Climate Processes Research in Australia

A report to the National Climate Science Advisory Committee

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Executive Summary

This report responds to a request by the National Climate Science Advisory Committee (NCSAC) for input to its strategic discussions in the area of climate processes research. Specifically, it summarises the current state of climate processes research in Australia, identifies gaps, and provides options for moving the area forward into the next decade.

The report is founded on two major initiatives. First, it presents the results of a large community survey on climate research in general and climate processes research specifically. In doing so, it refines the results of the recent Climate Science Capability Review conducted by the Australian Academy of Science. Second, the report details the outcomes of a workshop of current and emerging climate science leaders that discussed future priorities and options for future research coordination.

The report distinguishes *climate processes* from *climate phenomena*. *Climate processes* are the fundamental building blocks of the climate system. An individual climate process represents a particular interaction within the climate system. Examples for climate processes are the nucleation of cloud droplets, the uptake of CO_2 through leaf stomata, or the basal melt of ice sheets. *Climate phenomena* are the observable result of the complex interactions of climate processes. Examples for climate phenomena are the El-Niño Southern Oscillation (ENSO) or sea-level rise.

The key findings of the report are:

- Climate processes research provides the foundation to all climate research efforts. It is critical to the interpretation of the observational record. It underpins the understanding of the climate phenomena that influence Australia. It provides the knowledge embodied in modelling and prediction systems. Climate processes research is therefore fundamental in the provision of solutions to the challenges Australian society faces in relation to climate variability and change.
- A stocktake of climate processes research in Australia has revealed that:
    - A substantial effort in climate processes research exists across both government and university sectors.

    - Many of the key climate processes are well researched in Australia, but there are some gaps in which the research effort is either fragmented (e.g., cryospheric processes) or well below levels necessary to sustain the program of research (atmospheric physics).
    - In areas with unsustainably low levels of research capacity, Australia is in danger of losing critical expertise required to understand and develop prediction systems for climate phenomena such as ENSO or IOD.
- Confirming the findings of the Climate Science Capability Review conducted by the Australian Academy of Science in 2017, there are major shortcomings in the coordination of Australian climate research. As climate processes research can be carried out by small teams in isolation, it is particularly vulnerable to fragmentation; ensuring a high impact of climate processes research therefore requires a nationally coordinated program of work.
- Given the challenges above, this report makes the following recommendations:
    - Improving collaboration and coordination of climate processes research should be a priority for the short to medium term.
    - To maximise the effectiveness of the climate processes research program, it should be framed around compelling science questions that guide research towards solutions. We propose the following set of priority science questions to achieve this:
        - How is Australia's weather going to change in the future?
        - Can we anticipate climate surprises and their potential effects on Australia?
        - What aspects of Australian climate are predictable?
        - How does the cycling of energy, water, carbon, and nutrients interact with Australia's climate?
        - How does climate affect the habitability of Austral-Asian region?
- The report outlines a possible implementation pathway for the above recommendations targeted at increasing the impact that climate processes research has on the delivery of climate services to end users. The proposed implementation pathway includes three phases:
    - *Phase 1 - A community-wide research network*: The report recommends transforming the existing community research effort through moderate funding for a research network. This funding would be targeted at research collaboration, rather than research itself. It would support a small number of part-time network coordinators, provide opportunities for national and international researcher exchanges and organize community workshops using the science framework discussed above.
    - *Phase 2 - Accelerator Institutes:* After the successful establishment of a nationwide research network, the report recommends identifying key areas of climate processes research where a small dedicated effort could provide significant impact. The report recommends the establishment of small (10-20 staff) short-term (3-5 years) Accelerator Institutes in these critical areas. The institutes should be staffed by a combination of secondments from the partners as well as new hires as required.
    - *Phase 3 - A national climate research institute:* If, and only if, the first two phases have been successful, the report recommends revisiting the establishment of a national climate research institute. While the establishment of such an institute

would provide the most efficient framework for climate processes research, the consultation as part of this report concluded that the community is currently not ready for such an enterprise. However, this may change significantly if Phases 1 and 2 above are successful in transforming climate research in Australia.

- The report notes that Australia has a strong foundation in climate processes research, but that there are critical gaps emerging. The most important of those are key areas of atmospheric physics, cryospheric processes and model development. The report recommends closing these gaps by targeting ongoing recruitment to these areas and embedding them into a strong science framework, such as the one highlighted above.

1 Introduction

Our climate is changing. With the 2015 Paris agreement, the governments of the world have acknowledged this fact and have collectively established a framework to set mitigation targets aimed at limiting increases in global-mean temperature. This has dramatically shifted the goal posts for climate science (Marotzke et al., 2017). It is no longer sufficient for climate science to provide information on global and continental scales in order to support mitigation decisions. Instead, the climate science community must increase its efforts to provide information on how global changes manifest themselves regionally.

