an Australian plan to develop a science of the whole Earth system* (2010, Australian Academy of Science)
- *A plan for implementing climate change science in Australia* (2012, Department of Climate Change and Energy Efficiency).

Figure 5: Funding flows in climate science



Source: Australian Climate Science Capability Review. Not all funding flows shown.

These documents provided a plan for the future of earth system science and climate change science, which essentially covers climate science. These plans remain valid, but implementation has effectively ceased. These documents could easily form the basis of a renewed strategic planning exercise.

The review has found that the previous structures for leadership and coordination of climate science, where CSIRO and BoM worked with the appropriate Commonwealth department and the academic sector, have been somewhat disrupted since those documents were created. The unexpected decision of CSIRO to downscale its climate science activities in 2016 injected further uncertainty into the climate science effort and demonstrates the clear need for an effective mechanism to coordinate climate science. Section 5 of this review canvases some possible future models to coordinate climate research in Australia.

3 STATUS OF AUSTRALIAN CLIMATE SCIENCE CAPABILITY

A core task of this review is to make an assessment of the current state of Australian climate science capability. To do this, information from submissions has been collated and cross-referenced with interviews and workshop consultation processes. The assessment of capability level (or status) reflects a number of factors, including:

- resources available to the capability area
- relationship to locally important climate science issues
- relationship to urgent globally important climate science issues
- confidence of respondents in their ongoing ability to carry out their activities.

Capabilities have been assessed as:

Adequate (green): The capability is functioning currently at an adequate level and appears to be able to continue for the foreseeable future.

Vulnerable (yellow): The capability is currently functioning at a sub-adequate level and/or would be endangered by any significant setback (for example, loss of unique expertise or equipment failure).

Endangered (red): The capability is currently either expected to cease functioning, or is currently functioning at a skeletal level that is completely inadequate to national need.

This review has attempted to assess each capability at a national level rather than an institutional level. Institutional capabilities contribute to a national capability, and an assessment of resources required to bring the capability to an adequate level relates to the entire, national capability, not an institutional level. In some cases, institutional capability may be functioning significantly better or worse than the overall national capability. For each area of climate science (observations, understanding, modelling and services), a summary table of the capability is provided, as well as explanatory notes for each capability assessed as less than adequate.

3.1 CLIMATE OBSERVATIONS

3.1.1 Climate observations capability summary

See Table 1 (next page).

3.1.2 Atmospheric chemistry

Compared to the northern hemisphere, the southern hemisphere is very sparsely characterised in terms of its observations of those trace gases that are radiatively active and are important 'climate forcers'—both short and long lived. Measurements are essential to develop and constrain models and to measure impact of mitigation efforts. Australia has been a world leader in greenhouse gas measurement programs in this region, but is currently under-resourced in terms of staff and finances.

More technical staff are needed to operate and maintain increasing numbers of instruments and visit field sites for routine maintenance, and additional science capability is needed to handle increasing volumes of data and to provide a growing demand for top-down emissions verification under the Paris Agreement.

Without these observations, Australia will be flying blind into the 21st century as it will not have the independent evidence to corroborate the effectiveness of emissions mitigation strategies. This could lead to poor public policy development and to considerable mistrust or lack of transparency across geographic regions (cities/states/nations) and industrial sectors.

There is a need to reduce uncertainty in aerosol impact on the climate system, by improving the representation of atmospheric chemistry processes in models including aerosol microphysics and chemical composition and by developing fully coupled Earth system models. Observations are needed to develop and test these new model capabilities including enhanced aerosol observation programs. With the requirements for the 'Global Stocktake' under the Paris

Table 1: Climate observations capability summary

Observations	FTE	Institutions	Additional resources required
Domain: Atmospheric measurements			
Surface temperature, precipitation, wind, etc.	17	BoM AAD AIMS	
Atmospheric chemistry (including ozone and greenhouse gas measurement)	32	Cape Grim / BoM Gaslab / CSIRO ANSTO (Tracers, radon, isotopes) AEROSPAN (aerosols) / CSIRO Universities—Melbourne, Wollongong, others	6 FTE
Domain: Oceanographic measurements			
Ocean hydrography (including carbon)	9	Argo floats, moorings, oceanic carbon, other marine observations / IMOS and CSIRO	3 FTE and $1m p.a. operating expenses
Sea ice measurements	2	AAD	
Domain: Land-based measurements			
Carbon, water fluxes	3	OzFlux /TERN/ CSIRO	4 FTE and $1m p.a. operating expenses
Surface hydrography	6	BoM	
Antarctic ice sheets	3	AAD	
Domain: Historical measurements			
Ice core records	4	ANSTO, AAD Icelab / CSIRO	2 FTE
Early instrumental records	2	BoM	
Other paleo climate records and proxies (including coral and dendroclimatology)	21	ANSTO Universities—other AIMS	

Source: Australian Climate Science Capability Review.

Key: Adequate Vulnerable Endangered

Agreement there will also be a considerable international push to provide top-down constraints on greenhouse gas emissions on a regional scale. This is will require a significant expansion of the observational networks required to produce data sets and capacity in inversion modelling. Although Australia has the seeds of the capability to do this work, increases in resources will be required to meet international requirements. This review recommends an additional staffing of 6 FTE in this area of observations of atmospheric chemistry and aerosols.

3.1.3 Ocean hydrography (including carbon)

Australia is an island in the middle of three vast oceans: the Indian, Pacific, and Southern oceans. The heat stored in these oceans control the seasonal, multi-year and longer term climate of Australia, including the frequency of extreme events. The oceans are where 93% of the additional heat of climate change is to be found. The Southern Ocean takes up more anthropogenic heat and carbon dioxide than any other latitude band of the ocean; changes in the ability of the Southern Ocean to absorb and store heat and carbon dioxide will influence the timing and magnitude of climate change.

There is an increasing trend in the international community to focus on key deficiencies of understanding of ocean processes that have direct and indirect impact on the oceans' role in climate. For example, what controls the ocean uptake of heat, carbon, and other greenhouse gases? Are climate models correctly simulating the vertical and horizontal distribution of these properties? What are the dynamical, biogeochemical and ecosystem exchanges across the open ocean – shelf regions, and how are these likely to change? What is the impact on the coastal marine ecosystem, infrastructure and policy planning? What are the drivers and impacts of expanding oxygen minimum zones? How will the land glacial losses impact global and regional sea level rise?

