Mapping Australia's international climate science engagement

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Acronyms and abbreviations

AAD	Australian Antarctic Division
ACCESS	Australian Community Climate and Earth System Simulator
ACCSP	Australian Climate Change Science Program
ACE CRC	Antarctic Climate and Ecosystems Cooperative Research Centre
ADF	Australian Defence Force
AGAGE	Advanced Global Atmospheric Gases Experiment
AIMS	Australian Institute of Marine Science
ANDS	Australian National Data Service
ANSTO	Australian Nuclear Science and Technology Organisation
ARCCSS	ARC Centre of Excellence for Climate System Science
AusCOM	Australian Climate Ocean Model
BOM	Bureau of Meteorology
CABLE	Community Atmosphere Biosphere Land Exchange (model)
CAWCR	Collaboration for Australian Weather and Climate Research
CCAM	Cubic Conformal Atmospheric Model
CEOS	Committee on Earth Observation Satellites
CICE	Los Alamos sea ice model
CLEX	ARC Centre of Excellence for Climate Extremes
CMIP	Coupled Model Intercomparison Project
CNES	Centre National d'Études Spatiales (National Centre for Space Studies, France)
CSHOR	Centre for Southern Hemisphere Oceans Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DSPC	(WMO) Data Collection or Production Centres
ENSO	El Niño – Southern Oscillation
ESCCH	Earth Systems and Climate Change Hub
ESFG	Earth System Federation Grid
ESM	Earth System Model
GA	Geoscience Australia
GAW	Global Atmosphere Watch
GASLAB	Global Atmospheric Sampling Laboratory
GCOS	Global Climate Observing System
GEO	Group of Earth Observations
GOOS	Global Ocean Observing System
GOS	Global Observing System
ICELAB	Ice Core Extraction Laboratory
IGBP	International Geosphere-Biosphere Programme
IMOS	Integrated Marine Observing System
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
JMA	Japan Meteorological Agency
LAPAN	Lembaga Penerbangan Dan Antariksa Nasional (Indonesian National Institute of Aeronautics and Space)
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (Spatial Geophysics and Oceanography Studies Laboratory, France)
MOM	Modular Ocean Model
NASA	National Aeronautics and Space Administration (US)

NCAR	National Centre for Atmospheric Research (US)
NCI	National Computational Infrastructure
NCRIS	National Collaborative Research Infrastructure Strategy
NCSAC	National Climate Science Advisory Committee
NeCTAR	National eResearch Collaboration Tools and Resources Project
NESP	National Environmental Science Program
NIWA	National Institute of Water and Atmosphere Research (NZ)
NOAA	National Oceanic and Atmosphere Administration (US)
OSTST	Ocean Surface Topography Science Team
PAGASA	Philippine Atmospheric, Geophysical and Astronomical Services Administration
RDS	Research Data Services
SCOR	Scientific Committee for Ocean Research
TERN	Terrestrial Ecosystem Research Network
TCCON	Total Carbon Column Observing Network
UM	Unified Model
WCRP	World Climate Research Programme
WIS	WMO Information System
WMO	World Meteorological Organisation
WOMBAT	World Ocean Model of Biogeochemistry and Trophic-dynamics

Note: Please also see list accompanying Figure 4.

Key findings

1. Australia is a significant net importer of climate science knowledge and information
2. The geographical scope of Australia, its territories (particularly the Australian Antarctic Territory) and its extended economic zone represent a large area of responsibility; the sphere of Australia's climate science operations is the largest in the southern hemisphere.
3. Australia's ability to access and deliver benefit to national and regional users from climate science knowledge and information is based on:
    a. our strong domestic climate science capability and international reputation for excellence
    b. national and institutional involvement in collaborative research projects and in bi-lateral and multi-lateral climate programs
    c. strong representation of Australian scientists in membership and leadership roles of international climate projects and programs
    d. the significant internationalisation of Australia's climate science workforce (both international employees and Australian scientists who have trained oversees).
4. Australia has opportunities to **significantly extend and enhance the direct and strategic benefits to Australian and regional users of climate information from involvement in global climate science**. Opportunities include:
    a. leveraging international investment and capability to address domestic information needs and science priorities through enhanced involvement in EU Horizon 2020 climate research programs, the Copernicus program, new satellite missions, the World Climate Research Programme, the expansion of Argo and other observational and modelling projects
    b. enhancing provision of climate services in Australia and in the region—particularly the South Pacific—and initiating or joining regional research programs with funding from the World Bank and the Green Climate Fund
    c. ensuring a continued international research focus on southern hemisphere priorities such as El Niño, Antarctica and the Southern Ocean, and the Great Barrier Reef, by ensuring continued research activities and stewardship of and access to Australian data collections
    d. capitalising on Australia's reputation for scientific excellence and its appeal as a destination for work and study to attract world-class climate scientists and students.
5. To realise these benefits for Australia, **a number of risks must be managed or mitigated**. Risks include:
    a. reduced domestic climate science capability in priority areas
    b. reduced specialist and technical support for climate scientists, affecting development of Australian climate models that inform international programs, and for analysis of Australian regional models in overseas developed models.
    c. reduced or lapsed financial membership of international programs such as the World Climate Research Programme.
    d. lack of ongoing funding support for maintenance and development of national climate observation and monitoring infrastructure, including the Integrated Marine Observing System (IMOS), and for the operation of blue-water research vessels, the RV *Investigator*, and Antarctic research icebreaker RV *Aurora Australis* and its replacement the RV *Nuyina*.
    e. loss of representation of Australian scientists in general and leadership roles in international climate science and committees, given geographical challenges.

Executive summary

Australia plays a key role in the international effort to understand climate variability and change. The human expertise, knowledge base and research infrastructure Australia has built up over decades is the most significant climate science capability in the southern hemisphere, and Australian climate scientists have been well represented on international climate committees and organisations. Australian climate models and observation infrastructure have an international reputation for quality, and their products are utilised by climate authorities and end users in Australia and abroad.

This significant international role, enabled by our strong domestic climate science capability, allows Australia to leverage and benefit from an extensive network of international climate research infrastructure and bilateral and multilateral climate research programs. These benefits include access to satellite observation systems, highly sophisticated climate model components, collaborative research programs on issues of priority to Australia and the region, the opportunity to influence the investment of international research capabilities, and extensive international training and mobility of our climate science workforce.

Climate science is highly international. Scientific analysis of the global climate system requires a worldwide network of observations, which feed into models that are used to understand climate processes and their impacts. The challenge of improving understanding, prediction and projection of global climate variability and change is too big for any one country to address. The interconnected nature of climate processes means collaborative international effort is essential.

But climate science is also highly local. Climate science provides information that affects sector-wide decisions in agriculture, environmental management, water security, urban and coastal planning, finance, insurance, meteorology, public health and disaster management. There is a strong and increasing demand for the downscaling of global- or regional-level climate information to local areas, such as a river catchment or bushfire risk zone. There is also a strong and increasing demand for predictions and models from sub-seasonal forecasts to decadal and even century-scale predictions. This high demand for specific, applicable knowledge requires Australia to have the scientific capability to make use of international climate science resources. Australia must be involved in international climate monitoring and other global projects to gain the benefit of the global research effort.

Ultimately, Australia is a net importer of climate science information and expertise, and will continue to be reliant on international partnerships and collaborations for the foreseeable future.

However, our ability to benefit from international infrastructure and expertise cannot be taken for granted, and will always be conditional on Australia playing its role as steward of southern hemisphere climate science and observation, engaging appropriately with other developed countries in collaborative international climate research programs, and ensuring Australia has the scientific capability to exploit these opportunities.

As such, it is vital Australia is ‘at the table’, active and heard on the key issues and directions in international climate science research and in science diplomacy more broadly.

This report to the National Climate Science Advisory Committee describes Australia’s international climate engagement in terms of (1) knowledge and information access and exchange; (2) physical infrastructure access; (3) researcher mobility and exchange; and, to the extent information was available, (4) funding flows. It also identifies a number of risks and opportunities for Australia’s engagement in international climate science, across the immediate (near), medium and longer terms, all of which are readily actionable by public policy makers.

Key immediate risks include:

- loss or reduction of Australia's leadership role in international climate science coordination—including the Intergovernmental Panel on Climate Change (IPCC), the World Climate Research Programme (WCRP) and the Scientific Committee on Ocean Research (SCOR)—resulting in reduced influence on the direction of such programs and reduced access to their outputs. Mitigation of this risk involves ensuring sufficient long-term stable support for Australia's participation in such fora and strong contribution to their ongoing programs
- inadequate or reduced quality contribution to Coupled Model Intercomparison Project Six (CMIP6), resulting in poorer quality, less useful outcomes from the project and a loss of the international reputation gained through participation in CMIP5. This project also serves as a critical development and validation framework for the Australian Community Climate and Earth System Simulator (ACCESS) model, which is fundamental to Australian climate services. Mitigating this risk requires adequate support for ACCESS and the analysis of the suite of CMIP6 models in terms of key climate priorities for Australia and our region.

Notable medium-term risks include:

- inadequate southern hemisphere climate observations leading to a loss of continuity of observations. These observations are a necessary part of national and international understanding of climate variability
- loss of model development capability (in particular, further development of ACCESS) which could be addressed by providing additional development resources. ACCESS is used by many Australian researchers and agencies, and is central to Australia's climate prediction capability. ACCESS represents a central point of engagement with international climate researchers, notably through intercomparison projects such as CMIP6
- more general reduction of climate science capability in Australia, resulting in the loss of capacity for long-term analysis, forecasting, mitigation and adaption. This could be resolved by implementing the recommendations of the Australian Academy of Science's *Australian climate science capability review* (2017).

There are also a range of opportunities for strengthening Australia's international science engagement that could directly address Australia's climate priorities. Near- and medium-term opportunities include:

- leveraging international investment and focus on domestic and regional priorities such as El Niño, Antarctica and the Southern Ocean, and the Great Barrier Reef through enhanced involvement in collaborative climate research programs
- enhancing provision of existing climate services in the region and the South Pacific through funding programs from the World Bank and the Green Climate Fund.
- improving coordination of Australia's climate science pipeline by implementing the recommendations of the Academy's *Australian climate science capability review* (2017)
- attracting and retaining international climate scientists to work in Australia by ensuring our visa laws support this.

Longer-term opportunities include:

- benefiting from an enhanced observing system for global climate, particularly southern hemisphere components
- obtaining benefit from ongoing support for the European Union's Earth Observation Programme, Copernicus, through continuing coordination and support for satellite calibration and validation activities
- enhancing Australia's capabilities in integrated assessment modelling to better understand the impacts of climate change and the effectiveness of different adaptation measures

- developing CSIRO's Northern Territory Baseline Air Pollution Station at Gunn Point in the Northern Territory to improve tropical atmospheric composition measurements.

To influence the direction of and benefit from the outcomes of this research, Australia and its scientific community must be actively engaged in key international mechanisms. Climate science is too important a challenge for Australia to be a marginal player in key international science research and policy processes.

1. Background

In 2016, the Australian Government established the National Climate Science Advisory Committee (NCSAC) to provide strategic direction for Australian climate science research. The NCSAC comprises senior representatives from across Australian climate science research, investment and policy agencies and institutions.

To inform the NCSAC, the Australian Academy of Science (the Academy) has been commissioned by the Department of the Environment and Energy to report on domestic climate science capabilities and linkages to international capabilities and collaboration. This report explores climate research as it relates to fundamental climate processes, climate variability, and the study of human-caused long-term changes to the climate. Climate science in this sense can be defined as: observations of climate variables; understanding of climate processes; modelling of the climate; and provision of services relating to climate information derived from observations, understanding, and modelling. The full terms of reference are in the Appendix, Section 7.3.

In 2016 and 2017 the Academy undertook a review of Australia's climate science capability and found some areas of climate science to be moderately or critically under-resourced, including climate modelling, micrometeorology and boundary layer dynamics, atmospheric chemistry measurements, sea-level observations, and terrestrial carbon and water flux measurements (Australian Academy of Science 2017).

Following on from the review, this report investigates the critical linkages of domestic capability to international capabilities. It presents a snapshot of Australia's current involvement in the international climate science effort, and explores the benefits, risks and opportunities associated with that involvement.

Information was collected by survey of individual climate scientists and key organisations engaged in climate science. A total of 63 individual surveys were returned. In addition, organisational surveys were returned by the Australian Antarctic Division (AAD), the Australian Institute of Marine Science (AIMS), the Bureau of Meteorology (BOM), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Integrated Marine Observing System (IMOS), the ARC Centre of Excellence for Climate Extremes (CLEX), and the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC). The survey information supplemented the expertise of a report steering committee of some of Australia's most eminent climate scientists, listed Appendix 7.2.

1.1. Australia's need for climate science

Australia has known of humanity's role in climate variability and change for decades, with the Australian Academy of Science releasing a report on human contribution to climate change in 1976 and CSIRO releasing climate projections in 1992 (Whetton, Grose and Hennessy 2016). In 1990, the global consensus on human contribution to climate change was delivered through the first Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), which also called for a high degree of international cooperation (IPCC 1990).

The interconnected nature of climate processes means collaborative international effort is required; the research effort needed is beyond the contribution of any single country. Australia has developed significant infrastructure and human expertise over the past 20 years to connect us to the international research effort with the aim of contributing to global knowledge. This also means we rely on international contributions and collaborations to meet national needs.

Australia is at risk from the impacts of climate variability and change. Seasonal climate variability, driven by coupled ocean-atmosphere systems such as the El Niño – Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), have profound impacts on primary industries.. Sea-level rise threatens our coastal infrastructure and populations. Changing rainfall patterns have implications for our water infrastructure and security. Observing, understanding and predicting changes to the climate will help Australia to meet these challenges with adaptation strategies that support long-term prosperity, security and health.

Australia relies on climate science to inform sector-wide decisions. Agriculture, environmental management, water security, urban and coastal planning, finance, insurance, meteorology, public health and disaster management all use and value climate science. Wherever climate information is needed to inform local decisions, Australia needs a domestic capability. For example, since 2002 Australia has suffered more than $14 billion of insurance losses from natural disasters, and the Australian Government's costs were estimated at over $13.5 billion (Australian Productivity Commission 2014). These costs are expected to increase with changes in the intensity of extreme weather events due to climate change. Understanding changes to intensity, frequency and areas of impact will give decision-makers the information they need for sectors and locales to adapt and become more resilient.

Box 1: Climate Science for defence and national security

Climate change is a 'threat multiplier', meaning it can exacerbate other global stressors. For example, climate change can intensify the frequency and severity of droughts, extreme weather events, water shortages and disease. These have implications for regional stability, and therefore poses a risk to national security. This will lead to increased pressure on the Australian Defence Force and Border Force (Press, Bergin and Garnsey 2013).

It is likely the Australian Defence Force (ADF) and Australian Border Force will increasingly need to respond to humanitarian crises, especially in the Asia–Pacific region. The US and UK have taken significant steps to integrate the effects of climate change into their strategic defence planning (Climate Council 2015). For the ADF and other agencies to be well placed to deal with exacerbated global stressors, Australia needs a climate science pipeline to provide the information about likely impacts and response needs. This will help to ensure that Australia is progressing in step with its allies in mitigating and responding to the impacts of climate change.

1.2. Australia's domestic climate science capability

Australia's climate science capability has grown through stable investment over the past 25 years. This has been achieved through the long-term research funding and direction provided by the Australian Climate Change Science Program (ACCSP) and its successor, the Earth Systems and Climate Change Hub of the National Environmental Science Program (NESP), the university sector, and the Collaboration for Australian Weather and Climate Research (CAWCR). These programs developed Australia's Earth System Model, ACCESS, and expanded climate observation infrastructure that connected Australia to the international community. A result of this long-term investment is that Australia is well represented in global collaborative organisations and consortia. Australia's involvement in leading the direction of climate science at an international level is underpinned by our contribution to the collaborative scientific effort. Australia's influence and ability to benefit from international partnerships is tied to its scientific credibility.

The Australian climate science research effort can be understood through four broad themes: observing, understanding, modelling, and providing information. Australia has approximately

420 full-time equivalent (FTE) researchers working in these areas across publicly funded research agencies, universities and collaborative institutions (Fig. 1). CSIRO and the university sector (not including staff associated with cooperative research centres (CRCs) and centres of excellence (CEs) are the largest contributors with 95 FTE each, followed by BOM with 85 FTE, and the ARCCSS/CLEX with 72 FTE. The ACE CRC and the publicly funded research agencies AAD, AIMS, the Australian Nuclear Science and Technology Organisation (ANSTO), and Geoscience Australia (GA) contribute a further 72 FTE collectively in strategic areas (Fig. 1 and Fig. 2).