The requirement for regional-scale climate projections to support policymaking puts research into the detailed workings of the climate system ever more at the heart of the climate research effort. Answering critical questions for society, such as: "By how much will the temperature and rainfall in various parts of Australia change by 2050?" is intimately entwined with questions related to the fundamental processes that make up the climate system, such as: "How do low-level clouds react to changes in vertical motion or atmospheric stability?" or "How do plants regulate water and carbon exchanges in a warmer and more CO_2-rich environment?". Without answering questions of the latter kind, answers to the former will remain elusive at best and misleading at worst.

The purpose of this report is to provide a snapshot of the current state of research focused on climate processes within Australia, and to provide guidance toward future resourcing and coordination of climate process research in Australia. *Climate processes* are the fundamental building blocks of the climate system. An individual climate process represents a particular interaction within the climate system, from the microscopic processes involved in forming cloud droplets, to the processes governing the vast currents in the ocean. While there are many hundred such processes, the main groups of climate processes that are researched in Australia are listed and briefly described in Appendix 2.

Climate processes combine and interact in often complex ways to reveal the many *climate phenomena* that we observe and aim to understand and predict. For example, the El Niño – Southern Oscillation (ENSO) represents a phenomenon that is highly influential to Australia's climate. However, as depicted in Figure 1, ENSO itself is not a singular climate process. Rather, it is made up of the interaction of a number of different processes within the atmosphere and ocean. Changes of the trade wind system, summarized as *atmospheric dynamics*, cause changes in the ocean circulation described through both *large-scale* and *mesoscale ocean dynamics*. In combination with *mixed-layer processes* this leads to a change of the sea-surface temperature (SST) in the Pacific Ocean. The SST changes in turn are communicated to the lowest layers of atmosphere through process summarised as *air-sea interaction*. *Turbulence* and *convection* transfer the low-level imprint of the SST higher into the atmosphere, where they combine with *cloud microphysics* as well as *radiation* to cause distinct heating patterns in the atmosphere. Those in turn change the *atmospheric dynamics* and cause changes to the trade winds, closing the loop above.

It is worth noting that each of the process categories used in the example above are themselves a collection of many individual processes. For example, the term microphysics comprises dozens of different processes from the nucleation of cloud drops to the evaporation of rain. This seemingly simple example illustrates the depth of understanding required to fully comprehend even just one of the many phenomena that influence Australia's climate (Descriptions of the main climate phenomena researched in Australia are given in Appendix 2). Without such understanding, it will be impossible to fully describe, understand and predict Australia's climate, its variability, or how it may change under the influence of anthropogenic forcing.

The numbers in Fig. 1 identify the current Full Time Equivalent (FTE) research effort dedicated to the processes involved in ENSO in Australia (see section 3). These numbers illustrate that many of the key processes that collectively establish the ENSO phenomenon are well researched in Australia. This is particularly true for atmospheric and ocean dynamical processes. It is equally evident that there are major gaps in our ability to close the important feedback loops involved in ENSO; the research effort focussed on atmospheric radiation, turbulence and microphysical processes is well below the critical mass to needed to sustain a meaningful science capability. It is essential to recognise and alleviate these gaps, as a comprehensive understanding and ability to simulate this incredibly important phenomenon hinges on the weakest link in the chain. As a result, the loss of expertise in key atmospheric physical processes will inhibit the community's ability to comprehensively study ENSO. This highlights the need for a strategy to support a comprehensive program of climate processes research in Australia.

Climate processes research in Australia is undertaken by all participants in the climate research effort. This includes government organisations as well as the university sector. The most prominent government organisations contributing to climate processes research are the Bureau of Meteorology and the CSIRO, with smaller efforts at ANSTO, the AAD and AIMS. The university sector is currently most prominently represented through the ARC Centre of Excellence for Climate Extremes, which unites groups at the University of New South Wales, Monash University, the University of Melbourne, the Australian National University and the University of Tasmania. However, the overall effort is distributed much more widely and includes many groups in universities across all states.

The widely distributed approach to climate processes research enables even small groups to contribute. This provides a particular challenge to effectively organising the research effort. While the processes in Fig. 1 can be studied in isolation, it is their interactions that establish the ENSO phenomenon and that make them important to the climate system. Hence, a meaningful program on climate processes research must be deeply collaborative among often small and disperse groups, a topic we will return to in later sections of this report.