However, due to funding pressures in Australia over recent years, we have lost the ability to undertake process studies in our oceans from our research vessel. The RV *Investigator* is available for research voyages for 180 days a year, and yet the research community submits around 800 days each year of research for the ship. The assessed high-quality research proposals would more than fill the RV *Investigator* for 300 days per year (its maximum capacity). While only a fraction of these extra ship-days would be for climate-related voyages, this review adds its weight to the call of the National Marine Science Plan (2015) for extra resources to enable the RV *Investigator* to be at sea for 300 days a year. In addition, this review calls for $300,000 p.a. of dedicated funding to enable climate researchers to undertake voyages on the RV *Investigator*.

On-going observing systems (such as Argo) are also under funding pressure. For example Tropical Moored Arrays and enhanced tropical Argo have not been supported by Australia. The data streams from these programs are needed for many purposes, including to initialise climate prediction systems. The difficulty in maintaining the Argo array is partially due to the leveraged nature of research funding in Australia. This means that when there is a reduction in support for these activities in, for example CSIRO or BoM, the reduced effort is amplified by the requirement that IMOS funding be matched. An injection of funding is needed for these on-going observational programs, funding that is untied to matching requirements.

The next decade will see the advent of 'Deep Argo' as a major international program. This will be a critical program for international science as it will allow for the first time the heat budget of the ocean, and hence of the global climate system, to be well-constrained. (The current Argo program accurately constrains the heat budget for the top 2000 m of ocean only.) This will be key information for model evaluation, and has implications for estimating climate sensitivity. Australia has had a major role in the Argo program, but unless extra resources are found, Australia will not play a role in Deep Argo. This review recommends the provision of $700,000 p.a. dedicated to funding observing systems in the ocean (moorings and Argo, including Deep Argo).

This review considers that 3 additional FTE are needed in this area of ocean hydrography (including carbon) as well as an equipment budget of $1 million p.a. ($300,000 + $700,000 p.a.), to reinstate Australia's capacity to fully engage internationally, gaining the benefit of the skillful analysis of all the oceanographic data collected by our international partners, and providing oceanographic initial conditions for multi-year climate modelling activity.

3.1.4 Carbon and water fluxes over land

OzFlux is the Australian observation network providing the observations of energy, carbon and water exchanges between the atmosphere and key Australian ecosystems. OzFlux measurements are designed to:

- understand mechanisms controlling exchanges of carbon, water vapour and energy between terrestrial ecosystems and the atmosphere over a range of time and space scales. This is important in many applications, but specifically to enhance the way these processes are incorporated into climate models
- provide data on carbon and water balances of key ecosystems for model testing
- provide information to validate estimates of net primary productivity, evaporation, and energy absorption using remotely sensed radiance data
- provide data to validate new developments in micrometeorological theory for fluxes and air flows in complex terrain
- provide high precision CO_2 concentrations measurements for use in regional, continental and global atmospheric inverse studies of the carbon cycle (OzFlux, 2016).

These observational activities feed directly into the CABLE model via enabling improvements to algorithms and via constraining the fluxes in CABLE. There are 35 measurement sites, although currently only 24 sites are active. Even these 24 sites are vulnerable to setbacks (e.g. major sensor failure), and staff are currently stretched too thinly to ensure high quality data is collected at active sites. Global climate models need to represent the land–air interactions realistically, and if we in Australia do not do the required research, no one else will do it for us at the level required in this country. Globally the biosphere has been a substantial net sink of carbon dioxide, but it is unclear how long this will continue, and OzFlux measurements are essential in detecting this contribution of Australia to the net global biospheric sink.

This review considers that a minimum increase of 4 FTE is required together with an on-going expenditure of $1 million p.a. in order to provide to observational constraints on Australia's emissions of greenhouse gases and the effectiveness of mitigation strategies.

3.1.5 Ice core records

The collection and analysis of ice cores from Antarctica is an important activity in climate science because it provides the history of Earth's climate over past millennia. The properties of the ice, and the inclusions within the ice, are used to reconstruct a climatic record through isotopic analysis. This enables the reconstruction of local temperature records and the history of atmospheric composition. This is an area of climate science in which the world has looked to Australia's leadership role, given our proximity to Antarctica and our claims to Antarctic territory. In this regard it is heartening that the recently announced 20-year action plan of the Australian Antarctic Division includes the development of a deep-field overland science traverse capability and mobile research station infrastructure including the quest for a million-year-old ice core. This review concludes that there is a need for an additional 2 FTE in the analysis of ice cores.

3.2 CLIMATE UNDERSTANDING

3.2.1 Climate understanding capability summary

See Table 2 (next page).

Table 2: Climate understanding capability summary

Field of study	FTE	Institutions	Additional resources required
Domain of study: Atmospheric processes			
Climate variability, modes of variability (e.g. ENSO) and atmospheric dynamics	37	CSIRO BoM Universities—CoE Universities—other	5 FTE
Climate chemistry	27	CSIRO Universities—other	
Atmosphere processes and feedbacks	8	Universities—CoE	
Radiative forcing	4	BoM Universities—other	4 FTE
Climate change detection and attribution	6	Universities—other AAD (1)	
Antarctic /Southern Ocean regional climatology	4	AAD (2) CSIRO (2)	
Convection processes	5	Universities—other	
Extreme weather events	27	Universities—CoE Universities—other BoM GA	
Greenhouse gas emissions estimation	5	CSIRO	2 FTE
Domain of study: Oceanic processes			
Analysis of sea-level observations	4	CSIRO ACECRC	2 FTE
Southern Ocean processes	12	ACECRC CSIRO	2 FTE
Sea ice processes and change	9	ACECRC AAD	
General oceanic processes and change	16	Universities—CoE CSIRO Universities—other	
Domain of study: Land processes			
Antarctic ice sheet understanding	5	ACECRC	
Surface forcing and feedbacks	20	Universities—CoE BoM	
Boundary layer dynamics / micrometeorology	1	CSIRO	2 FTE
Biogeochemistry	10	Universities—other	
Domain of study: Analysis of climate observations			
Analysis of ice-core records	9	ACECRC AAD Universities—other CSIRO	
Analysis of coral paleoclimate	6	AIMS	
Analysis of isotope / tracer observations	2	ANSTO	
Uncertainties	5	Universities—other	
Integration of historical climate observations	5	Universities—other	

Source: Australian Climate Science Capability Review.