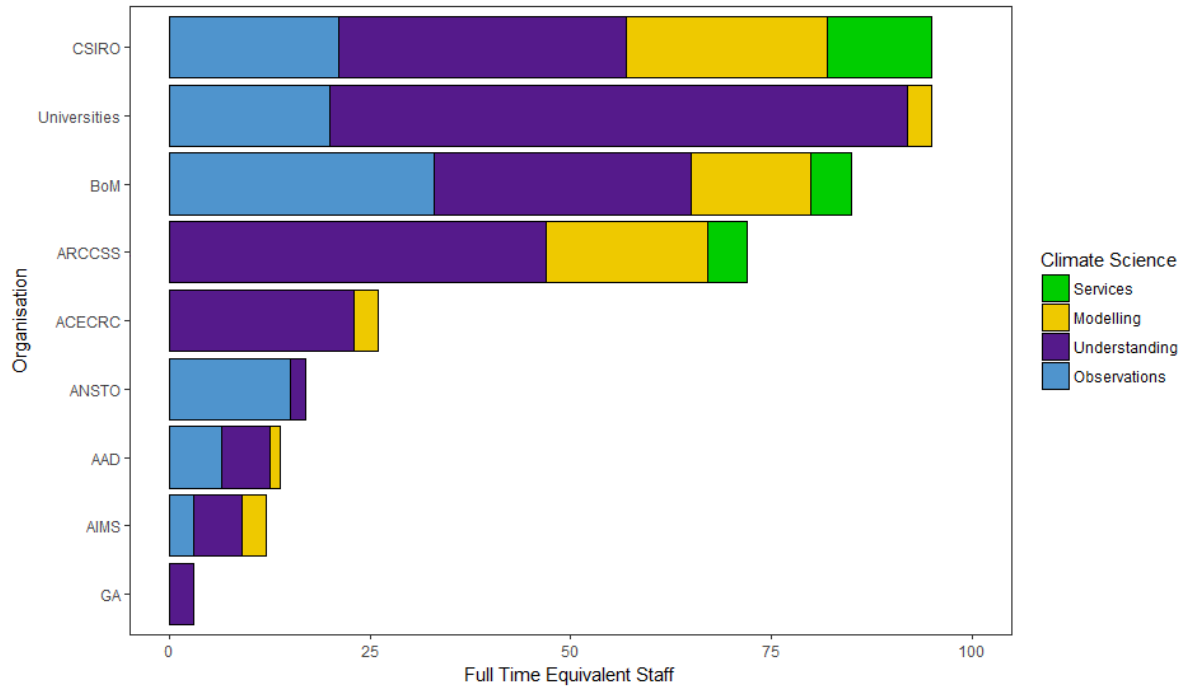

Figure 1. Research contribution of publicly funded research agencies, collaborative institutions, and the university sector (aggregated, exclusive of staff at the Centre of Excellence for Climate System Science or Climate Extremes, and the Antarctic Climate and Ecosystem Cooperative Research Centre). This includes GA, AIMS, AAD, ANSTO, ACE CRC, ARCCSS, BOM, university sector, and CSIRO.

Over the last 10 years, key coordination of climate research has been provided by CAWCR–a collaborative mechanism between CSIRO and BOM–and the university sector. CAWCR has underpinned much of the research effort by acting as the 'backbone' for infrastructure and modelling development, with CSIRO and BOM acting as custodians of climate models and data. The university sector has a crucial role in researching climate processes and makes significant contributions to model development. By virtue of the breadth of disciplines involved in climate science, the research effort is highly interdisciplinary and highly interconnected. All Australian climate research depends to varying degrees on models, climate observation infrastructure (*in situ* and satellite), and research output such as journal articles.

The 2016 review of domestic climate science capability identified several areas where national coordination and resourcing of climate science needed to be improved. Since then, some climate science capability has been centralised to institutions such as CSIRO's Climate Science Centre and the CLEX, and collaborations such as the NESP Earth Systems and Climate Change Hub. National coordination is still lacking, but these institutions are well connected and have strong collaborations. The establishment of these institutions partly addresses the completion of the CAWCR program; however, they have different research aims and purposes. This means overall climate science capability, especially in climate model development, is still at risk.

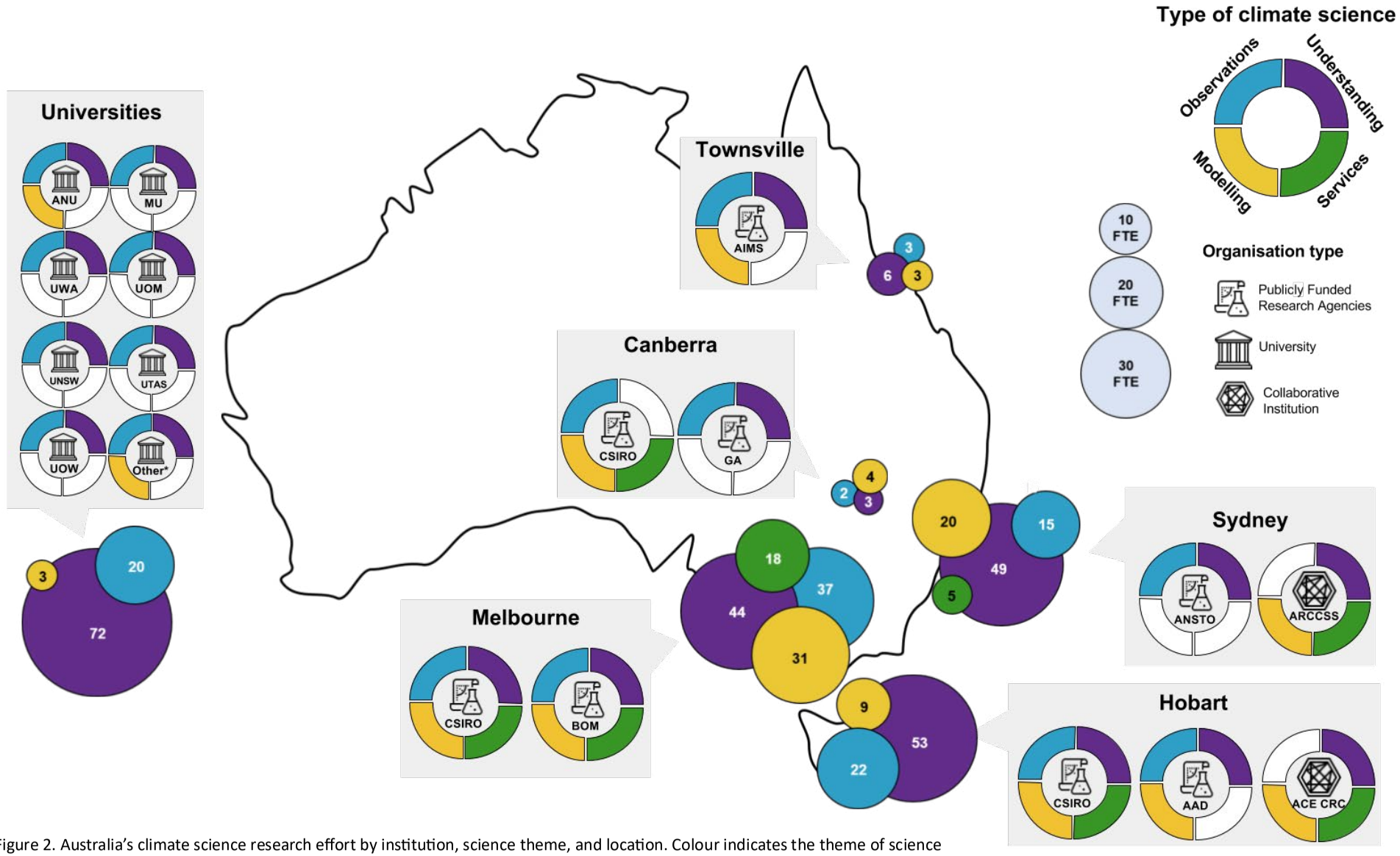

Figure 2. Australia's climate science research effort by institution, science theme, and location. Colour indicates the theme of science undertaken by the organisation, the bubbles indicate the magnitude of the science effort (measured as full-time equivalent) by location. Science theme is defined by the Australian Climate Science Capability Review (Australian Academy of Science 2017).

A reduction in Australia's climate science capability presents a strong risk: that of losing the opportunity to apply international climate science in Australia's interests. The value of the research effort to Australia depends on the ability of Australian researchers to adapt models and observing systems to the Australian geographic context and translate complex science into useful services. Australian-specific research is not a priority for international agencies.

Australia's climate science effort can be described by the 'climate science pipeline' (Fig. 3).

Australia's observation infrastructure contributes to the global network of climate observations that span the temporal and spatial ranges necessary for climate researchers to understand the physical processes behind climate systems.

Research informs climate modelling (and vice versa), and the need for observational infrastructure. These activities are supported by high-performance computing and eResearch infrastructure, which provide the processing capability for global climate models and the tools to share and use large quantities of data.

Climate science and modelling provides the basis for climate services, which is the information needed by citizens, businesses and governments to make decisions. These could be an insurance company determining its exposure to increasing risks of natural disasters, fire agencies assessing seasonal bushfire risk, emergency service workers building resilience in communities, farmers planting crops, or governments deciding whether to change building codes. Useful climate information is in high demand, from sub-seasonal to decadal and 100-year forecasts.

The value of climate science to Australia comes from climate services. To ensure public and business sectors can derive maximum value from the science, the entire pipeline needs to be supported.

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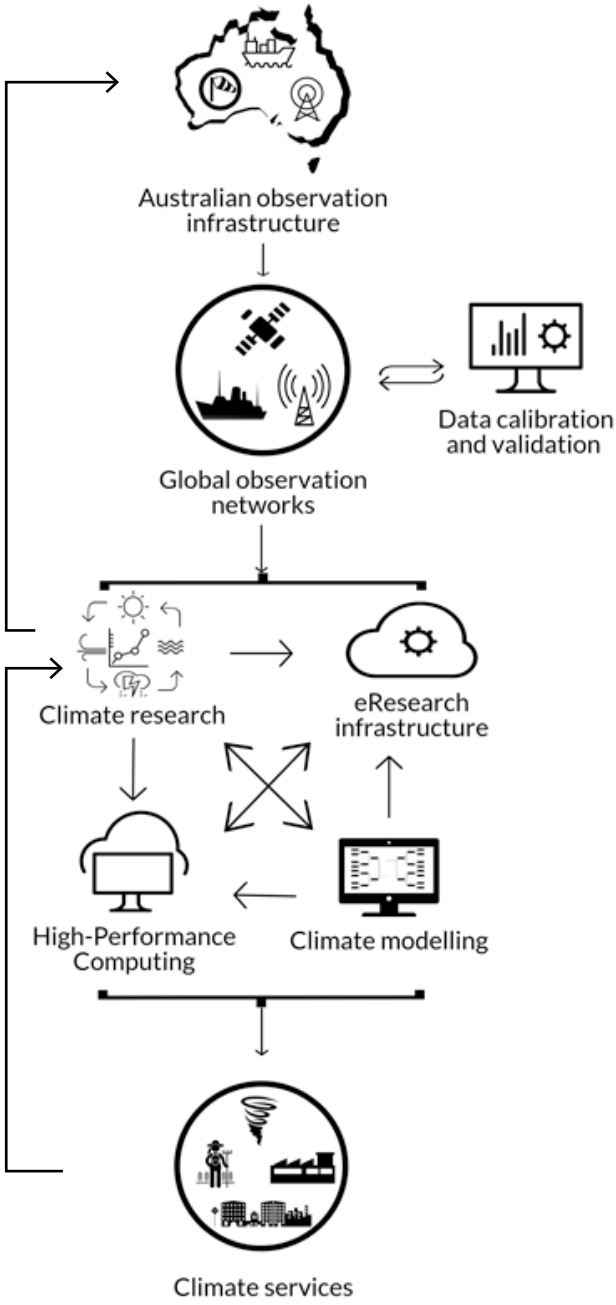

Figure 3. The climate science pipeline. This process represents the interdependency of activities needed for climate science.

1.3. Australia's place in international climate science

Australia's climate science capability and research over recent decades has positioned it as a key player in the international climate science community. Australia has a strong climate modelling capability, an excellent university research sector, and a dispersed network of observation infrastructure providing critical information for otherwise underrepresented geographic areas. Australia's capability is a crucial link in the international effort to better understand the climate system.

Australia is in a unique geographical position. As an island continent located between the Southern, Indian, and Pacific oceans, Australia is the only advanced economy in the southern hemisphere conducting significant climate research. Australia has the third largest maritime exclusive economic zone, covering environments from the tropical north to the polar south. This provides it with a 'blue economy'—the economic activity generated from marine resources—valued at $50 billion per year (National Marine Science Committee 2015). By virtue of its location, Australia also plays a key role in the international arena for observations of weather and climate as well as atmospheric constituents, and supports key global observation sites such as the Cape Grim Baseline Air Pollution Station.

Australia also provides expertise in climate science and climate change adaptation and mitigation to Pacific Island and Southeast Asian nations. BOM is part of the Climate and Oceans Support Program in the Pacific (COSPPac), which supports Pacific Island countries to adapt to and mitigate the impacts of climate variability, in partnership with meteorological agencies in these countries. CSIRO provides climate research and service to South-East Asian nations under contract.

Australia is one of the original claimants to Antarctica. Climate observing infrastructure in Australian Antarctic Territory (which is the majority of East Antarctica) and on sub-Antarctic islands provides information which otherwise would be underrepresented in observation networks. Our understanding of oceanography and sea-ice dynamics that comes from this research provides more refined weather and climate models, a better understanding of the ecosystem dynamics, and a better understanding of how sea levels may change in the future. Our understanding of the contribution of the East Antarctic ice sheet to sea level rise and the role of the Southern Ocean on Australia's weather are key research areas with national and international importance.

BOM is highly active in the World Meteorological Organisation (WMO), operating as a global information systems centre in the WMO Information System (WIS) as well as operating a number of WMO data collection or production centres (DCPCs). These centres are specialist centres for particular data types, and include space weather and tsunami data as well as climate data. These operations facilitate the collection, dissemination and exchange of climate data and products within the Pacific – Southeast Asian region.

This climate science capability equips Australia with the understanding and observations needed to refine international models and research for the Australian geographic context. Australia is reliant on Australian researchers being able to adapt international climate science to the southern hemisphere and Australia's needs, a task the international climate science community will not undertake on our behalf. Australia's modest investment in this existing capability connects it to the much larger international research effort, adapting international investments for the nation's benefit.

2. Infrastructure and information

Australia's climate infrastructure and information can be characterised as climate observation networks, climate models, high-performance computing and associated infrastructure for dealing with very large data sets, science infrastructure including research vessels and laboratories, and the outputs associated with them. Australian climate science is strategically integrated with the research direction of the international climate community. This has ensured that Australia's infrastructure, data output and models are embedded in international networks (Fig. 4).

Climate science is by necessity an international discipline. The atmosphere and oceans are global and the climate of an individual region cannot be understood in isolation from the global nature of the climate system. International open data policies recognise the global nature of climate science by ensuring nearly all model output, data from observation networks and research output is freely available. These outputs are the result of infrastructure, the human capital maintaining and operating it and a significant investment in data management, processing and storage. The value of this global data is incalculable, and while it is free, a domestic climate science capability is needed to make use of it.

Informal relationships exist with international colleagues where domestic researchers provide development support (in the case of climate models) or calibration and validation services (in the case of satellite data). For example, an investment of approximately $60 million has been made by agencies such as AAD, CSIRO and IMOS in satellite calibration and validation infrastructure and activities, with an additional $10 million per year for maintenance and running costs. This supports infrastructure like CSIRO's Aerospan and the Terrestrial Ecosystem Research Network's (TERN's) OzFlux networks which are also used for other research purposes. In turn, this small investment unlocks access to the $100 billion international investment into Earth Observing System (satellite) infrastructure (Malthus et al. 2014).

2.1. Climate observations

Australian climate observation infrastructure consists of widespread atmospheric, terrestrial and oceanic monitoring instrumentation and systems. Australia's unique geography means it was historically a leader in observations of Antarctica and the Southern Ocean—two systems which play a major role in global climate dynamics. Increasing research effort and investment from other Antarctic Treaty partners active in East Antarctica—such as China, Korea and India—and the Southern Ocean has markedly changed the research effort in the region in recent years. Australia plays an important and influential role in international investment and research collaborations in the region.