The Australian Academy of Science (AAS) undertook a Climate Science Capability Review in 2017. It assessed the climate science effort as a whole and concluded that despite its significant science capabilities, there were several critical gaps, most notably in climate modelling, some areas of climate understanding and integrated assessment modelling. The AAS review also noted "weaknesses in coordination and resourcing arrangements for Australian climate science that create avoidable inefficiencies". It recommended sizeable increases in personnel in a number of areas as well as offering options for improvements in coordination. While comprehensive, the review did not investigate climate processes research efforts in Australia to a great level of detail.

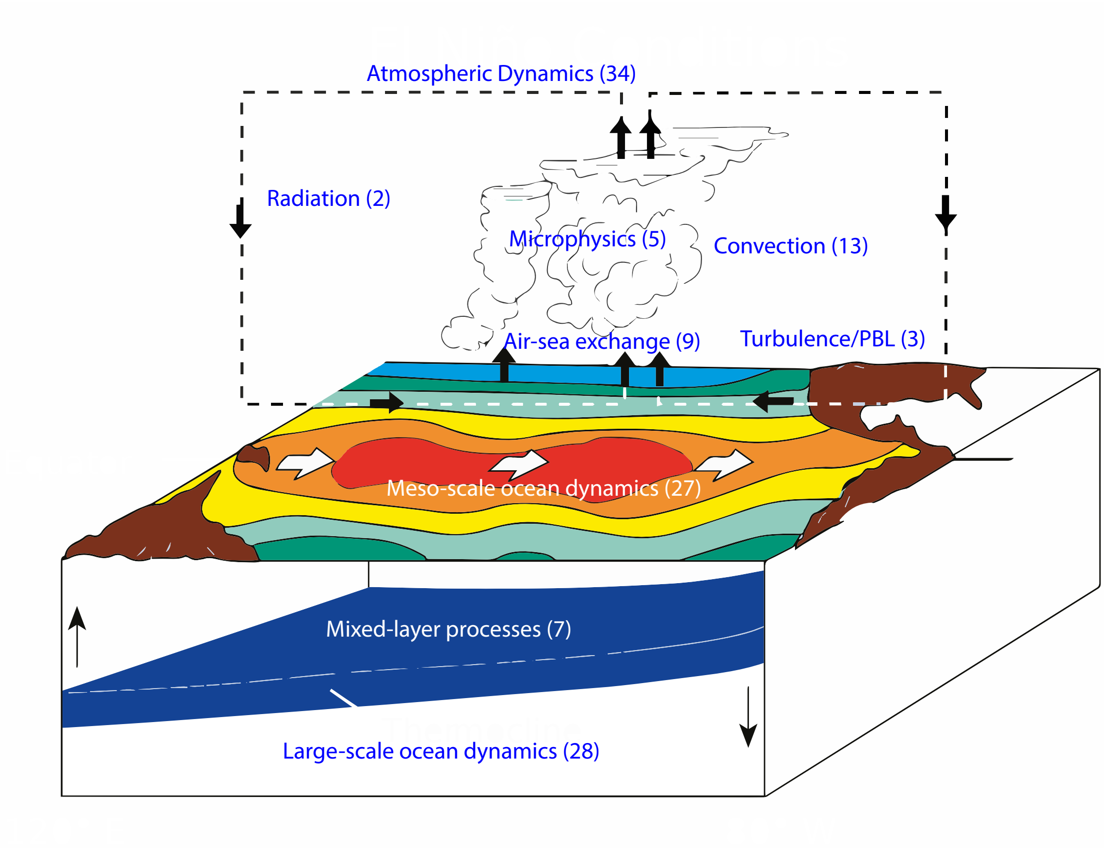

Figure 1 – Schematic of the ENSO climate phenomenon and the major climate processes involved. Numbers indicate the current FTE dedicated to research on the particular processes in Australia. See section 3 for more detail.

Building on the findings and recommendations of the Academy report, this document establishes a more in-depth picture of the status quo of Australian climate processes research. We are motivated by the terms of reference provided by the NCSAC (Appendix 3). The report is based on a community-wide consultation process. This was achieved in two ways. First, a survey of current efforts in climate processes research was undertaken (Section 3, Appendix 4). The survey approached team leaders across the entire climate research community who were asked to provide information on their team's research efforts. Second, a two-day workshop of current and emerging leaders from all major research organisations was held to discuss gaps, priorities and approaches to future research on climate processes. This workshop influenced all major discussions in this report.

The report is structured as follows. Section 2 outlines the challenges ahead. This includes scientific, technological and organisational challenges. Section 3 provides the main outcomes of the community survey. In doing so, it summarises the status quo in climate processes research in Australia. This sets the scene for a discussion of strengths, weaknesses and gaps in the current effort in Section 4. Section 5 looks ahead and aims to identify priorities for future research. It also provides options for further discussion on how to best implement the vision provided in the earlier sections of the report. Section 6 provides a short summary of the main conclusions.