Key: Adequate Vulnerable Endangered

3.2.2 Climate variability and modes of variability

Australia's economy and environment is greatly affected by the El Niño – La Niña oscillation that inflicts droughts and floods on the northern and eastern parts of our country. While we have developed increasing skill in seasonal forecasting, this skill is unable to predict the onset of an El Niño event more than a few months in advance. Our coupled models also display persistent errors in simulating tropical processes, resulting in anomalous features such as the cold tongue in the equatorial Pacific. Other countries are investing in field experiments and other evaluation studies which will give them insight into these poorly-represented processes and how their models are representing them.

Australia has relatively few atmospheric dynamicists who are capable of undertaking this critical work of understanding the physical processes at play on time scales of days to seasons to multi-year time scales. One of the most pressing questions for Australia is whether the El Niño oscillation is expected to become more or less frequent as the climate warms. This is a question of such importance for the nation that it must be addressed on a variety of fronts, using observations, theoretical studies and modelling. This review concludes that extra research effort is needed at the level of 5 FTE in the understanding of climate variability.

3.2.3 Radiative forcing

One of the most uncertain aspects of atmospheric models used in climate forecasting is the way that clouds and aerosols are represented in these models. The radiation balance of the atmosphere is affected by the reflectivity of clouds and aerosols, and the absorption by various greenhouse gases. How will the prevalence and the type of clouds change as the concentrations of greenhouse gases and of aerosols change in the future? As important as radiation and the effects of clouds and aerosols are on climate change projections, Australia has only four staff working in this area. This review finds that this research effort should be doubled, requiring an additional 4 FTE.

3.2.4 Greenhouse gas emissions estimation

Under the Paris Agreement there is a need to provide top-down constraints on greenhouse gas emissions, so that these emissions can be estimated on a regional scale and be checked against the bottom-up estimates of greenhouse gas emissions provided by various nations. This greenhouse gas estimation activity uses the measurements of greenhouse gas concentrations together with atmospheric model output on the transport of the atmosphere to infer the strength of the greenhouse gas sources. This activity is needed to validate estimates of greenhouse gas mitigation activities using farming practices and other carbon sequestration approaches.

In recent years Australia's level of activity in greenhouse gas estimation has decreased, and yet it is clear that this capability will be in greater demand in the future. Accordingly this review recommends an additional 2 FTE in greenhouse gas estimation.

3.2.5 Understanding of oceanic processes

The critical role played by the Southern Ocean in the climate of the southern hemisphere and the planet, together with Australia's proximity to the Southern Ocean, demand that Australia must play a leading role in this area of science. Collaboration between CSIRO and the ACECRC over many years has supported Australia's Southern Ocean expertise, and has also developed a leading capacity in the melting of ice beneath ice shelves in Antarctica.

The largest uncertainty in projections of long-term sea level rise is the response of the ice sheets to warming of the ocean and atmosphere, and this work is under threat due to the term of the ACECRC expiring in 2019. In addition, CSIRO's sea-going activities need increased support to allow the addition of new observational techniques (deep Argo) to elucidate the deep ocean changes that are occurring in our sector of the Southern Ocean.

Australia has played a leading role in the analysis of sea level observations, and the understanding of the causes of the global rise in sea level in the past century. This work at CSIRO has been drastically cut back, and yet the need for this understanding has not diminished, with sea level rise predicted to be one of the most costly economic and social hazards in the future.

This review concludes that it will take an additional 4 FTE to allow Australia to regain its leading position in Southern Ocean and sea level rise research, while the funding cliff that is emerging with the demise of the ACECRC is an even more serious issue that will materialise in 2019. Australia must not relinquish its world-competitive position in understanding the melting of ice shelves in Antarctica and their contribution to sea level rise, as well as the flow of ice sheets in Antarctica.

3.2.6 Micrometeorology

A key part of Australia's ACCESS modelling capability is the land surface model, CABLE, a component of ACCESS that is fully Australian in origin. The advanced nature of CABLE is seen as a major incentive for Australia–UK collaboration by the UK's Met Office Hadley Centre for Climate Change. CABLE was originally built on the understanding of physical turbulent transfers of energy, momentum and carbon between vegetation canopies and the atmosphere, incorporating knowledge gleaned from field measurements, wind tunnel modelling and basic theory. Later development of CABLE added plant physical ecology and carbon cycle science.

Australia's capability in modelling and understanding of boundary and surface layer dynamics has also declined over many years, from the position where Australia was a world leader in both fields to one where we have only residual capability—and this is under real threat. This situation is particularly serious because it impacts directly on Australia's climate modelling capability over a range of space and time scales and on our capacity to observe the terrestrial carbon cycle and the success of attempts to sequester carbon dioxide in the landscape (bio-sequestration) and in geological features (carbon capture and storage). Both of these processes are critical to the Australian Government's strategies to meet commitments made in late 2015 at the Paris meeting of the Conference of the Parties to the Framework Convention on Climate Change.

This capability and expertise in boundary layer and micrometeorology in Australia is about to cease in 2016, and this review considers that this places CABLE in the position of not being able to maintain its world-leading position for land fluxes in the Australian region. For this reason this review argues that 2 FTE be allocated as a matter of urgency to micrometeorology.

3.3 CLIMATE MODELLING

3.3.1 Climate modelling capability summary

See Table 3 (below).

3.3.2 Climate modelling—general

The national climate modelling activity in Australia occurs under the umbrella of ACCESS, the Australian Community Climate and Earth System Simulator. ACCESS aims to provide an Australian world-class modelling capability coordinated across partner institutions that can:

1) project future climate change at global and regional scales
2) interpret observed trends and changes
3) facilitate Australian research in model development such as model parameterisation testing or the impact of improved emissions or land surface data sets
4) provide a well-supported modelling system for efficient use by Australian climate research and climate services communities

Table 3: Climate modelling capability summary

Model / activity	FTE	Institution	Additional resources required
Domain: Integrated climate models			
ACCESS—Development, operations and maintenance	23	CSIRO BoM AAD Universities—CoE	14 FTE
Multiyear prediction	8	CSIRO	
Domain: Land modelling			
CABLE	15	CSIRO Universities—CoE Universities—other	2 FTE
Domain: Atmospheric modelling			
Unified Model	7	BoM Universities—CoE	2 FTE
Dynamical downscaling	4	CSIRO Universities—CoE	3 FTE
Atmospheric chemistry and transport modelling	3	CSIRO	2 FTE
Domain: Oceanic modelling			
MoM, others	10	CSIRO Universities—CoE	3 FTE
Sea ice modelling	3	ACECRC AAD	3 FTE
Reef oceanographic modelling	3	AIMS	
Domain: Integrated assessment models			
Coupled global/national IAM	0	CSIRO	4 FTE

Source: Australian Climate Science Capability Review.