BOM operates a national network of meteorological observation stations that provide key climate observations of land, upper atmosphere, oceans and cryosphere. The organisation works closely with researchers and other users of meteorological information. As Australian's national meteorological service, BOM has primary responsibility for working with the WMO, which facilitates global meteorological cooperation.

Pivotal observation infrastructure for Australian terrestrial and oceanic observations is coordinated by the national programs TERN and IMOS, respectively. These collaborative institutions align well to international programs through standardised data collection and management practices; maintaining international leadership allows Australian researchers to influence the development of these practices.

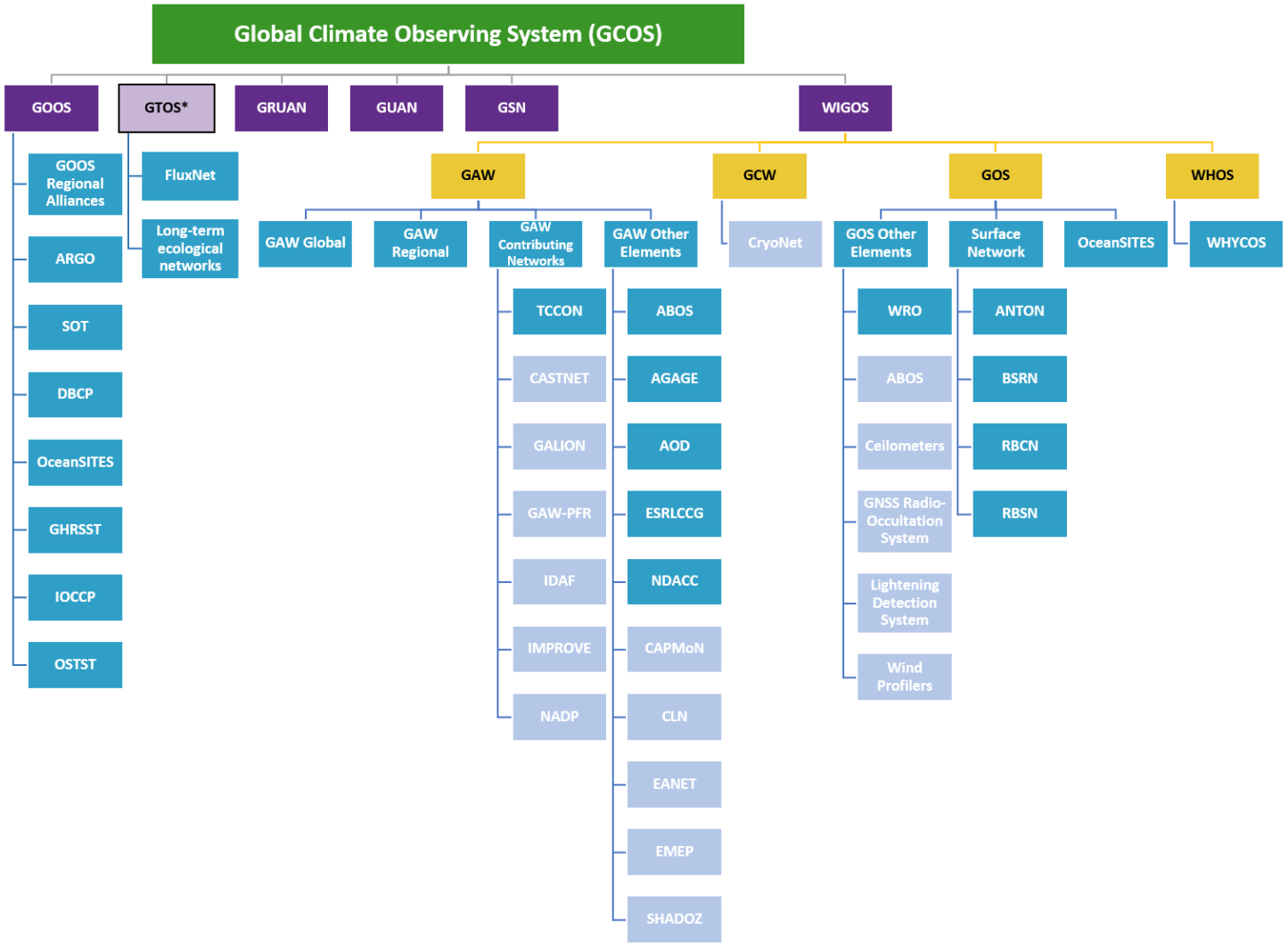

Figure 4. Australian contributions to international climate observation networks (solid blue). Networks to which Australia does not contribute are in light blue. *The development of the Global Terrestrial Observing System (GTOS) is ongoing; however, Australia's TERN is actively involved in similar national and international networks including the Asia–Pacific Biodiversity Observation Network and various long-term ecological research networks, which are working towards the GTOS.

Acronyms and initialisms	
ABOS	Aircraft Based Observing System (including IAGOS)
AGAGE	Advanced Global Atmospheric Gases Experiment
ANTON	Antarctic Observing Network surface synoptic station
AOD	Aerosol Optical Depth (Including AERONET)
ARGO	Argo program of drifting sub-surface floats
BSRN	Baseline Surface Radiation Network
CAPMoN	Canadian Air and Precipitation Monitoring Network
CASTNET	Clean Air Status and Trends Network
CLN	NOAA CREST Lidar Network
DBCP	Data Buoy Cooperation Panel (Including IPAB and the Global Drifter Program)
EANET	Acid Deposition Monitoring Network in East Asia
EMEP	European Monitoring and Evaluation Programme
ESRLCCG	NOAA-Earth System Research Lab Carbon Cycle Greenhouse Gases
GALION	GAW Aerosol Lidar Observation Network
GAW	Global Atmosphere Watch
GAW-PFR	GAW Precision Filter Radiometer Network
GCOS	Global Climate Observing System
GCW	Global Cryosphere Watch
GHRSST	Group for High Resolution Sea Surface Temperature
GNSS	Global Navigation Satellite System
GOOS	Global Ocean Observing System
GOS	Global Observing System
GRUAN	GCOS Reference Upper-Air Network
GSN	GCOS Surface Network
GTOS	Global Terrestrial Observing System
GUAN	GCOS Upper-Air Network
IDAF	IGAC/DEBITS AFRICA
IMPROVE	Interagency Monitoring of Protected Visual Environments
IOCCP	International Ocean Carbon Coordination Project
NADP	National Atmospheric Deposition (NADP)
NDACC	Network for the Detection of Atmospheric Composition Change
OSTST	Ocean Surface Topography Science Team
RBCN	Regional Basic Climatological Networks
RBON-Pilot	Regional Basic Observing Network
RBSN	Regional Basic Synoptic Networks
SHADOZ	Southern Hemisphere Additional Ozone sondes
SOT	Ship Observing Team
TCCON	Total Carbon Column Observing Network
WHOS	WMO Hydrological Observing System
WHYCOS	World Hydrological Cycle Observing System
WIGOS	WMO Integrated Observing System
WRO	GOS Weather Radar

International coordination of climate observation networks is coordinated by the Global Climate Observing System (GCOS) working with the Group of Earth Observations (GEO). They have defined essential climate variables, representing the climate, oceanic and terrestrial measurements needed to understand climate processes. Having access to these observations means being able to monitor climate variability and change, improve and use climate models, assess adaptation and mitigation needs, and downscale global climate models to more policy relevant spatial resolutions.

Much of Australia's observation infrastructure used in climate science serves other national requirements. For example, BOM's surface network was established to provide Australia's weather information. IMOS provides data for the management of off-shore industries, oil-spill emergency management, port administration, ecosystem conservation and military support. TERN provides end-user data for land and resource managers, threatened species conservation and carbon accounting.

Operational funding for Australia's climate observation infrastructure has traditionally been subject to budgetary constraints. More recently, funding has declined further, leading to the closing of or an uncertain future for important infrastructure. Approximately 28% of Australia's OzFlux network (representing 10 sites) and 37% (four sites) of the Aerospan network have closed due to lack of funding, and further reductions are likely. The provision of stable, predictable funding for observational infrastructure is needed to ensure continuity of measurements and strategic planning. Oceanic and terrestrial observation infrastructure are funded by the Australian Government's National Collaborative Research Infrastructure Strategy (NCRIS) and partners, which could be an appropriate mechanisms if predictable funding was provided on longer timeframes. Most atmospheric infrastructure is funded by BOM, but this infrastructure is generally geared towards physical weather and climate observations such as temperature, humidity or rainfall rather than more specialised analyses such as atmospheric chemistry or aerosol analysis.

Many climate observations occur via Australia's maritime research fleet, which includes the CSIRO-managed Marine National Facility, RV *Investigator*, the AAD's icebreaker RV *Aurora Australis*, and the AIMS vessels RV *Cape Ferguson* and RV *Solander*. Given that Australia has the world's third largest ocean territory and a substantial Antarctic claim, this fleet may not be sufficient. The investment in a new research and resupply icebreaker, RV *Nuyina* (due 2020), and the RV *Investigator* has been welcomed. However, the RV *Investigator* is only funded for 180 out of a possible 300 days per year; providing support for additional research days would capitalise on the multi-billion infrastructure investment represented by the research vessel and accelerate Australia's Antarctic research programs.

A table of Australia's observation network is provided in the Appendix, Table A1.

Oceanic

Australia's IMOS is a regional alliance of the Global Ocean Observing System (GOOS) and provides the backbone of sustained observations essential for climate research. IMOS brings together 17 organisations that manage or contribute to national marine observing facilities. It is funded under NCRIS and managed by a consortium of institutions as an unincorporated joint venture. Some facilities are regional components of international networks (e.g. Argo floats and the Deep Water Mooring Facility), others provide data to calibrate and validate earth observing systems (e.g. Satellite Remote Sensing Facility), or contribute to international collaborative monitoring and research (e.g. Wireless Sensor Network). All data is provided through a data repository. Australia's unique location relative to the Southern Ocean and Antarctica means IMOS has already contributed to significant advances in the understanding of oceanic processes that affect climate. IMOS has made fundamental contributions to climate

science over the past decade, including significantly improved quantification of Earth's perturbation energy budget, which is critical in validation of climate models and in observational estimates of climate sensitivity to anthropogenic forcing. However, IMOS facilities' existing funding level only meets minimal operational expenses, with concerns for the ongoing funding of the IMOS managed Deep Water Moorings Facility. To sustain the observations of the IMOS backbone, long-term (as opposed to annual) funding is required. Further, Australia has not been able to capitalise on some areas of monitoring or continue to invest in emerging programs at the rate that is desirable, such as extensions of Argo to biogeochemistry or the deep ocean (below 2000m). IMOS is currently incomplete and should be extended as new capabilities are developed. The IMOS backbone also enhances process studies of ocean mixing or air–sea interaction necessary to understand particular phenomena important to the Australian climate.

Terrestrial

Australia's Terrestrial Ecosystem Research Network (TERN) is a terrestrial observing network jointly funded by NCRIS and its organisational partners. This is an observation network of similar importance to North America's continental National Ecological Observatory Network and Europe's Integrated Carbon Observation System. While no comprehensive international terrestrial observation network currently exists, the Global Terrestrial Observing System (GTOS) is currently being negotiated. TERN has been active in coordinating a framework of measurements with international counterparts, including facilities in the USA, Brazil, Chile, Mexico, Venezuela, the EU, Japan, China, South Korea and the Philippines.

Atmospheric

BOM operates the majority of Australia's atmospheric observing network via its network of weather stations, predominantly undertaking physical atmospheric measurements such as temperature, pressure and precipitation). The network extends to the Southern Ocean (Macquarie Island) and Antarctica. These are well connected to the WMO's Global Observing System (GOS), and the associated GCOS Surface Network, GCOS Upper-Air Network, and GCOS Reference Upper-Air Network. Observational infrastructure investigating atmospheric composition (e.g. greenhouse gas or ozone depleting gas concentrations) is coordinated by the WMO's Global Atmospheric Watch (GAW). Cape Grim, Tasmania, operates as a Global Atmospheric Watch premier baseline station, one of three in the world and the only one in the southern hemisphere. The Cape Grim Baseline Air Monitoring Station measures the full suite of greenhouse, ozone-depleting and reactive gases, as well as aerosols and radon. It is the most important atmospheric measurement site in Australia and one of the most important globally. It is principally operated by BOM in partnership with CSIRO, and includes significant investment from CSIRO, ANSTO and the University of Wollongong. In addition to Cape Grim, there are 23 GAW regional sites associated with the BOM weather station network, and two Total Carbon Column Observing Network (TCCON) sites operated by the University of Wollongong.

CSIRO lead atmospheric greenhouse monitoring within the Australian Antarctic Program, with monitoring stations at Casey, Mawson and Macquarie Island. The NZ National Institute of Water and Atmospheric Research (NIWA) also has long-term atmospheric monitoring on Macquarie Island for nitrogen dioxide. BOM and AAD staff assist with each of these monitoring projects. The inclusion of atmospheric composition measurements in international networks requires the measurements to be calibrated to international standards. CSIRO's Global Atmospheric Sampling Laboratory (GASLAB) and the ice-core counterpart Ice Core Extraction Laboratory (ICELAB) provides the WMO-recognised calibrations needed to report to the GAW program.

Satellite calibration and validation services

Australia's climate observation infrastructure provides important satellite calibration and validation services to international space agencies. OzFlux (a TERN facility), Aerospan (a network operated by CSIRO), the Bass Strait satellite altimetry calibration and validation sites (operating under IMOS), and vegetation validation activities operated by the university sector are examples of Australia's calibration and validation activities (Appendix Table A2). The information that is produced by this infrastructure is in some cases beyond its primary purpose, but some are designed as essential international calibration infrastructure, such as IMOS's Satellite Remote Sensing Facility. These services contribute to the goodwill that ensures Australia's continued access to international satellite infrastructure and data, and are crucial to evaluate—and in some cases correct—satellite observations over the southern hemisphere.

2.2. Climate observation dependencies

The efforts of thousands of international climate scientists and billions of dollars of infrastructure are freely available to Australia. Australia is a major beneficiary of open access information, without which it would not be able to run climate or weather models.

While Australia's contribution of data to the international community is comparatively small, it does include observations and models specific to its geographical context. Australia's contribution covers a region that may not always be a focus of the great majority of national climate science programs, but which is a critical piece of the global climate puzzle. Australia's contribution also encourages and facilitates the investment of northern hemisphere nations' resources in our region, and allows access to critically important northern hemisphere observations.

Data is accessed by open data portals coordinated by international networks, peer-to-peer transfer, or through data user groups. In this respect, Australia's data and computer services are important science enablers for domestic scientists and the end users of climate services. The goodwill that underpins this data sharing stems from the global challenge of climate science. This is an acknowledgement of the need for data beyond the capability of any one nation to generate.

Access to this data underpins much of Australian climate science research. Information collected from a survey conducted by the Australian Academy of Science for this report of 63 Australian climate scientists indicated that 76% of respondents would not be able to continue their research without access to international data (Fig. 5). While this high dependency is a risk to Australia, all nations have similar dependencies on collective information.

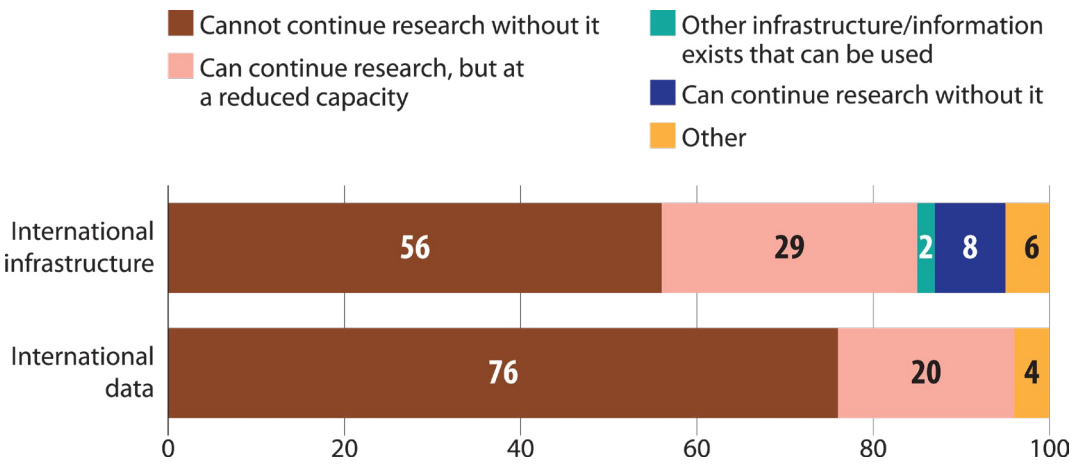

Figure 5. The dependencies of Australian climate scientists for international infrastructure and information

Earth observing satellite dependencies

Australia has no Earth observing satellites and is entirely reliant on international organisations for access to this critically important infrastructure. Data streams from these satellites are often freely available or given in exchange for comparatively small calibration and validation contributions, such as Aerospan. The announcement of an Australian Space Agency in September 2017 gives an opportunity to coordinate Australia's provision of satellite services to international space agencies. The data received from Earth observing satellites is critical for all facets of Australia, including weather forecasting, agriculture, disaster response, land management, bushfire risk analysis and climate science.