Key: Adequate Vulnerable Endangered

5) provide seamless meteorological forecasts for time scales from days to centuries.

ACCESS includes five components: (1) the Unified Model (UM) atmospheric model and associated model systems; (2) the Modular Ocean Model (MOM) ocean model; (3) the OASIS Coupler; (4) the CICE sea ice model; and (5) the Australian Community Atmosphere Biosphere Land Exchange (CABLE) model for calculating land-atmosphere fluxes. It relies on world-class computational and storage facilities, Earth Systems Grid (ESG) etc.

Australia possesses the only world-class climate modelling capability in the southern hemisphere. Understanding of Southern hemisphere climate processes is essential for Australia, while for northern hemisphere mid-latitude groups it is of secondary priority. Globally, the ACCESS model contributions to the Coupled Model Intercomparison Project Phase 5 (CMIP5) perform strongly across a range of evaluation measures in comparison to other CMIP5 models in international model evaluations. Regionally, the ACCESS model has been rated overall best of all CMIP5 models across a range of evaluation metrics for Australian climate. The Australian-built CABLE model for calculating land–atmosphere transfers is crucial for the accuracy of the combined ACCESS model, since the Australian landscape is quite different to those of northern hemisphere continents.

Aerosol and atmospheric chemistry changes are important for determining global and regional climate change outcomes. Anthropogenic aerosols are currently understood to be offsetting about a third of the warming resulting from increased greenhouse gas concentrations globally. Given that there has already been about 1 °C of surface warming globally since pre-industrial times, the future concentration of aerosols becomes critical in the ability to meet the ambitious warming targets of the Paris Agreement.

ACCESS is an Australian community effort involving several Australian institutions and with deep international collaboration. The immediate impetus for this collaboration is that the complexity and scope of climate and Earth system modelling is expanding substantially, in terms of:

- the sophistication of the physical parameterisations
- the range of climate forcing agents to be simulated
- the inclusion of the full carbon cycle and atmospheric chemistry
- increased model resolution.

World-class climate modelling of such a scale is beyond the capability of any individual institution and requires a coordinated national approach. Future climate models will require significant increases in supercomputing power and mass storage capabilities. There is currently no detailed strategy on how Australia can best address this major challenge. The supercomputing facility at NCI is approaching its end-of-life stage and although a case is being made for a significant upgrade there is uncertainty on how funding will be sourced. In contrast, international agencies have well-developed plans based on availability of extremely fast (exascale) supercomputers by the mid-2020s.

A major resource that is lacking from now onwards is experienced staff. This is a result of staff reductions associated with the ending of the ACCSP, and the increasing complexity of climate modelling as a field of science as described. The total staff FTE expected to be applied to climate modelling (CSIRO and BoM) in 2016–17 is approximately 60% of that during 2009–12. This has impacted Australia's ability to:

1) process and quality control large volume model output data for distribution to the broader research community
2) enhance model systems to make the model itself readily accessible by the broader research community
3) couple model components together, including validation, to ensure that key Australian components, such as the CABLE land surface model, remain part of the coupled system
4) develop the sea ice component of the model
5) develop related regional climate modelling capability, in particular to take advantage of a new Met Office initiative in convective-scale regional climate modelling
6) further develop the ACCESS global atmospheric chemistry model. For example, there are persistent biases in the mean state of the ACCESS model over Australia and these biases are affecting our ability to improve both weather and climate forecasts. The atmospheric component of ACCESS, the Unified Model which was developed in UK and performs well in that region, but to date, Australia does not have the person-power and has not devoted the resources to understand and correct the biases in this model in our region.

The original ACCESS project plan in 2005 specified an ongoing staffing need of about 78 FTE. During 2009–12, Australia had about 32 FTE (CSIRO and BoM) working on ACCESS climate model development and CABLE application, and Australia was fortunately able to achieve a world-class coupled model for contribution to IPCC AR5. Australia's current commitment to ACCESS climate model development and CABLE application is about 21 FTE which is far below the 2005 ACCESS project plan's 78 FTE. The present ACCESS capability provides a base on which to expand, but the commitment to climate modelling is well below the levels required to ensure that our climate projections attain world-class standard. There are shortages of expertise in modelling (numerics, physics, evaluation, data assimilation); understanding key drivers of climate in the Australian region; and supercomputing (CPU, storage and, increasingly, software engineering). The shortages in the area of computer scientists and software engineers has become particularly acute in the past few years as the complexity and the size of climate models has continue to increase (of the extra 14 FTE earmarked for ACCESS in Table 3, 6 are computer scientists). These shortages are impacting on the quality of information that can be provided, with the risk that the output of ACCESS in the near future will be inferior to the projections provided by overseas institutions. This would represent a significant economic burden on the community as it would need to adapt to climate change using forecasts that are nowhere near as accurate or reliable as they could and should be.

One area where Australia is currently lacking adequate scientific capacity is the modelling of the Antarctic ice sheet response to warming conditions. The Antarctic ice sheet response is fundamental to long term sea level rise projections, but currently there is not the Australian ice sheet modelling capacity to take advantage of the significant relevant Australian Antarctic observational programs. It is critical that the ACECRC is funded beyond its funding cliff in 2019, and that the research effort of the ARC Gateway Special Research Initiative be continued beyond 2018.

There is also the likelihood that conditions on a decadal scale will be heavily influenced, or dominated by, decadal variability, as has been the case in the past. Such dominance could be at global scale, e.g. another perceived 'hiatus' in warming following the recent large El Niño, or an 'accelerated warming' period due to a positive phase in the Pacific decadal variability, or it could be evident more locally in terms of pronounced multi-year variability in rainfall and water availability. Australia currently lacks capacity for multi-year prediction, even though the topic is of immense economic and social interest to many stakeholders. Several northern hemisphere countries are investing in multi-year prediction systems, and Australia needs to begin this activity with commitment or it will be unable to provide policy-relevant forecasts to the community. This area of multi-year forecasts is technically very difficult, and as a research activity it is not guaranteed success. However the potential benefits are too great for Australia to ignore this new research direction. Skills at predicting the phases of ENSO and of the Interdecadal Pacific Oscillation will improve multi-year climate forecast capacity to allow warnings of an impending 'hiatus' in global warming, or its opposite, namely a period of 'accelerated warming' such as we have experienced in the past three years. Australia's climate is strongly affected by ENSO, and it is appropriate that we devote significant research activity to understanding these processes and to providing skilful forecasts on the multi-year time scale at a refined regional scale. For these reasons CSIRO's announcement in mid-2016 regarding the addition of 15 FTE staff to produce a prototype decadal prediction model is very welcome. While these staff are still being recruited at the time of writing this review, these new staff have been included in the tables of this review.

The effects of climate change often impact most strongly through changes in extremes. In the Australian context over the next 20 years, the likelihood is for increased severity of heat waves, and, potentially, drought and flood, with resulting impacts on vulnerable terrestrial ecosystems and services. Earth system modelling allows the ability to both project potential changes in extremes over the next several decades, and to predict extremes on short time scales of days to weeks (improved short term prediction being a significant contribution to an overall adaptation strategy). Critical to the simulation of extremes, in particular heat waves, is the quality of the land surface and boundary layer component, CABLE. Dynamical downscaling uses high-resolution atmospheric models that better resolve the surface topography and convective processes, and enable climate change forecasts at regional scales.

The Green Climate Fund was set up by the Framework Convention on Climate Change to support mitigation and adaptation in developing nations given a 2 °C target, with pledges to the fund being doubled at COP21 to $20 billion over the next five years. Australia should use ACCESS and CABLE to provide scientific support to other countries in our region to address such issues.

Australia's current high-performance computing capability is close to sufficient for the science questions that Australia is pursuing at present. But this review considers that we need to move to higher resolution climate models which requires much greater computing power and data storage facilities; and we need to address the community needs for decadal climate prediction at the regional scale. These multi-year, fine scale climate predictions are not currently possible. The delivery of such a capability is a very challenging research task, but the economic pay-offs for cost-effective adaption are so great that this review is convinced that this is the right time to tackle this challenge. The provision of this decadal prediction capability also requires a substantial increase in supercomputing resources. Note that this review has not canvassed in detail the magnitude of the increases in computing infrastructure that is required.

Climate science requires the use of multiple models to assess the range of future projections of climate change. There is a quadrennial set of globally coordinated model experiments to compare the output of different climate models. Australia participates in this Coupled Model Intercomparison Project (CMIP) through contributing experiments with ACCESS and analysing output from the CMIP database. For CMIP5, output from this large dataset was hosted at the National Computational Infrastructure. There is an urgent need to provide for the hosting of CMIP6 data, commencing in 2017.

This review has examined the various aspects of climate modelling and concludes that it should be regarded as a national resource, similar to the research vessel RV *Investigator* being a national facility. Resources currently devoted to ACCESS fall far short of placing Australia's modelling capabilities in a leading position. Australia is a large continent in an under-modelled hemisphere, while its climate modelling effort is only a small fraction of that deployed in the USA or in Europe.

Integrated Assessment Modelling explores the interactions between the physical climate model, an economic model, a demographic model and models of land use changes and carbon fluxes. These techniques model the real-world interactions between the results of government policy on the climate, and demographic and refugee implications for Australia. Calculations of the costs of damages to the economy by climate change or of the costs of mitigating it—for example by limiting emissions through carbon pricing—was initially the domain of economic modellers. Earlier versions of Australia's Global Integrated Assessment Model (GIAM) have been able to model the costs of mitigation, with the benefits of damage averted, in a dynamic way. As a result, it was immediately used in the 2008 Garnaut Climate Change Review and a later version of was used in Professor Garnaut's 2011 follow-up review.

This review finds that an additional 33 FTE staff are needed in this area of climate modelling.

3.4 CLIMATE SERVICES

3.4.1 Climate services capability summary

See Table 4 (below).

3.4.2 Climate projections, products and services

The climate predictions arising from climate research activities need to be processed in a variety of ways to address the issues of concern for different stakeholders. Typically this involves using the simulations from many global climate models, incorporating peer-reviewed and transparent methods to identify those models with the highest skill; and credible methods to provide more regionally-specific information. The next-users of climate modelling output involve researchers or consultants who work closely with the climate modelling groups. These next-users provide climate information useful to end users. End users are decision-makers who use climate science and other information to generate outcomes and impacts, such as changes in behaviour, policy and investment. Frequently there are researchers who are expert in a certain industry and environmental sector, and who work with both next-users and end users to interpret and tailor packaged climate change projections into the most useful form. For example, the Climate Risk and Resilience Group at CSIRO Land and Water use the information produced by climate services specialists to link climate information with real-world application in areas such as primary production, insurance, commerce and emergency services. Another example is the use of information produced by climate services specialists to examine impacts on human health, including expected changes in the prevalence of mosquito-borne diseases.

The capacity in climate projections, products and services has undergone a major reduction with the completion of the program of research to support regional natural resource management (NRM). This program supported CSIRO, BoM and universities to work with NRM bodies in innovative new partnerships to provide regional-level climate projections and information to aid decision making. Further investment in regional partnerships would make relevant information available to local industry, local government and community groups to support improved understanding of climate change and decision making at local levels.

This review has canvassed several groups of next-users, but did not have the time and resources to gather input from the wide range of organisations in the end user community for this climate information. The review has formed a view on the under-resourcing of this next-user type of climate services activity in Australia, but it is likely that the unmet need in climate services is larger than was able to be determined.

In Australia and across the Asia–Pacific region there is growing demand for regional climate projections, information, products and services. For example, between 1 January 2015 and 22 July 2016, the Climate Change in Australia website, based on CMIP projections assessed jointly by BoM and CSIRO, had almost 160,000 unique users, and in the same period CSIRO handled 124 help desk requests. In contrast to this increasing demand for climate information, there has been a marked decline in staff, particularly in CSIRO in recent years. The review considers

Table 4: Climate services capability summary

Activity	FTE	Institution	Additional resources required
Domain of activity: Oceanic			
Sea level, waves and coastal extremes	5	CSIRO	3 FTE
Domain of activity: Atmospheric			
Climate projections, products and services	18	CSIRO BoM Universities—CoE	9 FTE

Source: Australian Climate Science Capability Review.

Key: Adequate Vulnerable Endangered

that current Australian capability in this area is insufficient, and there is a pressing need to improve projections of extreme weather events to meet the demand for adaptation planning and disaster risk management. As a nation we are missing an opportunity to deliver more impact and to help Australian industry and communities adapt to climate change.