BOM's Associate Membership of the Committee on Earth Observation Satellites (CEOS) allows BOM opportunities to contribute to international Earth observation activities and opportunities for international collaboration.

The EU's Copernicus program includes a fleet of next-generation sentinel satellites which provide a comprehensive suite of atmospheric, terrestrial, oceanic and climate measurements. Australia has gained access to this program through a Memorandum of Understanding which sees Geoscience Australia (representing a consortium that includes CSIRO and state and federal agencies) providing regional data services and coordinating calibration and validation activities. Australia's contribution to satellite calibration and validation activities improves the accuracy of satellite measurements, and therefore research output and down-stream climate projections and reanalyses.

The goodwill underpinning this beneficial exchange was threatened in 2016 with potential cuts to observation systems used by international space agencies. The Ocean Surface Topography Science Team (OSTST), made up of USA and French satellite agencies including NASA, the US National Oceanic and Atmospheric Administration (NOAA), the French Centre National d'Études Spatiales (CNES), Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), and other international contributors, highlighted Australia's important contribution by stating in an open letter:

> *"In addition to the detrimental effect on research and accuracy of predictions for the Australian region, this decision will also impact on the international collaboration programmes, built up progressively over the last 20 years."* (Bonnefond et al. 2016)

While there is no suggestion Australia is at risk of losing satellite access, there is a risk Australia will not have the human capital to make full use of the data, and the data itself will be less accurate for Australian measurements.

A table of Earth observing satellites used by Australian climate scientists is provide in Appendix Table A3.

2.3. Models

Earth system models simulate climate processes and their interactions with biogeochemical cycles. Organisations typically develop specific expertise in modelling one domain of the climate system, such as ocean, atmosphere or terrestrial biogeochemistry. These are combined in coupled models to produce Earth system models. Models have many applications, including weather forecasting, climate predictions and projections, water and land management, carbon accounting and integrated environmental assessments. An important function of models that is often overlooked is that their demand for complementary information on all the interacting components of the climate system provides an important framework and prioritising mechanism for wider research efforts into climate processes. By

defining the parameters of the data required for models, the collection of data is standardised and prioritised.

Australia has successfully developed a coupled earth system model, the Australian Community Climate and Earth System Simulator (ACCESS) model. This is the result of more than a decade of collaborative development by BOM, CSIRO (through CAWCR) and universities with major international partnerships. It was largely funded through CSIRO, BOM and the ACCSP (which ran from 1989 to 2016), with growing contributions from universities.

At its core, ACCESS is 3 million lines of code representing a conglomerate of the Australian Community Atmosphere Biosphere Land Exchange (CABLE) model, the UK Met Office's Unified Model, the Los Alamos Sea Ice Model (CICE), NOAA Modular Ocean Model, and the EU's OASIS coupler (Fig. 6). ACCESS is run on the National Computational Infrastructure (NCI) and is connected to Australian climate scientists through Australia's eResearch infrastructure.

The investment in model development has allowed Australia to leverage the existing capability of international models to the Australian geographic context, which is significantly different to the northern hemisphere environments the models were originally developed for. Australia is the only country in the southern hemisphere investing in ongoing model development (Fig. 7). The development of the CABLE land-surface model, the World Ocean Model of Biogeochemistry and Trophic-dynamics (WOMBAT) model, the adaptation of ocean and ice models to form the Australian Climate Ocean Model (AusCOM), and the carbon cycling model CASA-CNP have enabled and unlocked this potential at much lower cost than building a new model from scratch.

The CABLE model and the regional downscaling Conformal Cubic Atmosphere Model (CCAM) are used extensively around the world. CABLE is used by 67 institutions (23 Australian and 43 international) in 14 countries. CCAM is used for high-resolution climate and weather modelling by the Council for Science and Industrial Research (South Africa), the Council of Science and Industrial Research (India), the Indonesian space agency LAPAN, the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), and Vietnam universities at no cost. Similarly the Australian climate science community uses a wide range of international models for research (Appendix Table A4).

ACCESS provides a unified national weather prediction and climate projection capability with its ability to run on timescales of hours to centuries (Keenan and Cleugh 2011). In 2010, BOM transitioned its weather forecasting modelling to an adaptation of ACCESS, which greatly improved forecast accuracy (Bureau of Meteorology 2010). For climate studies, two versions of ACCESS were run in the Coupled Model Intercomparison Project Phase 5 (CMIP5, 2010–14), which formed part of Australia's contribution to the IPCC's AR5. CSIRO is coordinating the development for ACCESS for CMIP6 (running 2015–20), supported by the NESP Earth Systems and Climate Change Hub (ESCCH). It is intended that terrestrial and oceanic biogeochemistry will be included by coupling the Australian developed CASA-CNP and WOMBAT models, respectively. However, the ACCESS development team has consistently been staffed well below optimum capacity, with a further 25% reduction in staffing over the last three years; the resourcing for ACCESS development is now at a critically low level. This poses risks to Australia's ability to deliver necessary climate and weather information to end users through the climate science pipeline.

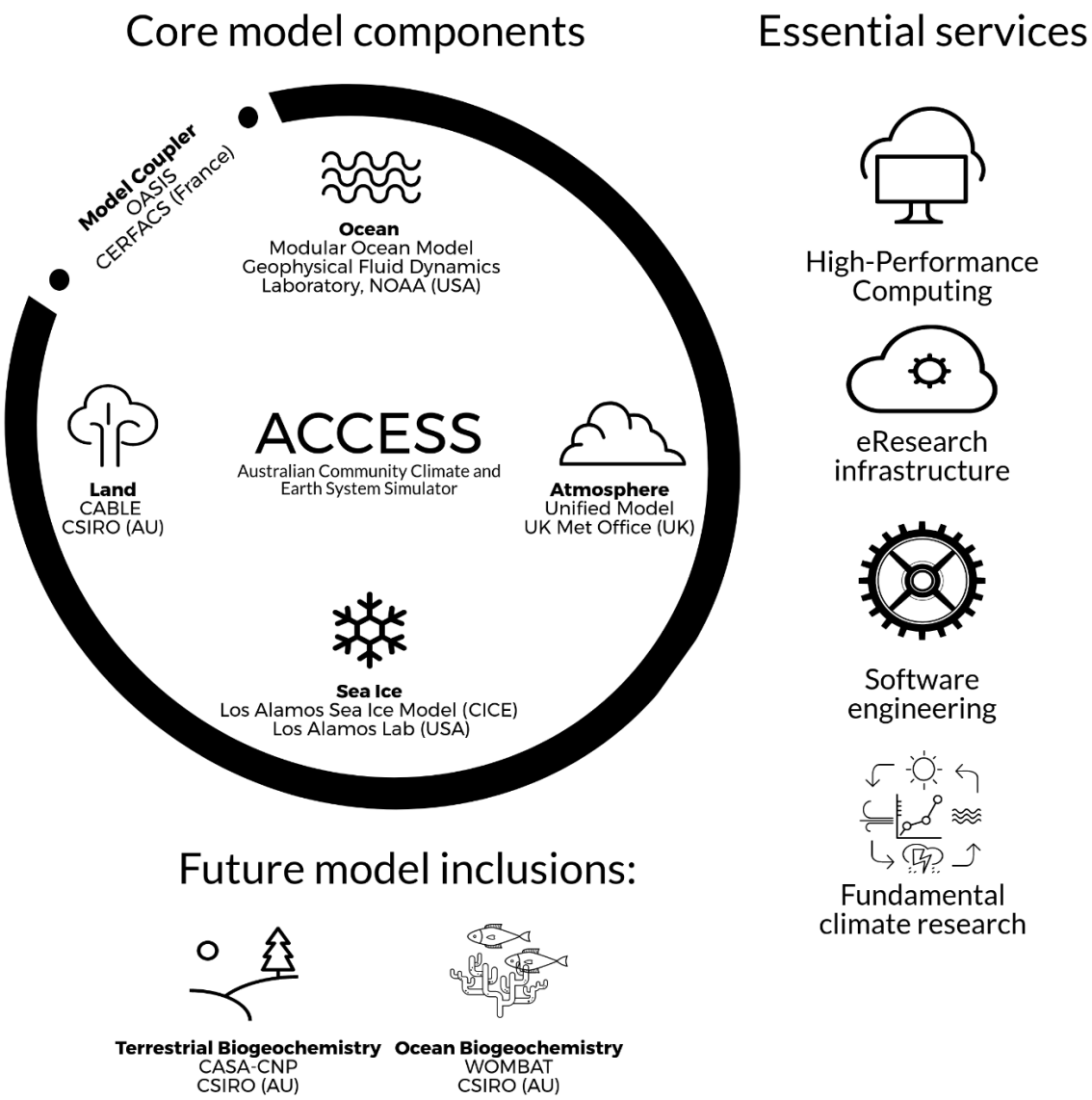

Figure 6. Australian Community Climate and Earth System Simulator (ACCESS) model, its components, and the essential services required for it to function.

Figure 7. Countries involved in model development for CMIP6. Australia is the only southern hemisphere country undertaking climate model development and research. The Brazil Earth System Model is a compilation of Indian and USA models and South Africa's model is comprised of Australian model components.

eResearch infrastructure

Australia maintains two high-performance computing centres: the NCI and the Pawsey Centre. The NCI undertakes the majority of climate science computing, and hosts the Earth System Federation Grid (ESFG) node which is an international open-source computation platform enabling world access to petascale[1] scientific data and processing. This platform hosts Australia's CMIP activities, including the CMIP6 outputs. These are the 'gold standard' climate projections that represent the output of a five-year internationally coordinated research collaboration comprising the best climate models from around the world; the Australian eResearch infrastructure and human investment are therefore important for providing and facilitating national access to international modelling results.

The National eResearch Collaboration Tools and Resources Project (Nectar) provides online tools for international collaborations, which Australian researchers use to access international observation data and modelling outputs. Its Climate and Weather Science Laboratory, developed by BOM, CSIRO, ARCCSS and NCI, allows for information sharing and collaboration in climate and weather research. The tools Nectar provides allows scientists to access high-performance computing, data storage, and the data output from Australia's ACCESS model experiments. The Australian National Data Service (ANDS) provides data curatorship for climate scientists. This service connects hundreds of individual projects to increase the value of research data. Research Data Services (RDS) provides the data storage infrastructure through a dedicated high-bandwidth, low-latency inter-connection network that provides the storage infrastructure for national data collections. Nectar, ANDS, and RDS are strategically aligned as Australia's eResearch data services.

1 Petascale computing refers to a computer system capable of reaching or exceeding one petaflops, i.e. one quadrillion floating point operations per second. Petascale computing is essential to climate simulations. The ESFG anticipates scaling to exascale level–1018 floating point operations per second in the near future.

Box 2: Coupled Model Intercomparison Project (CMIP)

CMIP provides Australia with an opportunity to test and improve its climate model by leveraging the efforts of other countries. CMIP is a coordinated effort to compare climate models to better understand their regional or temporal biases, and produce international consensus on internationally important climate science questions. CMIP is undertaken by the world's best climate models, with each project phase lasting approximately five years. There are three components to each CMIP phase:

1) Compare model forecasts for a set of common experiments and historical simulations to provide the basic comparison of climate models and allow for comparisons to past project phases.
2) Standardisation of model outputs, and international coordination of the modelling experiments to ensure quality control and accessibility.
3) A set of endorsed Model Intercomparison Projects. These are model experiments on specific topics to fill in gaps in science knowledge.

Participation in CMIPs also give an opportunity to further Australian understanding of climate processes and ensure international models are accurate for Australian projections.

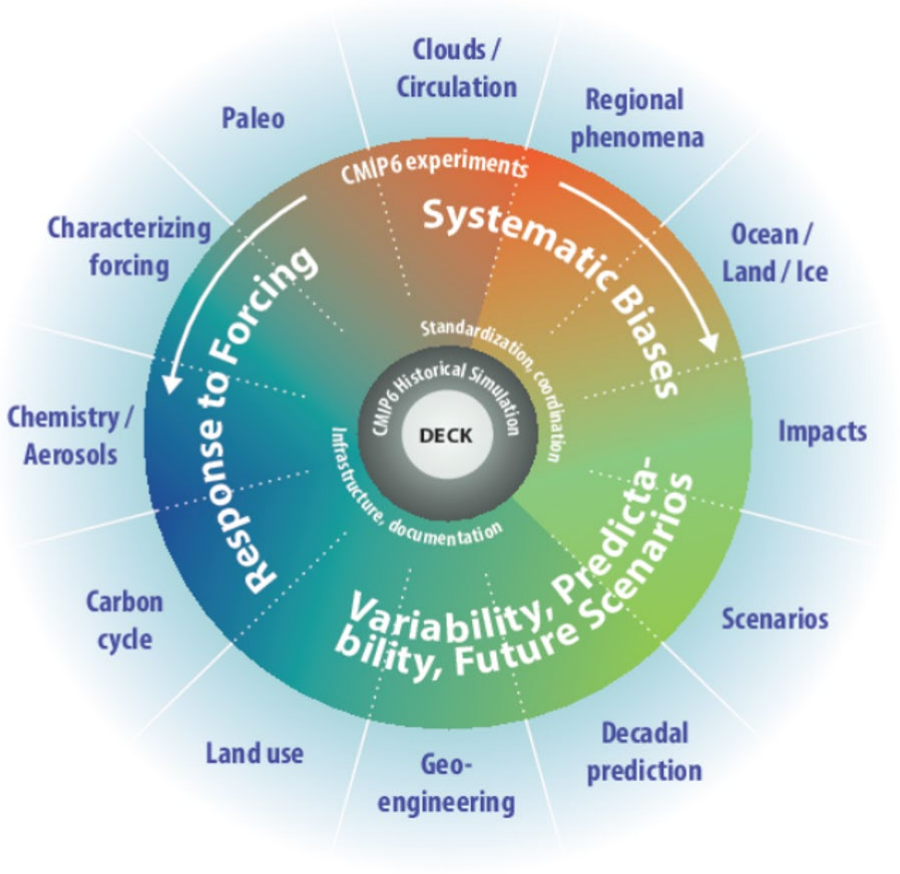

Figure 8. Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design (Eyring, et al. 2016).

The DECK consists of a set of standard experiments which remains common between CMIP phases to provide comparable output. CMIP addresses three broad questions:

- How does the Earth system respond to forcing?
- What are the origins and consequences of systematic model biases?
- How can we assess future climate changes given internal climate variability, predictability, and uncertainties in scenarios?

2.4. Model dependencies

Climate models use numerical techniques to solve coupled equations representing the various interacting processes that affect climate. These include equations of fluid motion and thermodynamics that capture air and water movement, convection cloud formation and precipitation, freezing and melting, as well as parameterisations of biological and ecological processes that modulate the carbon cycle. These parameterisations are a mixture of basic theory and empiricism rooted in observations. Models can be run in partial mode, for example to predict atmospheric behaviour when the ocean conditions are assumed known or vice versa, or in fully coupled mode to model the entire Earth system. Earth system models or global climate models like ACCESS are massively detailed and correspondingly computer resource intensive. Simple models are therefore used to investigate specific situations or to downscale the results of global climate simulations to regional or finer scale. Models are essential tools that allow us to link the ever-increasing understanding of specific climate processes together while taking into account the complex feedbacks between these processes that act at different time and space scales. As a result they are the only way known to reconstruct past climates or predict future climates under various scenarios of human activities.