This review recommends an additional 12 FTE in climate services.

4 A VISION FOR AUSTRALIA'S CLIMATE SCIENCE FUTURE

Every business and every community activity in Australia is and will be affected by climate variability and change. Climate variability and change affect, for example, our primary industries, coastal infrastructure, water infrastructure, generation and delivery of energy, transport systems and planning systems and building codes. They also influence the movement of people deeply affected by rising seas, extreme storms and droughts. Given the pervasive nature of these changes, that these changes are occurring over the relatively short time scale of a human generation, and that these changes are affecting virtually every aspect of our economy, this review has found that Australia's climate research capability needs to be significantly larger than it is at present.

Australia needs climate science to inform an effective national response to the challenges of a variable and changing climate. To respond effectively, Australians need to know: How much and how fast will climate change in the future? How can we slow the rate of climate change? How can we effectively adapt to changes we can't avoid? How can we exploit the opportunities and minimise the risks from climate variations next season, next year, next decade, or next century? To answer these questions, Australia needs a climate science capability that:

- ranges from fundamental understanding to delivery of relevant products to decision-makers
- integrates observations and modelling
- spans timescales from weather to climate change
- spans disciplines (atmosphere, ocean, land, cryosphere, biosphere)
- is a global leader in processes affecting the Australian region
- is well-integrated with, and provides for the needs of, climate knowledge users.

Over the next decade or two, there will be a growing emphasis on delivery of climate services: climate knowledge targeted to decision-makers in government, industry and the community. To be relevant, this information must relate to the time and space scales of the decisions being made. A resilient, healthy, productive and prepared Australia requires the development and delivery of operational climate services, that is, climate information prepared, interpreted and delivered to meet society's needs. This is as important to Australia, and the region, as national security considerations. As such, the provision of climate services and the underpinning climate science needs to be resilient to the consequences of any market failure in the delivery of public-good, science-based climate information to end users.

Decisions made (or not made) in the next 10 to 20 years will commit us to irreversible changes. At present rates, we will consume the carbon budget that allows us to stay below 2 °C of global warming in just two decades. Recent studies suggest crossing this threshold will lead to irreversible loss of mass from the ice sheets equivalent to metres of sea level rise in the next two centuries.

The COP21 agreement spells out that signatories will increase their investment in critical climate science, however Australia has recently been moving in the opposite direction. The COP21 agreement also commits signatories to provide climate science needed by less-developed countries to respond effectively to climate change. Australia has made important contributions in this area in the past (e.g. the PCCSP and PACCSAP programs).

Australia should invest in climate science with a positive and exciting vision of the role of climate research and climate services in its economy. We need a vision where we settle for nothing less than world-leading science in our observations, understanding and modelling of future climate change and the application of this knowledge to ensure the future prosperity and well-being of Australia and our southern hemisphere neighbours. As the leading developed nation in the southern hemisphere, and as a nation that is heavily impacted by the El Niño phenomenon, we should adopt the climate science vision that Australia will be the recognised authority for climate information for all countries in our region.

5 CHALLENGES AND SOLUTIONS FOR AUSTRALIAN CLIMATE SCIENCE

The main challenges for climate science capability in Australia relate to the coordination and resourcing of climate science, current capability gaps, and future planning and strategy.

5.1 COORDINATION AND RESOURCING

Coordination and leadership of climate science in Australia has been provided principally by collaboration between the two dominant organisations in the field: the BoM and CSIRO. This review has found, however, that coordination and resource arrangements have not kept up with the changing situation in climate science. The downsizing of CSIRO's climate capability has led to considerable disruption in the collaboration. Additionally, universities are playing an ever-increasing role in climate science, particularly in climate understanding, climate modelling and climate adaptation.

The decision by CSIRO in February 2016 to significantly reprioritise its climate research was unexpected among the climate science and broader community. It did not seem possible to arrange for orderly transitions of capabilities in climate science, as changes were likely to happen too quickly. CSIRO's shock announcement regarding climate research funding reflects more generally on the difficulty in funding public good research in Australia in recent years. Such public good research is often very cost effective in terms of the economic costs averted using knowledge generated, but by its very nature the costs of this type of research cannot be captured through a user-pays system and so is a classic 'public good' of economic textbooks. CSIRO's later decisions to not carry out its original plan in full has meant that there has been more time for reflection and for the sector to reorganise itself to a certain extent, albeit in an ad-hoc fashion.

Additionally, this review has found that the financing arrangements for climate science outlined in section 2.4.3 are overly complex. The current regime seems to impose an unnecessarily large administrative burden on operational scientists to secure, coordinate and report on resourcing from many different sources, which is an inefficient use of limited scientific resources. While proper accountability of public moneys is of course very important, there is definitely scope to streamline arrangements for funding climate science, particularly when the vast majority of resourcing is originally drawn from one source.

It is clear that a new coordinating mechanism is needed that can take into account the strategic development of climate science capability, the national need for weather and climate services, the relationships between climate science and other parts of environmental science and Australia's response to climate change. Aligning coordination with streamlined funding arrangements also presents an opportunity to maximise the value of the climate science investment, ensuring that directed resourcing is able to directly fund capabilities.

The next section will propose a number of possible models for coordinating climate science activities in Australia. Although this review deals with the physical science components of climate science and climate change research, it would be necessary for any solution to include all aspects of climate science and climate change research in Australia to ensure a holistic coordination of the science and research needs for Australia's response to climate change.

Any proposed mechanism for coordination and resourcing should have the following attributes:

- **National focus, mission-driven**: The mechanism should have an explicit aim or objective of ensuring the provision of climate science related to the national interest and assessing needs and capabilities.
- **Strategic outlook**: The mechanism should have a level of autonomy to allow a strategic focus on delivering nationally relevant climate science, with the capacity to take scientific and stakeholder advice.
- **Continuity of function**: The mechanism should have some degree of security to allow for longer-term planning, as climate science is a long-term, national need.

- **Effective coordinator**: The mechanism should have a practical, effective avenue to coordinate climate science and research and to encourage collaboration across the climate science effort. In a practical sense, this generally amounts to control of resources.
- **End user engagement**: The mechanism should have government, industry and community end user engagement and representation in the coordination, design and implementation of relevant areas of the research.

These elements will allow for a coordination mechanism that has the confidence of the climate science community, and has the best chance of maximising the value of climate science investments. These elements imply that no one organisation should be regarded as independent of the others in the delivery of a coordinated response to the national need for climate science.

Here we list five possible options for coordination and funding of climate science in Australia. These options differ in their diversity (the number of bodies doing the research) as well as in their governance. This review does not advocate any specific option.

5.1.1 Possible models for coordination and resourcing of climate science

Option 1: A new Office of Climate Research

A new (possibly small) office is created, associated with but outside the Department of Environment and Energy, that would:

1) assess Australia's needs for climate science and research, reflect government priorities, and assess the level of capability to meet those needs
2) ensure the provision of necessary climate science, research and services through administration of a streamlined system of directed resourcing, and commissioning research activities where necessary
3) plan for development of climate science and research capabilities and infrastructure, in consultation with the climate science and research community.

Coordination would be achieved by the climate science and research community working with the office, which would act as a broker between the climate research sector and governments and other stakeholders.

Option 2: Transferring responsibility to the Bureau of Meteorology

The Bureau of Meteorology is made responsible for all weather and climate research in Australia, and resources are directed into BoM to enable this course of action. This has a number of attractive features—having all weather and climate science together would simplify coordination, and potentially remove resourcing inefficiencies. Additionally, BoM's focus on information and service delivery and its strong stakeholder relationships would allow for climate information and products to be rapidly disseminated to end users and the public. BoM would have the ability to contract out parts of the research and development effort where appropriate.

However, although BoM has had a successful research and development program, it is not clear it has appropriate organisational structure to manage the entire climate research effort. Also, parts of the climate science effort are much more multidisciplinary than BoM's core activities, and it does not currently enjoy the same level of autonomy to set its own research agenda as the non-APS PFRAs.

Option 3: Transferring responsibility to CSIRO

Responsibility for maintaining climate science capacity is vested specifically within CSIRO. CSIRO is resourced to provide infrastructure and support for Australian climate science as a national resource. CSIRO would work with other research facilities and groups in collaborative research programs under a long-term strategic plan developed by the CSIRO board. This mechanism would capitalise on CSIRO's current expertise and long experience in the field of climate science, and leverage existing infrastructure.

CSIRO has the autonomy and capacity to coordinate and direct such a research effort. However, resources provided to CSIRO for this purpose would need to be quarantined as being for this purpose only, through a Ministerial determination under s9 (1) (a) (iv) of the *Science and Industry Research Act 1949*, or similarly binding mechanism.

Option 4: A new Climate Research Centre

A new, multi-node, non-government national climate research centre is established, taking under its umbrella existing capability in the research agencies and universities. The practical effect would be along the lines of combining the NESP ESCC hub, the ACECRC, the Centre of Excellence, the CSIRO climate centre and parts of the collaborative research infrastructure, and forming strong links with BoM.

The centre would have as its remit to coordinate, commission and conduct climate research in Australia, and have control of a significant portion of the national climate research investment to effect coordination and collaboration. It would have a significant critical mass, and would be highly mission-driven and could effectively plan for the development of climate science and research capability. It would also have the ability to form strong links with other parts of the climate and environmental research effort. However, it would be somewhat further from government than the new Office of Climate Research model, and its planning may place less emphasis on national needs compared to other models.

A new Climate Research Agency

Under this mechanism, a new PFRA for climate research would be established, similar to the Australian Institute for Marine

Science. The agency would have the remit to coordinate, commission and conduct climate research in Australia, and have control of a significant portion of the national climate research investment to effect coordination and collaboration. It would further have responsibility for being the principal advisor to government on climate science, and would be responsive to government and community needs through a Statement of Expectations.

As a semi-autonomous PFRA, the agency would have the ability to plan strategically to develop the climate science capacity in Australia and to coordinate effort among the various players in the sector. A new PFRA would have strong continuity of function once established, but centralisation of resources and expertise may lead to a lack of sources for contestable expertise and advice to inform policy.

5.2 FILLING CURRENT CAPABILITY GAPS

Whatever the future method of coordination and resourcing, there is currently a significant number of capability gaps that the review has identified. Most pressingly, these relate to the ongoing development of general climate modelling capability in Australia, certain areas of climate understanding (micrometeorology and boundary layer dynamics), and the development of models that take into account complex interactions between humans and climate. This review has also identified a significant number of areas that are currently at risk in each of the areas examined (climate observations, understanding, modelling and services).

These capability gaps must be filled to maintain an adequate national climate science capability. If these gaps are not filled, the effects will not be immediately catastrophic, but Australia will increasingly be less and less able to have a sufficient level of information to make informed decisions that involve an element relating to climate, including access to information from other nations. Similarly, without a commitment to filling capability gaps, orderly succession planning becomes impossible, and it may not be possible to acquire expertise when it is most needed.

The review has recommended that to bring Australia to an adequate level of climate capability, an additional 77 FTE staff (approximately), along with their operating expenses, are required. Additionally, approximately $2 million per annum in cash is required to bring the marine and terrestrial observational networks up to standard.

The review makes no comments about which institution should house these new staff—it is likely they would need to be spread across research agencies and universities and this would best be determined by the sector as a whole, through a coordination body.

It is likely that this additional investment would need to be staged so as not to grow the climate science effort too quickly—staging additional investment would allow for time to select the most appropriate and best quality expertise.

5.2.1 Future arrangements for the ACECRC

The ACECRC is currently funded until 2019. In line with new policy that CRCs must be industry led, it is unlikely that the ACECRC will be able to access funding under the CRC program in future. However, the ACECRC houses a considerable store of expertise, and its capabilities are relied on to help execute Australia's Antarctic strategy.

The capability that is currently resident within the ACECRC, including the ARC Gateway Special Research Initiative, will need to be retained in some form, so consideration must be given to the most appropriate way to house that expertise if the CRC is not to continue in its current form.

5.2.2 Workforce succession planning

Although current capability gaps are likely to be able to be filled relatively easily, some consideration needs to be given by a planning exercise into workforce planning, and particularly how current expertise resident in senior staff will be transferred to junior staff in an orderly way. Consideration will need to be given to retaining more junior climate scientists in Australia so that there is a sufficient pipeline of expertise able to maintain capability in the long term.

5.3 STRATEGY AND IMPLEMENTATION

A last challenge that faces climate science capability is the lack of an overall active strategy. Although documents do exist that plan for the future of climate change science, their implementation has ceased. Policy signals from government have been mixed, and little strategic planning has taken place. Although this review has largely canvased the short-term future, it is essential to implement a new or renewed strategy to ensure that actors in the climate science community can appropriately develop their own plans for the future.