Climate models can be used to produce multiple outputs:

- **Reanalysis**: Using models to generate climate datasets that are spatially and temporally consistent. This approach incorporates all available observations of climate variables into a model to dynamically estimate the climate at each time point, and fills the gaps of the observation network.
- **Reconstructions**: Modelling experiments where paleoclimate records, including those derived from ice cores, sediment cores, tree rings and corals can be used to understand how well climate models can simulate climate change in response to historical events and thus how the climate may respond to future changes.
- **Climate predictions and projections**: Using models to forecast the most likely future climate scenarios (predictions), or to project future climate responses in different scenarios (projections). Climate predictions and projections use climate observations, known parameters that affect climate processes such as atmospheric concentration of CO2, and complex climate models such as ACCESS to project the climate in the future. Forecasts can be used to predict seasonal climate variations like ENSO, which have implications for agriculture, industry and public health. They can also be used to guide mitigation and adaptation responses to the impacts of climate change, for example by changing building codes and land use policies to better adapt to a changing climate.
- **Sensitivity experiments**: Modelling experiments which aim to understand how climate is affected by changes to atmospheric conditions (known as climate forcing), such as an increase in atmospheric CO2 concentrations.

Australian researchers depend on organisations undertaking modelling work for global forecasts and reanalysis datasets. Responses to the previously mentioned survey of climate scientists highlighted the European Centre for Medium-Range Weather Forecasts, NOAA's Earth System Research Laboratory, NASA's Jet Propulsion Lab (ocean and sea ice), the UK Met Office Hadley Centre, the New Zealand MetService, the European Centre for Medium-Range Weather Forecasts, the University of Wisconsin and the Japan Meteorological Agency (JMA) as major sources of such datasets. BOM in particular is currently making a large investment in a reanalysis dataset for the Australasian region. This project also includes liaising with NIWA to coordinate further regional reanalysis tasks. A list of the international reanalysis datasets used by Australian researchers is at Table A4.

The World Climate Research Programme sponsors the standardisation and comparison of international models through CMIP. In CMIP's 5th phase, Australia made one of 13 national submissions, and provided the only climate and Earth system model created in the southern hemisphere and with a southern hemisphere focus. Australia's contribution ensures that international models include key southern hemisphere processes—especially those affecting Antarctica and the Southern Ocean—and that these processes are integrated into world models. In the 6th phase, this project has expanded to include South Africa (sponsored by CSIRO) and Brazil (using a compilation of USA and Indian model components). The CMIP experiments include constructing and examining models of future climates under a range of greenhouse gas emission scenarios.

The synthesis of this information largely defines the global knowledge on climate change and informs the IPCC assessment reports. Because of the many national contributions and the cross-validation of multiple models, the outcomes of CMIP are considered authoritative climate models. Australia's access to and involvement in CMIP was seen by many survey respondents as important for Australian and world climate modelling, and essential for long-term confidence in the models. Australia's involvement in CMIP develops and validates ACCESS as a national capability. Australia's involvement also facilitates the utilisation of other model outputs for various climate-related services in Australia, such as planning and adaptation for extreme fire weather, flooding and inundations, and heatwaves.

Modelling is often conducted at a coarse resolution because the supercomputing requirements of higher resolution modelling can be excessive. The process of converting coarser to higher resolution outputs necessary for regional and local impacts and adaptation studies is termed downscaling. This involves including regional geographic features and observations in regional climate models. Downscaling provides the most useful outputs to communities, governments and businesses as it forecasts at a scale appropriate for local decision-making.

Using climate models

The conversion of climate science to climate services begins with specialised data processing, management, and the development of a next- or end-user interface. This is largely realised through model downscaling, which provides climate information at spatial scales relevant to businesses, property owners and local councils.

Because of the high resolution required, downscaling has a large computing resource requirement. Australia lacks the high-performance computing infrastructure to undertake significant model downscaling activities. However, ACE CRC has undertaken some downscaling work for the Tasmanian Government and Victorian alpine resorts, and UNSW's Climate Change Research Centre downscaled CMIP3 data for the NSW and ACT governments. These involved taking global models with resolutions of 200 x 200 km down to resolutions of approximately 10 x 10 km. Once downscaled, eResearch infrastructure and software engineers process the data to provide a user interface for easier access and navigation of the information (Ekström, Grose and Whetton 2015). The information can then be processed by climate service providers to provide syntheses and tailored products according to the needs of the end-user.

A list of international climate models used by Australian researchers is at Table A5.

2.5. Research output

Australia engages in highly collaborative research in fields of climate science, but also receives research of national interest produced without the direct involvement of Australian researchers (defined as being authors on research publications).

In areas of research which specifically relate to Australia, such as Australia and drought, climate, rainfall or El Niño, approximately 25% of studies include an Australian and non-Australian author. A further 20-30% of studies are undertaken without the involvement of an Australian author. Australian climate observations and model output makes such studies possible.

On topics of interest to the Australian climate which are not specific to Australia, the international community plays a much larger role—producing 85% of studies related to the climate and Antarctica or the Southern Ocean (Table 1).

The proportion of studies that are collaborative, that is include both Australian and non-Australian authors, has been increasing in previous years (Fig 9), particularly on research that specifies Australia.

The large number of studies of Australia's climate being conducted by international scientists without the collaboration of Australian scientists suggests there is ample room to expand Australian climate research and increase understanding of the Australian climate.

Table 1. Research output collaborations (as journal articles indexed by Web of Science) averaged for the years 2015–16. Australia's climate science involves a lot of cooperation with international colleagues, and climate science is often conducted without involving Australian scientists. Science undertaken without Australian input is only possible by access to Australia's climate observations and modelling output.

Topics	Total papers	# (%) with Australian authors	# (%) without an Australian author	# (%) with both Australian and non-Australian authors
Antarctica AND climate	845	127 (15%)	718 (85%)	83 (10%)
Southern Ocean AND climate	2072	339 (16%)	1733 (84%)	225 (11%)
Great Barrier Reef AND climate	399	237 (59%)	162 (41%)	125 (31%)
Australia AND El Niño	152	106 (70%)	46 (30%)	41 (27%)
Australia AND climate	2868	2143 (75%)	725 (25%)	713 (25%)
Australia AND drought	523	415 (79%)	108 (21%)	128 (24%)
Australia AND rainfall	990	807 (82%)	183 (18%)	238 (24%)

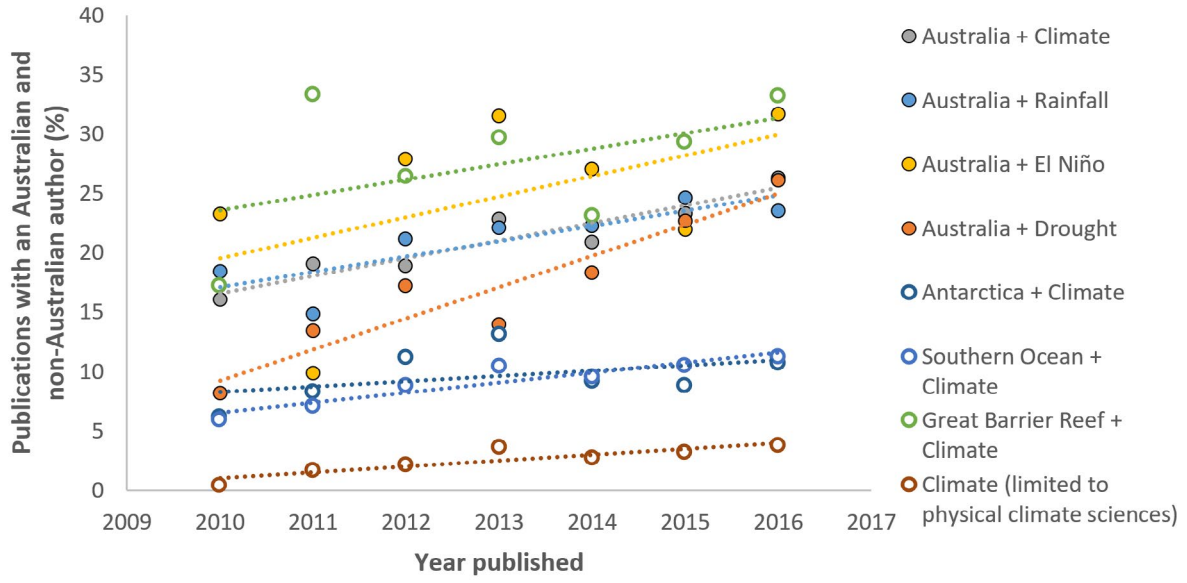

Figure 9. The percentage of published articles that include both an Australian and non-Australian author for various topics of importance to Australia. All topics have increased the proportion of collaborative studies in the past five years.

3. Human capital

Australia's climate science workforce is well connected with international colleagues. Climate science careers are internationally mobile—approximately 25% of Australia's climate scientists are not Australian citizens, and 85% have trained or worked internationally, typically through postgraduate study or postdoctoral fellowships (Fig. 10). Australian climate researchers also regularly provide training to their international colleagues, with 60% providing training to international colleagues either in Australia or overseas.

3.1. International mobility

Most domestic climate researchers have undertaken a postgraduate degree, paid employment (commonly a postdoctoral fellowship) or a research exchange in another country (Fig. 10). From the responses of Australian climate scientists surveyed, the USA was the most common country, followed by Germany, France, Canada, the UK and the Netherlands.

Climate research also provides opportunities for Australian researchers internationally and vice versa. Australia's high quality research system has made it a particularly attractive place to work and study. For example, 40 international students (24 in Australian universities and others in Argentina, Brazil, China, Saudi Arabia, the Netherlands and the US) are currently working on the CABLE model. A strong domestic climate research presence also attracts international scientists to visit Australia. Such movement of scientists promotes active international research collaborations and productive scientific output that is beneficial to Australia as a host nation, and to climate science as a whole.

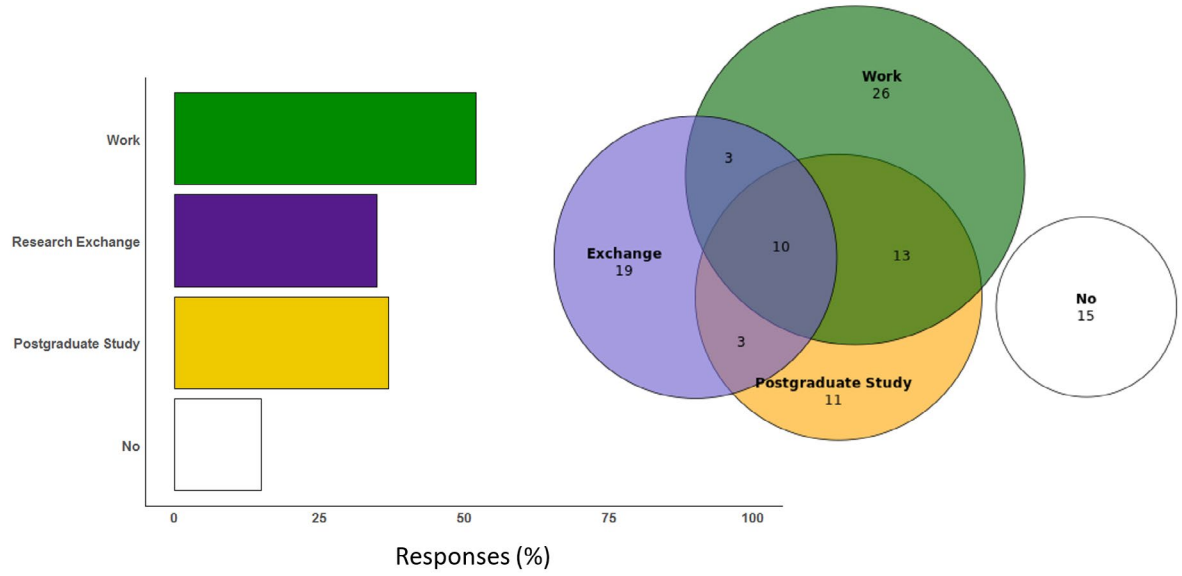

Figure 10. Proportion of Australia's climate scientists who have undertaken work or training internationally. Based on survey responses, 85% of domestic climate scientists have worked or undertaken a research exchange or postgraduate degree at an international institution (left figure, as percent of responses). The Venn diagram represents the scientists who have engaged in more than one type of international activity (right figure, percent of responses).

3.2. Science leadership and coordination

Australia has a strong leadership position in international climate science, due to our historically outward looking climate science programs and unique geographic location. Australia's representation on international committees coordinating climate science ensures

that our national interest is embedded in the international effort, which may otherwise be biased more than is already the case towards northern hemispheric concerns.

Approximately 50% of survey respondents are actively involved with international networks or committees. These engagements range from members of working groups and steering committees to the chairs of international collaborations (Table 2). Given the strong global coordination of climate science research direction, Australia's involvement in international working groups and steering committees is critical to ensuring climate models, global observation networks, and research are relevant to and inclusive of Australia.

A number of survey respondents raised concerns about Australia's support for climate scientists to actively participate in these forums. The non-payment of annual contribution fees reduces leadership opportunities in international networks. Additionally, several survey respondents suggested that meeting their responsibilities in these forums was made difficult by the simple lack of travel support.

The Intergovernmental Panel on Climate Change is responsible for synthesising climate science into assessment reports that comprehensively detail the knowledge of climate science and discuss the impacts, adaptation strategies and mitigation responses. These reports are written and reviewed by the best climate scientists around the world. The prestige of Australian climate scientists is exemplified by the number of contributors and reviewers involved with this process. For example, 40 Australian researchers were contributors and 52 were expert reviewers to the fifth assessment review report on the physical basis of climate science and human induced change (the section of climate science most related to the scope of this report). Australia was also well represented in IPCC coordinating roles compared to other countries (Table 3).

Table 2. Australia's engagement in international climate science coordination bodies.

Organisation	**Role**
World Climate Programme	
BOM	OPACE 1- Expert Team on Climate Data Base Management Systems
BOM	OPACE 1- Expert Team Data Rescue (ET-DARE)
BOM	OPACE 1- Co Leader Inter-programme Expert Team on the Climate Data Modernization Programme (IPET-CDMP)
BOM	OPACE 2- Expert Team on National Climate Monitoring Products (ET-NCMP)
BOM	OPACE 2- Task Team on Homogenization (TT-HOM)
BOM	OPACE 3- Joint CCl/CBS Expert Team on Regional Climate Centers
BOM	OPACE 3- Task Team on Regional Climate Outlook Forums (TT-RCOFs)
BOM	OPACE 3- Leader Task Team on Tailored Climate Information (TT-TCI)
RMIT	OPACE 2- Task Team on the Use of Remote Sensing Data for Climate Monitoring (TT-URSDCM)
Macquarie University	OPACE 3- Co-Leader Joint CCl/CBS Expert Team on Regional Climate Centers
UNSW	OPACE 2- Joint CCl/WCRP/JCOMM Expert Team On Climate Change Detection And Indices (ET-CCDI)
CSIRO	OPACE 2- Joint CCl/WCRP/JCOMM Expert Team On Climate Change Detection And Indices (ET-CCDI)
USQ	OPACE 4- Expert Team on the User Interface for Climate Services (ET-UICS)
World Climate Research Programme	
BOM	Leadership group Stratosphere-troposphere Processes And their Role in Climate (SPARC)
CSIRO	Co-Chair Ocean Model Development
CSIRO	Working Group on Coupled Modelling member
CSIRO	Member of the Joint Scientific Committee
ACE CRC	Member Global synthesis and Observation Panel
ACE CRC	Member of SORP- CLIVAR/CliC/SCAR Southern Ocean Region Panel

Table 2 (continued). Australia's engagement in international climate science coordination bodies.	
Organisation	**Role**
AAD	Leader of a Task Group of BEPSII- Biogeochemical exchange processes at Sea Ice Interfaces
AAD	Scientific Steering Group SCAR/CliC Antarctic Sea Ice Processes & Climate (ASPeCt)
UNSW	Co-Chair GEWEX Global Land/Atmosphere System Study
UNSW	Co-Chair GEWEX Hydroclimatology
UNSW	Member of SORP- CLIVAR/CliC/SCAR Southern Ocean Region Panel
Monash University	Member Global Atmospheric System Study
UTAS	Scientific Steering Group SCAR/CliC Antarctic Sea Ice Processes & Climate (ASPeCt)
Global Carbon Project	
CSIRO	Executive Director Global Carbon Project
CSIRO	Model contribution CSIRO-BOGCM
Ocean Surface Topography From Space Team (OST) - Sea Level Altimetry	
CSIRO	Principle Investigator- Altimetry for Real Time Applications and Climate Studies relevant to Australia
World Meteorological Organisation Global Atmospheric Watch	
BOM	Scientific Advisory Group for Ozone
BOM	Expert Team on World Data Centres
CSIRO	Scientific Advisory Group on GHG
CISRO	Scientific Advisory Group on GHG
CSIRO	Scientific Advisory Group on Reactive Gases
CSIRO	The Environmental Pollution and Atmospheric Chemistry Scientific Steering Committee
UOW	Scientific Advisory Group on GHG
Cancer Prevention Centre	Scientific Advisory Group on UV Solar Radiation
Group on Earth Observations	
Geoscience Australia	GEO Principal
Geoscience Australia	Corresponding contact
Geoscience Australia	GEO Principal alternative
BOM	National Focal Point GOOS
CSIRO	Co-chair, Ocean Observation Panel for Climate (OOPC)
CSIRO	GOOS panel
CSIRO	GOOS Steering Committee
CSIRO	Member Global Temperature and Salinity Profile Project
AIMS	GOOS project officer
AIMS	GOOS Steering Committee leader
UTAS	Global Sea Level Observing System (GLOSS)
CSIRO	Co-chair, Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP)
Integrated Marine Biosphere Research (IMBER)	
CSIRO	Member SOLAS-IMBER working group on Ocean Acidification
CSIRO	Co-Chair of Surface Ocean CO2 Atlas, Southern Ocean Panel
Other	
CSIRO	Member of the task team on weather, climate, and fisheries (JCOMM / CAgM)
CSIRO	Member, Centre for Remote Sensing and Digital Earth
CSIRO	Member of Scientific Steering Committee, International Global Atmospheric Chemistry Project
CSIRO	Member, International Atomic Energy Agency (IAEA) Ocean Acidification Coordinating Panel
CSIRO	Co-chair, Interdisciplinary Biomass Burning Initiative IGAC/WMO/iLEAPS
CSIRO	Member, Scientific Advisory Committee on Ocean Acidification Monitoring and Mitigation program for Pacific Islands
BOM	Associate Member, CEOS

Table 3. Australia's contribution to the IPCC's Fifth Assessment Report (AR5) coordination roles, including Coordinating Lead Authors, Lead Authors, and Review Editors. Australia's representation in coordination role reflects its historically strong domestic capability.

Country	Coordinating Lead Author (out of 29)	Lead Author (out of 176)	Review Editors (out of 50)
Australia	4	8	1
Germany	4	8	1
New Zealand	0	3	1
United Kingdom	3	18	7
United States	8	43	11

4. Financial relationships

The collaborative nature of climate science that underpins free data access means that direct financial relationships are not as common as in other disciplines. Data from Australian observation networks (comprising only a few per cent of the total data available globally) and models are generally provided free through online data portals, online community-of-practice groups, or by peer-to-peer data exchange. Open data is the expectation in climate research and this provides immense financial benefit to Australia. Researchers typically use data generated from other groups to undertake their own research. This may be in the assessment of model accuracy, the application of analytical approaches to global rather than regional processes, and the development of climate projection reanalyses which provide critical climate services for decision-making. Where subscription or partnership arrangements exist, such as Australia's access to the UK Met Office's weather and climate model (the Unified Model or UM), the time and financial contributions support ongoing development and improvement of the model through the UM Partnership (Fock et al. 2016). The UM Partnership also includes Korea, New Zealand and India as well as the UK.

Access to international satellite data is of particular importance to Australia. In return for satellite data that underpins climate modelling, weather predictions and associated economic benefit, Australia contributes to international in situ observing programs and provides satellite calibration and validation services. For example, Australia provides one of four calibration data streams for ocean surface topography satellites, and the only one situated in the southern hemisphere.

The majority of ARC funding for climate science goes towards projects with international collaborations. In the past two years, 78% of funded climate science projects had international partners, representing 92% of the funding provided (65% if funding for the CLEX is excluded).

4.1. Collaborative institutions

Collaborative research institutions and programs like ACE CRC, CSHOR, ARCCSS, NESP, and CLEX partner with international organisations. The international partners provide financial contributions and, more importantly, in-kind support to common research themes. These have led to the development of Australia's climate model, improved weather prediction services, and more useful climate services for state and local governments.

Collaborative institutions also facilitate foreign investment. Australia's climate science pipeline makes it an attractive asset that can be used to undertake research on behalf of other nations. The newly established CSIRO Climate Science Centre is currently undertaking climate research funded jointly or wholly by international organisations to the value of $15 million. These projects leverage Australia's climate observation network, and include comprehensive modelling evaluations, training and information services.

Australia maintains a financial relationship with the UK Met Office for access to the UM. BOM and CSIRO's collaboration CAWCR is one of five 'core partners' of the UM, along with South Korea, India, New Zealand and the UK. These partners each provide a staff contribution of 5 FTE towards model development and a yearly financial contribution of approximately $85,000. In return, Australia receives access to modelling tools, bespoke data feeds, technical support, and help to further develop the model in Australia's national interest. As Australia uses the UM as the atmospheric 'core' of its ACCESS model, this is a beneficial relationship that provides Australia a weather forecasting and climate model, with ongoing development and support.

4.2. Antarctica

The Australian Antarctic Territory occupies 42% of Antarctica, located in East Antarctica, where it operates three permanent year-round research stations and extensive logistics infrastructure. The AAD leads, manages and delivers the Australian Antarctic Program on behalf of the Australian Government. The Australian Antarctic Program is highly collaborative with scientific collaborations with more than 100 institutions and 20 countries. Hobart, as the home of the AAD, with support from the federal and Tasmanian governments, Tasmanian Polar Network, CSIRO, BOM, ACE CRC, and UTAS, has positioned itself as the gateway to East Antarctica, with research as a unique feature of this gateway. Many national Antarctic programs hold memoranda of understanding with the AAD. This has flow-on effects to the Tasmanian economy, with many international Antarctic program visitors and research ships coming to Hobart.

The AAD maintains strong relationships with other national Antarctic programs and international scientific collaborations benefit significantly from this, including through sharing logistics with other national programs operating in East Antarctica.

4.3. Membership of international organisations

Climate science is highly connected and coordinated internationally. International networks such as the World Climate Research Programme (WCRP), the World Weather Research Programme (WWRP), Global Climate Observing System (GCOS, which includes GOOS, GAW and GOS), the Global Carbon Project, the Scientific Committee for Antarctic Research, Future Earth, and the Committee on Earth Observing Satellites (CEOS), provide research frameworks and data standards, and create information platforms for climate scientists and science. Membership of these organisations normally incurs a small annual financial contribution (typically between $5000 to $50,000 per year). These contributions ensure Australia continues to guide international research direction and leverages cooperative projects and open data for its national interests. They also enable domestic scientists to apply for travel grants and research awards which extend the influence of Australian science internationally.

For more than 25 years, the Australian Academy of Science received funding from the Australian Government through the ACCSP, which was used to support the WCRP, International Geosphere-Biosphere Programme (IGBP), and Scientific Committee on Oceanic Research (SCOR), as part of the ACCSP's international reach. In 2016, however, the program was closed and consequently, financial support for WCRP, IGBP (now replaced by Future Earth) and SCOR ceased at the end of 2015. CSIRO, AAD and BOM are committed to continued support for the WCRP and SCOR for the immediate future, although long-term support remains uncertain. Australian scientists report a loss of international standing as a result of Australia not paying these relatively small contributions.

4.4. Information and infrastructure financial relationships

Australia has a number of financial relationships to maintain or operate infrastructure, or provide and manage information (Table 4).

Argo Australia is an IMOS facility connected to the international Argo Network that deploys thousands of robotic drifting probes which monitor ocean observations essential for climate research. Argo data is extensively used by organisations undertaking ocean or climate research. NCRIS provides $300,000 per year for the telecommunications requirements for the Australian Argo Fleet, which connects the drifting probes to the two global data assembly

centres in France and the USA. CSIRO contributes $100,000 to help manage these datasets and contributes capital to buy replacement equipment.

CSIRO undertakes contract work for Pacific and Southeast Asian countries, providing climate research and services. This is funded by the Asian Development Bank, World Bank and Pacific communities.

The Cape Grim Baseline Air Pollution Station is a collaborative atmospheric observation station with the following funding and support:

- BOM supports Cape Grim infrastructure
- BOM and CSIRO jointly fund the science program
- funding is received from MIT and NASA to support activities that contribute to the Advanced Global Atmospheric Gases Experiment (AGAGE)
- measurement systems used by AGAGE are developed and supported by the Scripps Institute of Oceanography (USA), the University of Bristol (UK), and the Swiss Federal Laboratories for Materials Science and Research. Of AGAGE's 14 sites, only two are in the southern hemisphere
- Cape Grim flask samples are used by NOAA (USA), Heidelberg University (Germany), Scripps Institute of Oceanography (USA) and the Max Planck Institute (Germany) as in-kind support for programs formally recognised as Cape Grim cooperative projects.

The cost of calibration standards used to compare Australian atmospheric composition measurements to international measurements of the WMO and AGAGE is paid by CSIRO and project partners.

Table 4. Major Australian financial contributions to international programs.

Organisation	Domestic partners	International partnerships	Description	Australian financial contribution
Centre of Excellence for Climate System Science	UNSW, MU, UTAS, ANU, UOM, ANDS, BOM, CSIRO, NCI, Department of Climate Change and Energy Efficiency, NSW Department of Environment, Climate Change and Water	Hadley Centre (UK), Centre National de la Recherche Scientifique (France), National Centre for Atmospheric Research (USA), National Centre for Atmospheric Science (UK), University of Arizona (USA)	Resolving uncertainties in regional climate science.	$21.4 million ARC funding from 2011-2017
Centre of Excellence for Climate Extremes	UNSW, MU, UTAS, ANU, UOM, BOM, CSIRO, NCI, Risk Frontiers Group Pty Ltd, NSW Office of Environment and Heritage	Met Office (UK), Swiss Federal Institute of Technology (Switzerland), Laboratoire Atmosphères, Milieux, Observations Spatiales (France), Centre National de la Recherche Scientifique (France), Institut national des sciences de l'univers (France), Institut Pierre Simon Laplace (France); National Center for Atmospheric Research, University of Arizona (USA), NOAA (USA), NASA Jet Propulsion Laboratory (USA), NASA Goddard Space Flight Center (USA); Max Planck Institute for Meteorology (Germany).	Research to understand and predict global climate extremes.	$30.05 million ARC funding and $62 million cash and in-kind commitments from participating organisations from 2017- 2023

Table 4 (continued). Major Australian financial contributions to international programs.				
Organisation	**Domestic partners**	**International partnerships**	**Description**	**Australian financial contribution**
Antarctic Climate and Ecosystem Cooperative Research Centre	AAD, BOM, CSIRO, UTAS, Department of the Environment and Energy	Alfred Wegener Institute (Germany), National Institute of Water and Atmospheric Research (NZ)	Research to understand how the physical environment of Antarctica and Southern Ocean are changing	Financial contributions from core partners, $25 million CRC program funding over 5 years, various externally funded projects
Centre for Southern Hemisphere Ocean Research (CSHOR)	UNSW, CSIRO, UTAS	Qingdao National Laboratory for Marine Science and Technology (QNLM)	Research to understand how southern hemisphere oceans influence global and regional climate.	$10 million in funding over 5 years from the Chinese government. Co-contributions from domestic partner organisations.
Unified Model Partnership	BOM, CSIRO	UK Met Office	Partnership agreement for Unified Model	5 FTE from the Bureau and CSIRO towards UM development. Yearly financial contribution (~$200K), jointly managed by the UM partners and invested in development.

5. Opportunities and risks

Australia cannot contribute to the global climate science effort if it does not have a domestic capability. Additionally, Australia cannot collaborate internationally without bringing something to the table. This is increasingly true as global political uncertainty may lead to reductions in the ability of Australia's most important international collaborators to maintain their generous contributions.

In 2016, the Australian Academy of Science's *Australian Climate Science Capability Review* identified areas of domestic investment that have fallen below critical mass to the point where they are considered by senior researchers to be compromised. To obtain the benefits of effective collaboration and to leverage international climate science towards Australian needs, Australia needs to ensure these base capabilities are maintained. The following areas are particularly under threat.

- **Australia's modelling capability** is critically under-resourced—advancement of ACCESS has stalled in lieu of maintenance to keep up with updates of its components. This jeopardises Australia's strong modelling reputation, built on good performance in previous IPCC Assessment reports, and most recently, CMIP5. It also risks ACCESS being left behind as international models become more advanced, not only through improvements in representation of basic biophysics but also of crucial biogeochemical cycling and land use change.
- **Observational infrastructure** is needed to ensure global coverage of international networks. Australia maintains observations in underrepresented locations including East Antarctica and the Southern Ocean and on Australia's land mass, where biogeographical properties such as aerosol climate and flora are globally unique. However, atmospheric composition observing infrastructure is limited to Cape Grim, RV *Investigator*, GASLAB and ICELAB. Observational infrastructure should be given stable and predictable funding and adequately cover underrepresented areas, such as the deep water moorings in the Southern Ocean and around and on Antarctica, and those that contribute to global carbon cycle estimation and satellite calibration and validation activities, such as OzFlux and Aerospan.
- **Antarctic and Southern Ocean climate science** is a major component of the Australian Antarctic Science Program. Over the last 25 years a significant proportion of this program has been delivered by the Antarctic Climate and Ecosystems Cooperative Research Centre and its core partners AAD, CSIRO, UTAS and BOM. Collectively the ACE CRC has provided specialist capability in translating climate research to services for international and national stakeholders. As current cooperative research centre funding rules mean that it cannot be funded beyond 2019, the capability that it has built needs to be preserved. The government is currently considering Antarctic science funding as a Year Two action under the Australian Antarctic Strategy and 20-year Action Plan.

Opportunities and risks for Australia's international climate science engagement are further listed on pages 39–41.

Table 5. Opportunities for Australia's climate science				
Opportunity	**Importance**	**International connection**	**Solution**	**Timeframe**
National coordination of Australian climate science	International engagement can be more efficiently coordinated by better coordination of Australia's climate science pipeline	International organisations and partners	Adopt recommendations of the Australian Academy of Science 2016 climate science review	Immediate
Increased engagement with Asia-Pacific nations through improved climate services	The Australian climate science pipeline can be used to provide tailored services to improve collaborations, the resilience of developing nations, and meet international obligations under the UNFCC	Asia-Pacific neighbours and international aid organisations including the World Bank and Green Climate Fund	Restore domestic capability. Engage with climate service providers in Australia	Long term
Attract and retain international climate scientists	Australia is an attractive location for international scientists to study and work	Attract international expertise to Australia	Ensure visa laws are conducive to retaining scientists with capabilities needed in Australia	Immediate
EU ERC's Horizon 2020 research programs	Australia has been invited to join large scale, well-funded research programs. Limited funding exists to connect Australian researchers with these programs	European Commission and European research community	Develop a program of funding to enable Australian researchers to participate in and contribute to Horizon 2020 projects, e.g.through a dedicated ARC program	Immediate
Ongoing support of the European Commission's Copernicus program	The Copernicus program provides information services based on Earth observing satellites and in situ data. Its integrated approach links observation infrastructure, eResearch tools, and modelling to provide directed services	Geoscience Australia provides data services to the Copernicus program to provide a regional data hub and acts as a coordination point for calibration and validation data	Continue coordination and support for satellite calibration and validation activities. Investigate opportunities for further collaborations	Long term
Maximise use and impact of integrated assessment modelling (IAM)	IAM integrates economic, population, and health processes into climate modelling to answer important questions about what the impact of climate change will be and what adaptation measures are effective	Combine international expertise in IAM with Australia's domestic climate modelling capability	Sustain funding	Long term
Engagement in major international collaborations	Leveraging international expertise for national benefit requires domestic capability which can be developed through collaborations in international missions.	CMIP6 Model Intercomparison Projects Biogeochemical Argo Deep Water Argo PACE aerosol mission GOCI-2 ocean colour mission SWOT swath altimetry mission	Provide ongoing, predictable funding to engage in international collaborations	Medium term
Develop Gunn Point, Northern Territory, into a baseline air monitoring station	Tropical atmospheric composition measurements are underrepresented in international observation networks. Gunn Point is in a good location and has a long history of weather measurements	Collaborations with WMO, AGAGE, GAW and others	Sustain funding	Long term