6 CONCLUSIONS

The two main conclusions of this review of Australia's climate Science Capability are that:

1) Implementation of an enduring arrangement for the coordination, facilitation and assessment of climate science and research in Australia, with capacity to assess Australian climate research needs and commission and coordinate research as appropriate. Such a coordinating mechanism should enable the clear identification of those responsible for ensuring the on-going provision of climate research and climate services, and should enable a more streamlined approach to the funding of climate research capabilities.

2) Climate science activity in Australia is carried out by approximately 420 full-time equivalent research staff. Approximately an additional 77 FTE staff, along with their operating expenses, are needed to provide the nation with adequate capacity to improve understanding and provide advice on strategies for cost-effective mitigation and adaptation to climate change, and to enable Australia to provide regional leadership in aspects of climate science for which Australia bears natural responsibility due to our location on the planet. These extra positions should be filled progressively over the next four years.

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APPENDIX A
LIST OF SUBMISSIONS RECEIVED

INDIVIDUAL SUBMISSIONS

The review is grateful to the following individuals that made submissions in their private capacities:

- Dr Kathy Allen
- Dr Patrick Baker
- Dr Nathan Bindoff
- Dr Roger Bodman
- Dr John Bye
- Dr Jill Cainey
- Dr John Church
- Dr James Cleverly
- Dist. Prof. Noel Cressie
- Dr Stephanie Downes
- Prof. John Finnigan
- Dr Christopher Fogwill
- Dr Pauline Grierson
- Dr Michael Grose
- Dr Liz Hanna
- Dr Bruce Harper
- Prof. Henk Heijins
- Dr Kevin Hennessy
- Dr Tony Hirst
- Dr Andrew Hogg
- Dr John Hunter
- Prof. Christian Jakob
- Dr Bill Johnston
- Prof. David Karoly
- Dr Melita Keywood
- Dr Paul Krummel
- Dr Clothilde Langlais
- Dr Rachel Law
- Prof. Mike Manton
- Dr Simon Marsland
- Dr Richard Matear
- Dr Peter May
- Dr Helen McGregor
- Dr John McGregor
- Dr Shayne McGregor
- Dr Peter McIntosh
- Dr Ross Mitchell
- Dr Jo Mummery
- Dr Clare Murphy
- Prof. Brian O'Brien
- Prof. Jean Palutikoff
- Dr Helen Phillips
- Prof. Andy Pitman
- Mr Neil Plummer
- Dr Kamal Puri
- Prof. Peter Rayner
- Dr Stephen Rintoul
- Dr James Risbey
- Dr Krystyna Saunders
- Dr Bernadette Sloyan
- Dr Neville Smith
- Dr Milton Speer
- Dr Andrea Taschetto
- Dr Pauline Treble
- Dr Blair Trewin
- Prof. Chris Turney
- Ms Mary Voice
- Assoc. Prof. Seth Westra
- Dr Matt Wheeler
- Dr Susan Wijffels
- Dr Alastair Williams
- Dr Matthew Woodhouse
- Prof. Colin Woodroffe
- Prof. John Zillman

An additional seven submissions were received from parties who wished to keep their submissions confidential.

ORGANISATIONAL SUBMISSIONS

The review is grateful for the assistance of the following organisations in preparing submissions:

- Antarctic Climate and Ecosystems CRC
- ARC Centre of Excellence for Climate System Science
- Australian Antarctic Division
- Australian Institute of Marine Science
- Australian Nuclear Science and Technology Organisation (ANSTO)
- Australian Water and Energy Exchanges (OzeWEX)
- Bureau of Meteorology
- CSIRO
- Geoscience Australia
- Great Barrier Reef Marine Park Authority
- Integrated Marine Observing System (IMOS)
- School of Ecosystem and Forest Science, University of Melbourne
- South-East Councils Climate Change Alliance Inc. (SECCA)
- Terrestrial Ecosystem Research Network (TERN)

COMMITTEE MEMBER BIOGRAPHIES

Professor Trevor McDougall FAA FRS (chair)

Trevor McDougall is Scientia Professor at the University of New South Wales, whose research interests revolve around physical oceanography and the modelling of oceanic mixing. He is also Vice-President of the International Association for the Physical Sciences of the Oceans. His career has included long periods at the Australian National University and CSIRO, with extensive experience working in the United Kingdom, the United States and Germany.

Associate Professor Julie Arblaster

Julie Arblaster is a researcher at the School of Earth, Atmosphere and Environment at Monash University. Her research interests include climate extremes and decadal variability, and she has extensive experience from the United States' National Center for Atmospheric Research and more than a decade working at the Bureau of Meteorology.

Dr Helen Cleugh

Helen Cleugh works at CSIRO as the Leader of the Earth Systems and Climate Change Hub of the National Environmental Science Program. Helen has worked as an atmospheric scientist for three decades and has an encyclopaedic knowledge of the climate research effort in Australia.

Professor David Griggs FTSE

David Griggs is Professor and the immediate-past Director of the Monash Sustainability Institute at Monash University. As well as being a highly respected climate scientist, he has an extensive history of working with internationally renowned climate science institutions, including as Deputy Chief Scientist at the UK's Met Office and as Head of the Intergovernmental Panel on Climate Change's Working Group I Technical Support Unit.

Professor Rod Keenan

Rod Keenan is Professor at the School of Ecosystem and Forest Science at the University of Melbourne. His research expertise includes forest ecosystem services, forests and climate change and environmental policy. He was director of the Victorian Centre for Climate Change Adaptation Research between 2009 and 2014, and has extensive knowledge of the end-uses of climate science.

Emeritus Professor Neville Nicholls FAA

Neville Nicholls is an Emeritus Professor at the School of Earth, Atmosphere and Environment at Monash University, having moved there after 35 years at the Bureau of Meteorology. He has more than four decades' experience in climate and weather research in Australia and extensive experience in the conduct of climate research in Australia's publicly funded research agencies.

Dr Graeme Pearman AM FAA FTSE

Graeme Pearman is a private consultant and holds an Adjunct Senior Research Fellowship at Monash University. Originally a plant physiologist, Graeme headed atmospheric research at CSIRO between 1985 and 2004. He is considered by many to be the father of climate change research in Australia and has written more than 150 papers on the subject.