Table 6. Risks to Australia's climate science				
Risk	**Importance**	**International connection**	**Solution**	**Timeframe**
Risks to international standing and reputation				
Loss of climate observation capacity	Australia leverages the outputs from its climate observational infrastructure for access to international outputs. Loss of continuous domestic observation capacity interrupts long-term data series and reduces the quality of climate research at many levels	Observational infrastructure is needed to ensure global coverage of international networks, especially in East Antarctica and the Southern Ocean	Ensure long-term, stable and predictable funding for observation infrastructure.	Medium term
Not being able to provide a contribution to CMIP6 that reflects meaningful development of Australia's ACCESS model in the past four years	Australia enjoys a strong modelling reputation from the performance of ACCESS in CMIP5. This has given Australian researchers influence in the international coordination of modelling activities, especially in the southern hemisphere	Participation in CMIP6 and continued engagement with the international modelling community	Adequately fund ACCESS and develop a holistic stable funding package which includes eResearch and software engineering support	Immediate
Australian scientists being unable to attend international organisations on which they hold leadership positions	International climate science organisations connect Australian science with international colleagues and promotes Australia's national agenda in large-scale well-funded programs. This furthers Australia's international reputation and 'soft power' through science. It also ensures Australian science aligns with and is recognised by international efforts	Australia's contribution to the leadership of international consortia and meetings, including the Intergovernmental Panel on Climate Change and the World Climate Research Programme	Support climate scientists to attend international meetings and contribute to international collaborations like the IPCC	Immediate
Australia losing capability to provide satellite calibration and validation services to international space programs	Australia has no Earth observing satellite infrastructure but receives extensive data from international satellite missions. By providing calibration and validation services, the accuracy of the data over Australia is improved and goodwill is maintained with organisations undertaking satellite missions	Contribute to and access global datasets	Ensure long-term stable funding for satellite calibration and validation infrastructure, especially Aerospan (CSIRO) and OzFlux (TERN)	Long term
Risks to Australia's ability to leverage international climate science to national needs				
Loss of model development capability due to chronic under-resourcing	ACCESS has a staffing of 27% of what was specified in the ACCESS project plan (21 FTE out of a required 78 FTE). Research scientists are undertaking the role of software engineers to maintain ACCESS and keep up with international model updates. This has led to poor research and climate service outputs, problems with staff retention, and the risk of losing modelling capability	Unable to adapt international model developments and data to Australia's unique landscape, flora, and climate conditions	Provide sufficient well-resourced software engineers, data scientists, and research scientists needed to maintain and further develop ACCESS. Provide funding commensurate with its national importance	Medium term
Loss of climate science capability in Australia	Aspects of climate capability are at risk of being lost due to retirement or job losses, including boundary layer and micrometeorology, integrated assessment modelling, and atmospheric aerosol measurements	Less able to apply international outputs in those fields to Australian context	Adopt recommendations of 2016 Australian Academy of Science climate science review	Medium term

Table 6 (continued). Risks to Australia's climate science				
Risk	**Importance**	**International connection**	**Solution**	**Timeframe**
Closure of the Antarctic Climate and Ecosystems Cooperative Research Centre	The ACE CRC provides specific Antarctic and climate science services to Australian businesses and governments using international information and infrastructure. Although the core partners may be able to replicate some services of ACE CRC, no domestic organisation currently has the capability to replace all of ACE CRC's services	Utilisation of international data and products. International sea ice charting. International scientific collaborations	Explore and implement mechanisms to effectively maintain or grow this capability	Long term
Losing leadership role in international climate science coordination	Not being fully involved with the World Climate Research Programme, Intergovernmental Panel on Climate Change, and other research collaborations severely restricts the extent to which Australian scientists can leverage the international climate science effort to national needs	International research collaborations provide high level science coordination and support. National science programs are typically aligned to these	Continue to properly support participation in international research collaborations e.g., the World Climate Research Programme, SCOR, and Future Earth	Immediate
Not meaningfully contributing to CMIP6	CMIP is a chance to test and benchmark ACCESS against world leading models, this helps identify biases in model output and overall improves accuracy and precision. The output of CMIP is used as the best available evidence for IPCC assessment reports. ACCESS is known as the best model for southern hemisphere observations based on its CMIP5 performance	Comparison of national modelling capability against international models. Chance to reinforce that Australia has maintained a world class climate model	Adequately fund ACCESS and develop a holistic stable funding package which includes eResearch and software engineering support	Immediate

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7. Appendix

7.1. List of survey responses received

Individuals

The report committee is grateful to the following individuals who responded to our survey in a private capacity:

Associate Professor Nerilie Abram
Dr Michael Ashcroft
Professor James Bowler
Professor John Church
Dr Stuart Corney
Professor Patrick De Deckker
Dr Catia Domingues
Dr Dietmar Dommenget
Dr Randall Donohue
Dr Stephanie Downes
Associate Professor Jason Evans
Dr Andrew Glikson
Dr Melissa Hart
Dr Will Hobbs
Associate Professor Andy Hogg
Dr Ryan Holmes
Professor Christian Jakob
Professor David Karoly
Dr Melita Keywood
Dr Marit Kragt
Associate Professor Todd Lane
Dr Simon Marsland
Dr Samuel Marx
Dr Terry O'Kane
Dr Bradley Odpyke
Dr Anthony Purcell
Professor Peter Rayner
Dr Tom Remenyi
Dr Robyn Schofield
Dr Martin Singh
Professor Will Steffen

A further 32 responses were made from individuals who wished to keep their submission confidential.

Organisational submissions

The report committee is grateful for the assistance of the following organisations for their contributions:

Australian Antarctic Division

Antarctic Climate and Ecosystems Cooperative Research Centre

Australian Institute of Marine Science

ARC Centre of Excellent for Climate System Science

Bureau of Meteorology

CSIRO

Integrated Marine Observing System

7.2. Committee member biographies

Emeritus Professor Neville Nicholls FAA

Professor 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.

Professor Jean Palutikof

Professor Palutikof is Director of the National Climate Change Adaptation Research Facility at Griffith University. Her research interests focus on climate change impacts, and the application of climatic data to economic and planning issues. She specialises in the study of changes in extreme events and their impacts, especially windstorm.

Professor John Church FAA FTSE FAMOS

Professor Church is an expert in estimating and understanding global and regional sea-level variability and change, and Earth's energy budget. He has made major contributions to international climate research over many years through membership and chairing of the Scientific Steering Group of the World Ocean Circulation Experiment and the Joint Scientific Committee of the World Climate Research Programme, and contributions to the Global Climate Observing System.

Professor Ian Allison AO FAA AAM FAMOS

Professor Allison is a pioneer of Australia's glaciological research, investigating shrinking ice shelves and the link to climate change. He has made significant contributions to the Intergovernmental Panel on Climate Change Assessment Reports. He has led the Ice, Oceans, Atmosphere and Climate program of the Australian Antarctic Division and was co-chair of the International Polar Year in 2007–08.

Professor John Finnigan FAA

Professor Finnigan is Director of the CSIRO Centre for Complex Systems Science. His research focuses on measuring and modelling complex physical and social–ecological systems. He joined CSIRO in 1972 and has been Chief Research Scientist with Land and Water, Atmospheric Research, and Marine and Atmospheric Research. He chairs the Australian Academy of Science's National Committee for Earth System Science.

Professor Matthew England FAA

Professor England is Deputy Director of the UNSW Climate Change Research Centre. His research explores global-scale ocean circulation and the influence it has on regional climate, large-scale physical oceanography, ocean modelling and climate processes, with a particular focus on the southern hemisphere. His work has made significant impact on the treatment of water-mass physics in models, on the methodologies of assessment of ocean and climate models, on our understanding of large-scale southern hemisphere climate modes, and on the mechanisms for regional climate variability over Australia.

7.3. Terms of Reference

The Australian Academy of Science will complete the following activities:

1. Develop an activity map showing locus of Australian climate science effort across by theme and organisation type, across all Australian universities and publicly funded research organisations engaged in climate research and services, including their linkages to international climate science organisations.
2. Identify and characterise *all* of the information and infrastructure relationships that exist between Australia's public climate science and climate information agencies and international equivalents, including:
    a. information and infrastructure partnerships;
    b. information and infrastructure dependencies (bidirectional and unidirectional);
    c. financial relationships, to the extent information is supplied and/or publicly available.
3. Identify and characterise *the majority* of information, infrastructure and human capital relationships that exist between Australian university climate research programs and international equivalents and agencies, including funding relationships where they exist.
4. Characterise human capital flows in terms of Australian and international climate scientist mobility (employment, training and exchange).
5. From this analysis, map Australia's key international climate science and information relationships and dependencies in terms of:
    1. Knowledge and information access and exchange;
    2. Physical infrastructure access;
    3. Funding flows;
    4. Human capital.
6. Referencing the strengths and weaknesses identified by the previous review in Australia's domestic climate science capabilities, identify and evaluate current and potential future risks and opportunities for Australia arising from its international climate science and information relationships and dependencies.
7. Present this information and analysis in a report/s delivered to the Department.

7.4. Table A1. Australian climate observation infrastructure

Table A1. Australia's climate observing network, by essential climate variable, and their contribution to international network, where applicable.

Climate observation	Network Type	Name	Agency	International network
Surface atmosphere				
Temperature	Surface network	ACORN-SAT Weather Stations	BOM	GOS, GSN
	Surface network	Bureau Weather Station	BOM	GOS
	Surface network	Antarctic Automatic Weather Station	AAD	Automatic Weather Station Project
	Ships	Australian Voluntary Observing Fleet	BOM	GOOS
	Buoy	Antarctic Drifting Buoys	AAD, ACE CRC	GOOS
	Buoy	Drifting Buoy Program	BOM	GOOS
Pressure	Surface network	Bureau Weather Station	BOM	GOS, GSN
	Surface network	Antarctic Automatic Weather Station	AAD	Automatic Weather Station Project
	Buoy	Antarctic Drifting Buoys	AAD, ACE CRC	GOOS
	Buoy	Drifting Buoy Program	BOM	GOOS
Wind speed and direction	Drifting Buoys	Drifting Buoy Program	BOM	GOOS
	Surface network	Antarctic Automatic Weather Station	AAD	Automatic Weather Station Project
	Surface network	Bureau Weather Station	BOM	GOS, GSN
	Radar	Ocean Radar Facility	IMOS	GOS, GSN
Precipitation	Surface network	Bureau Weather Station	BOM	GOS, GSN
Water vapour	Surface network	Bureau Weather Station	BOM	GOS, GSN
Surface radiation budget	Surface network	BSRN, GAW Regional and Global	BOM, CSIRO	GAW
Upper atmosphere				
Temperature	Ground based balloon	Bureau Weather Station	BOM	GOS, GSN
Wind speed and direction	Ground based balloon	Bureau Weather Station	BOM	GOS, GSN
Cloud properties	Ground based balloon	Bureau Weather Station	BOM	GOS, GSN
	Surface network	Aerospan	CSIRO	Aeronet
Atmospheric composition				
Carbon dioxide	Surface network	TCCON	UOW	GAW
	Surface network	Surface flasks	BOM	ESRL CCGG
	Surface network	Cape Grim Station	BOM, CSIRO, ANSTO, UOW	GAW
	Surface network	OzFlux	TERN	FluxNet
Methane and other long-lived greenhouse gases	Surface network	Cape Grim Station	BOM, CSIRO, ANSTO, UOW	GAW
	Surface network	GAW Regional	BOM	GAW
	Surface network	Surface flasks	BOM	ESRL CCGG
	Surface network	TCCON	UOW	GAW
Ozone	Surface network	Cape Grim Station	BOM, CSIRO, ANSTO, UOW	GAW
	Ground based balloon	GAW Regional	BOM	GAW
Aerosol properties	Surface network	GAW Regional	BOM	GAW
	Surface network	NDACC	BOM, UOW, NIWA	GAW
	Surface network	Aerospan	CSIRO	Aeronet

Table A1 (continued). Australia's climate observing network, by essential climate variable, and their contribution to international network, where applicable.

Climate observation	Network Type	Name	Agency	International network
Aerosol and ozone precursors	Surface network	GAW Regional	BOM	GAW
Surface ocean				
Temperature	Drifting Buoys	ARGO Australia	IMOS	GOOS
	Drifting Buoys	Drifting Buoy Program	BOM	GOOS
	Ships	Ships of Opportunity	IMOS	GOOS
	Moored buoys	Deep Water Moorings	IMOS	GOOS
	Ocean gliders	Ocean Gliders	IMOS	GOOS
	Tagged animals	Animal Tracking	IMOS	GOOS
	Drifting buoys	Antarctic Drifting Buoys	AAD, ACE CRC	GOOS
Salinity	Drifting buoys	ARGO Australia	IMOS	GOOS
	Drifting buoys	Drifting Buoy Program	BOM	GOOS
	Ships	Ships of Opportunity	IMOS	GOOS
	Moored buoys	Deep Water Moorings	IMOS	GOOS
	Ocean gliders	Ocean Gliders	IMOS	GOOS
	Tagged animals	Animal Tracking	IMOS	GOOS
Currents	Drifting buoys	Drifting Buoy Program	BOM	GOOS
	Ships	Ships of Opportunity	IMOS	GOOS
	Moored buoys	Deep Water Moorings	IMOS	GOOS
	Radar	Ocean Radar Facility	IMOS	GOOS
Sea level	Drifting Buoys	ARGO Australia	IMOS	GOOS
	Moored buoys	Deep Water Moorings	IMOS	GOOS
	Moored buoys and ships	Waverider Buoy Program	BOM	GOOS
	Surface network	SEA Level Fine Resolution Acoustic Measuring Equipment	BOM	GLOSS / GOOS
	Surface network	Coastal tide gauges	State Agencies	GLOSS / GOOS
Sea state	Moored buoys	Deep Water Moorings	IMOS	GOOS
	Moored buoys and ships	Waverider Buoy Program	BOM	GOOS
	Ships	Ships of Opportunity	IMOS	GOOS
	Moored buoys and ships	Australian Voluntary Observing Fleet	BOM	GOOS
Ocean surface stress	Moored buoys and ships	Australian Voluntary Observing Fleet	BOM	GOOS
Sea ice	Buoy	Antarctic Drifting Buoys	AAD, ACE CRC	GOOS
	Ships	Sea-ice observations	AAD	ASPeCT (WCRP)
	Observations	Snow on sea ice	AAD	ASPeCT (WCRP)
Subsurface ocean				
Temperature	Ships	XBT Probes + Ships of Opportunity	BOM, IMOS	GOOS
	Drifting Buoys	ARGO Australia	IMOS	GOOS
Salinity	Drifting Buoys	ARGO Australia	IMOS	GOOS
	UAV	Ocean Gliders	IMOS	GOOS
	Tagged animals	Animal Tracking	IMOS	GOOS
	Moored buoys	Deep Water Moorings	IMOS	GOOS
	Ships	Ships of Opportunity	BOM, IMOS	GOOS

Table A1 (continued). Australia's climate observing network, by essential climate variable, and their contribution to international network, where applicable.				
Climate observation	**Network Type**	**Name**	**Agency**	**International network**
Currents	Drifting Buoys	ARGO Australia	IMOS	GOOS
	UAV	Ocean Gliders	IMOS	GOOS
	Moored buoys	Deep Water Moorings	IMOS	GOOS
	Ships	Ships of Opportunity	BOM, IMOS	GOOS
Composition				
Oxygen	Drifting Buoys	ARGO Australia	IMOS	GOOS
	Unmanned autonomous vehicle	Ocean Gliders	IMOS	GOOS
	Ships	Ships of Opportunity	IMOS	GOOS
Nutrients	Drifting Buoys	ARGO Australia	IMOS	GOOS
	Unmanned autonomous vehicle	Ocean Gliders	IMOS	GOOS
	Ships	Ships of Opportunity	IMOS	GOOS
Inorganic carbon	Moored buoys	National Mooring Network	IMOS	GOOS
	Drifting Buoys	ARGO Australia	IMOS	GOOS
	Ships	Ships of Opportunity	IMOS	GOOS
Ocean colour	Unmanned autonomous vehicle	Ocean Gliders	IMOS	GOOS
	Drifting Buoys	ARGO Australia	IMOS	GOOS
Plankton	Drifting Buoys	ARGO Australia	IMOS	GOOS
Terrestrial hydrological				
River discharge	Surface network	Hydrologic Reference Station	BOM	
Groundwater	Surface network	Groundwater bores	BOM	
Soil moisture	Surface network	Supersite	TERN	
	Surface network	OzFlux	TERN	FluxNet
Terrestrial cryosphere				
Snow	Observations	Snow monitoring program	Snowy Hydro	
Terrestrial biosphere				
FAPAR (fraction of incoming solar radiation contributing to PAR)	Surface network	Supersite	TERN	
	Surface network	OzFlux	TERN	FluxNet
LAI (leaf area per ground area)	Surface network	Supersite	TERN	
Land-surface temperature	Surface network	Supersite	TERN	
	Surface network	OzFlux	TERN	FluxNet
Land cover	Surface network	Supersite	TERN	
Above-ground biomass	Surface network	Supersite	TERN	
Soil carbon	Surface network	Supersite	TERN	
Fire	Surface network	Aerospan	CSIRO	Aeronet

7.5. Table A2. Australia's calibration and validation activities

Table A2. Australia's calibration and validation activities				
Sites	**Organisations**	**What they do**	**International Network**	**Satellites**
Calibration				
Davis main Antarctic Fast Ice Network	AAD	Sea ice, meteorological data	WMO Global Cryosphere watch / GCOS	
AEROSPAN Sunphotometer Network	CSIRO	Aerosol types across Australia available via Aeronet	AERONET	
Vicarious Calibration, Atmospheric Measurement	CSIRO	Meteorological and atmospheric measurements	AERONET	
Vicarious radiometric calibration	DSITIA QLD	Vicarious radiometric calibration sites	USGS	
Ocean Altimetry	UTAS, CSIRO	Two field sites (Bass Strait and Storm Bay) for calibration and validation of ocean altimetry	GOOS	
SAR Corner Reflector Facility	GA	Calibration of space-borne SAR instruments	AusScope	
Macquarie Island radiosonde soundings	BOM	Meteorological profiles	WMO	
Validation				
Sea surface temperature	CSIRO, BOM, IMOS	Sea surface temperatures using both buoy and ship data	GOOS	NOAA-AVHRR, Himawari-8, Sentinel3
Solar irradiance	BOM	Validation of solar irradiance products		MODIS, NOAA_AVHRR
Aerosol product	CSIRO	Validation of MODIS atmosphere products, MISR aerosol products, AATSR	AERONET	AATSR, MODIS, Himawari
Lucinda Jetty Coastal Observatory	CSIRO, IMOS	IMOS national reference station. Sat ocean colour, optical properties, chl, suspended particulate material, coloured DOM	GOOS	MODIS, SUOMI NPP, OCM-2, Sentinel 3, HICO (on ISS)
Biological flux monitoring (OzFlux)	CSIRO, TERN	National ecosystem research network, consistent observations of energy, carbon, and water exchanges + micrometeorological measurements	FluxNet	various
Surface reflectance	Curtin, TERN	Hyperion surface reflectance, in-water inherent optical properties		MODIS, Hyperion
Biophysical map products	UQ , TERN	Biophysical map products		QuickBird, Worldview2, ALOS, Landsat, LDCM, SPOT, MODIS, Hyperion
Phenology product	UTS, JCU, TERN	Phenology and land surface temperature-derivative products at Supersites		Landsat, MODIS, NOAA-AVHRR, Hyperion
Soil moisture monitoring network (CosmOz)	CSIRO, Monash	Ground soil moisture probe network	SMAP	SMOS, Aquarius, AMSR-E, AMSR2, SMAP, MODIS
Groundcover	ABARES, UA, GA, TERN	Field observations for groundcover validation		MODIS
Disturbance	UOW	Disturbance validation		MODIS

Table A2 (continued). Australia's calibration and validation activities				
Sites	**Organisations**	**What they do**	**International Network**	**Satellites**
Vegetation properties	UQ, TERN,RMIT	High-resolution (30m) validation of groundcover and in situ terrestrial ecosystem observations and image validation	Landsat, QuickbBird, RapidEye, IKONOS, Landsat, Spot, MODIS, NOAA-AVHRR, DLR TET	
Rainfall product	BOM	Comparison and blending of rainfall gauge network to satellite products		Instruments including TRMM, microwave emissions
Fire products	CDU	Burnt area validation		AATSR, MODIS, Himawari, QuickBird, Worldview2, GeoEye, ALOS, Landsat, LDCM, SUOMI NPP, NOAA-AVHRR
Fire products	Landgate	Burnt area validation		MODIS, SUOMI NPP
Rainfall	BOM	Rainfall network		

7.6. Table A3. Satellites used by Australian climate scientists

Table A3. Satellites used by Australian climate scientists		
Satellite	**Agency**	**Purpose**
Jason 2- OSTM	NASA, CNES, NOAA, EUMETSAT	Physical oceanography, geodesy/gravity, climate monitoring, marine meteorology.
Jason 3	NASA, CNES, NOAA, EUMETSAT	Physical oceanography, geodesy/gravity, climate monitoring, marine meteorology.
NOAA-18	NOAA	Meteorology, agriculture and forestry, environmental monitoring, climatology, physical oceanography, volcanic eruption monitoring, ice and snow cover, total ozone studies, space environment, solar flux analysis, search and rescue.
NOAA-19	NOAA	Meteorology, agriculture and forestry, environmental monitoring, climatology, physical oceanography, volcanic eruption monitoring, ice and snow cover, total ozone studies, space environment, solar flux analysis, search and rescue.
MetOpA	EUMETSAT, NOAA, CNES, ESA	Meteorology, climatology.
MetOpB	EUMETSAT, NOAA, CNES, ESA	Meteorology, climatology.
Aqua	NASA, JAXA, INPE	Atmospheric dynamics and properties, including wind speed, upper air temperatures, water and energy cycles, cloud formation, precipitation and radiative properties, air/sea fluxes of energy and moisture, ozone concentration.
		Oceanic parameters including snow and sea-ice extent, heat exchange with the atmosphere and temperature.
Terra	NASA	Terrestrial biophysical parameters, including emissivity and temperature; aerosol, cloud water vapour, Ozone; snow cover; sea ice, sea ice motion. Operational polar weather and climate measurements. Fires and albedo.
Suomi NPP	NASA, NOAA	Operational polar weather and climate measurements. Ozone, cloud and aerosols, ocean colour, surface temperature.
Himawari-8	JMA	Meteorology, atmospheric and aerosol properties, ocean temperature.
Himawari-9	JMA	Meteorology, atmospheric and aerosol properties, ocean temperature.
CALIPSO	NASA, CNES	Aerosols, Cloud properties, Atmospheric temperature
Aura (MLS)	NASA	Chemistry and dynamics of Earth's atmosphere from the ground through the stratosphere.
Timed (Sabre)	NASA	Mesosphere and lower thermosphere energetics, chemistry, dynamics, and transport
MERLIN	CNES, DLR	Global atmospheric methane concentrations
OCO-2	NASA	High resolution CO2 measurements
EO-1 (Hyperion)	NASA	Terrestrial biophysical parameters, Sea Surface Temperature
GPM	NASA, JAXA	Precipitation measurements
Grace	NASA, DLR, GFZ (German Research Centre for Geoscience), ESA	Ice sheet and glacier mass balance; terrestrial hydrology; Development of gravity field models
CloudSat	NASA, CSA	Cloud physical parameters
CryoSat-2	ESA	Fluctuations in the mass of the Earth's major land and marine ice fields.
LANDSAT	US Geological Survey	Surface features and change; vegetation monitoring; ice motion (from feature tracking), etc
No longer being flown (data still used)		
TOPEX/Poseidon*	NASA,CNES	Ocean surface topography
SeaSat*	NASA	Ocean surface topography

Table A3 (continued). Satellites used by Australian climate scientists		
Satellite	**Agency**	**Purpose**
ICESAT (laser altimeter)	NASA	ice sheet mass balance, cloud and aerosol heights; land topography; vegetation characteristics
Envisat-ASAR (C-band)	ESA	Ice sheet mapping, motion, melt; snow climatology; sea ice mapping/motion; ocean waves; soil moisture; vegetation mapping; etc
GMS and MTSAT series (Himawari 1-7)	JMA	Meteorology.

7.7. Table A4. Reanalysis datasets identified by Australian researchers

Table A4. Reanalysis datasets identified by Australian researchers.		
Dataset	**Custodian Organisation**	**Purpose**
Reanalysis Datasets		
20CR	NOAA	Reanalysis of 20th Century weather observations, 1851-2012.
Australian Water Availability Project (AWAP)	CSIRO	Australian continental water availability, 1941-2014
Climate Forecast System Reanalysis (CFSR)	NCAR	Global, high resolution, coupled atmosphere-ocean-land surface-sea ice system, 1979-present
Common Ocean Reference Experiment (CORE)	NCAR	Global air-sea heat and water flux data, 1949-present.
CPC Merged Analysis of Precipitation (CMAP)	NOAA	Monthly global precipitation, 1979-present
Climate Research Unit datasets	University of East Anglia	Instrumental and paleoclimate data, 1850-present
ERA-Interim	ECMWF	Global atmospheric reanalysis dataset, 1979-present
ERA-20C	ECMWF	Surface pressure and surface marine winds reanalysis, 1900-2010.
ERA40	NCAR	Reanalysis incorporating satellite radiance data, cloud motion winds. 1979-present.
ERA5	ECMWF	Climate reanalysis dataset, 1950-present. Successor to ERA-Interim.
Extended Reconstructed Sea Surface Temperature (ERSST) dataset	NOAA	Global monthly sea surface temperature dataset, 1854-present.
Global Ocean Data Assimilation System (GODAS)	NCEP	High resolution multi-level ocean analysis, 1980-present.
Global Precipitation Climatology Centre (GPCC) dataset	NOAA	Global monthly precipitation dataset, 1901-present.
Global Precipitation Climatology Project (GPCP) dataset	NOAA	Global monthly precipitation dataset, 1979-present.
HadCRUT datasets	University of East Anglia/Hadley Centre	Combination of Hadley Centre sea surface temperature and UEA CRU land surface air temperature records, 1850-present.
Hadley Centre Sea Ice and Sea Surface Temperature (HADISST) dataset	UK Met Office.	Sea surface and sea ice temperature dataset, 1871-present.
International Satellite Cloud Climatology Project (ISCCP) datasets	NASA	Weather satellite cloud data, 1983-2009.
JRA 55	JMA	Full observing system reanalysis, 1958-2016.
Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2)	NASA	Comprehensive reanalysis dataset, 1980-present.
NCEP/NCAR Reanalysis project	NOAA	Analysis/forecast system, 1948-present.
Ocean Reanalysis System (ORAS)	ECMWF	Global ocean analysis, 1957-present.
Tropical Rainfall Measuring Mission dataset	NCAR	Evaluation of TRMM precipitation estimates, 1998-2009.

7.8. Table A5. Climate models used by Australian climate scientists

Table A5. Climate models used by Australian climate scientists.		
Model	**Developing Organisation**	**Use**
International Models		
Unified Model (UM)	UK Met Office, UK	Core atmospheric component of ACCESS
Modular Ocean Model (MOM)	NOAA, USA	Ocean physical model component of ACCESS
Met Office Surface Exchange Scheme (MOSES)	UK Met Office, UK	Land surface model component of ACCESS (older versions)
Joint UK-Land Environment Simulator (JULES)	UK Met Office, CEH NERC, UK	Land surface model component of ACCESS
Los Alamos Sea Ice Model (CICE)	Los Alamos National Laboratory, USA	Sea-ice model component of ACCESS
OASIS Climate Modelling Coupler	CERFACS and CNRS, France, and Deutsches Klimarechenzentrum, Germany	Model coupler for components of ACCESS
Multi-Column K Profile Parameterisation Ocean Model (KPP)	University of Reading, UK	Model used by researchers
Regional Ocean Modelling System (ROMS)	Rutgers University, USA	Model used by researchers
Model for Prediction Across Scales (MPAS)	Los Alamos National Laboratory and NCAR, USA	Model used by researchers
Earth System Modelling Framework (ESMF)	NASA; NSF NCAR, USA	Model coupler
Whole Atmosphere Community Climate Model (WACCM)	NCAR, USA	Model used by researchers
Generalised Ocean Layered Model (GOLD)	NOAA, USA	Model used by researchers
MetROMS (CICE sea ice model coupled to ROMS regional ocean modelling)	Norwegian Meteorological institute	Model used by researchers
Elmer/Ice (full-Stokes, finite element, ice sheet model).	CSC-IT Center for Science Ltd., Espoo, Finland.	Model used by researchers
SICOPOLIS (SImulation COde for POLythermal Ice Sheets)	Technische Hochschule Darmstadt, Germany / Hokkaido University, Japan	3D dynamic/thermodynamic model for sea ice
Parallel Ice Sheet Model (PISM)	University of Fairbanks, USA / Potsdam Institute for Climate Impacts Research, Germany	Model used by researchers
Ice Sheet System Model (ISSM)	NASA Jet Propulsion Laboratory, USA	Model used by researchers
CCSR Ocean Component Model (COCO)	University of Tokyo, Japan	Model used by researchers
UVic Earth System Climate Model	University of Victoria, Canada	Model used by researchers
LOVECLIM	Université Catholique de Louvain, Belgium	Model used by researchers
Community Earth System Model (CESM)	University Corporation for Atmospheric Research, USA	Model used by researchers
Domestic Models		
Australian Community Climate and Earth System Simulator (ACCESS)	CSIRO, BOM, UNSW, ANU, UoM, Monash, UTAS	Australia's Earth system simulator used for weather prediction and climate forecasting
Australian Community Ocean Model (AusCOM)	CSIRO, BOM, ACE CRC, UTAS, UNSW, Macquarie University	Ocean and sea-ice model components of ACCESS
Community Atmosphere Biosphere, Land Exchange (CABLE) model	CSIRO, BOM, UNSW, UTS/Curtin(?)	Terrestrial biogeochemistry model component of ACCESS, Contributes to South Africa's CSIR VRESM model
World Ocean Model with Biogeochemistry and Trophic-dynamics (WOMBAT)	CSIRO	Ocean biogeochemistry model component of ACCESS

Table A5 (continued). Climate models used by Australian climate scientists.		
Model	**Developing Organisation**	**Use**
Simple Carbon-Climate Model (SCCM)	CSIRO, BOM	Highly simplified deterministic model for integrated assessments or policy analysis
Calibrated Carbon Cycle Model- Carbon Nitrogen Phosphorus (CASA-CNP)	CSIRO	Global model of terrestrial biosphere
Framework for Ice Shelf- Ocean Coupling (FISOC)	AAD, ACE CRC, UTASw	Coupling ocean and ice shelf models to provide interactive development of cavity geometry
Monash Simple Climate Model (MSCM)	Monash University	A simple climate model for fast climate simulations
Models used for downscaling global models in Australia		
Cubic Conformational Atmospheric Model (CCAM)	CSIRO	Atmospheric downscaling model
BOM Statistical Downscaling Model (BOM-SDM)	BOM	
Weather Research and Forecasting Model (WRF)	NCAR, NOAA, Air Force Weather Agency, Naval Research Lab, University of Oklahoma, Federal Aviation Administration (US)	Downscaling model system used in NARCliM modelling and researchers - UNSW adaptations CORDEX registered
Beijing Climate Centre Climate System Model (BCC-CSM)	Beijing Climate Centre, China	
Beijing Normal University Earth System Model (BNU-ESM)	Beijing Normal University, China	
Canadian Earth System Model (CAN-ESM)	Environment Canada, Canada	
Complete Coupled System Model (CCSM)	NCAR, USA	
Euro-Mediterranean Center on Climate Change Carbon Earth System Model (CMCC-CESM)	European Network for Earth System Modelling, Italy	
National Centre for Meteorological Research General Circulation Model (CNRM-CM)	CNRM, France	
Geophysical Fluid Dynamics Laboratory Coupled Physical Model (GFDL-CM)	NOAA, USA	
Geophysical Fluid Dynamics Laboratory Earth System Model (GFDL-ESM)	NOAA, USA	
Hadley Global Environment Model - Carbon Cycle (HadGEM-CC)	Met Office, UK	
Institute Pierre Simon Laplace- Climate Model (IPSL-CM)	Institute Pierre Simon Laplace, France	
Model for Interdisciplinary Research On Climate (MIROC)	University of Tokyo, National Institute for Environmental Studies, and Frontier Research Center for Global Change, Japan	
Model for Interdisciplinary Research On Climate- Earth System Model (MIROC-ESM)	University of Tokyo, National Institute for Environmental Studies, and Frontier Research Center for Global Change, Japan	
Max Planck Institute- Earth System Model (MPI- ESM)	Max Planck Institute, Germany	
Meteorological Research Institute- Coupled Global Climate Model (MRI- CGCM)	Meteorological Research Institute, Japan	
Norwegian Earth System Model (NorESM)	Norwegian Climate Center, Norway	