2 The Challenges ahead

Society is increasingly relying on both scientific and practical information provided by weather and climate services for its decision making. This has increased the demand on climate science to answer societally relevant questions about the future of our planet globally, regionally and locally. Providing this information requires both a deeper understanding of the climate system and the translation of this understanding into predictive modelling tools for all timescales of interest. The scientific foundation upon which this understanding and modelling must be built lies in the study of climate processes and the climate phenomena that their interaction reveals. Addressing these challenges requires a well-coordinated research program that optimally combines observations of the past and present, models and theoretical insights.

Both the importance and challenges of constructing such a research program cannot be underestimated. The climate we observe and whose future we aim to predict is made of hundreds of individual processes. All of them are important, some of them are critical. For example, it has long been known that cloud processes, in particular those in low clouds, critically determine the climate sensitivity, i.e., the global mean temperature change for a given change in greenhouse gases, of most contemporary climate models. The processing of carbon by plants, including its limitations through nutrients and water, critically controls carbon feedbacks that affect the magnitude of longer-term climate changes as well as soil water availability, streamflow and water storages that serve the needs of towns, communities and ecosystems. Melt processes at the base of ice sheets, which strongly interact with the ocean circulation, are critical for sea level rise. These are but a few examples that connect societally relevant issues directly to climate processes.

Generally, observations of the climate system cannot directly reveal the operation of individual climate processes. While highly specialised field studies can in principle be focused on a particular process, such studies are rare and resource intensive. Typically, we observe climate phenomena rather than climate processes. As a consequence, developing understanding of the climate system requires both theoretical and computational models that interpret the observations and reveal the underpinning processes. Importantly, these tools are essential in separating the critical from the important processes, thereby providing prioritisation to the research effort.

Weather and climate models, such as the Australian Community Climate and Earth System Simulator (ACCESS) system in Australia, provide a unifying tool for climate processes research. They embody the collective knowledge of the climate science community and combine this knowledge with hi-tech solutions to meet the computing and data challenges associated with making practical predictions. Improving both our understanding of the climate system and predictions of its future requires an acceleration in our ability to simulate the climate faithfully. The challenge to respond to society's needs for more detailed, accurate, and perhaps more certain, climate information requires first and foremost a well-coordinated research effort underpinned by observational and modelling capabilities and tied together by climate processes research. This translates to three major sets of challenges for climate science and consequently its underpinning research on climate processes. They are i) the science challenge, ii) the technology challenge, and iii) the community challenge.

The science challenge

To be able to organise and prioritise a successful national effort on climate process research requires the identification of the main science questions that can underpin an impactful climate service in Australia. This is best achieved through a small number of simple yet deep, fundamental yet societally relevant, and challenging yet achievable, science questions. While a range of such questions could be considered, a number of recurrent themes emerged during community consultation. Informed by these themes, we suggest a set of five priority questions that encompass the science challenges for the Australian climate research community over the next decade:

- How is Australia's weather going to change in the future?
- Can we anticipate climate surprises and their potential effects on Australia?
- What aspects of Australian climate are predictable?
- How does the cycling of energy, water, carbon, and nutrients interact with Australia's climate?
- How does climate affect the habitability of Austral-Asian region?

We conjecture that these five simple questions can form the backbone of Australian climate research that strongly connects fundamental research to stakeholder needs. Answering these questions will deliver solutions to some of the most important challenges in mitigating and adapting to changes in the climate both driven by climate variability and anthropogenic forcing.

The "habitability question" provides the underpinning for the other four priority questions above, providing the nexus between different areas of climate science and between climate, climate impacts and the social sciences. Here, habitability is defined in a broad sense, encompassing habitability for humans as well as for other life, and as such it touches every aspect of society from human health to ecosystem viability, from agriculture and industry to national security. Future society, both locally and globally, will be critically shaped not by temperature and rainfall changes per se, but by how those affect the liveability for both humans and life in general in the regions of Australia and the world.

The "habitability question" itself informs and sets priorities for the other four priority questions. The "weather question" addresses how global changes will manifest themselves regionally as changes in the weather, including its extremes. This critically informs regional decision making on climate adaptation. The "surprises question" assesses the potential for surprises as the climate system undergoes major changes. This ranges from ice-sheet collapse with its effects on sea-levels to non-linear circulation responses with their effects on major Australian climate drivers. Improving our understanding of possible climate surprises is crucial in order to inform risk-based approaches to long-term planning both globally and regionally. The "predictability question" objectively identifies what information can truly be gleaned for the future and quantifies the uncertainty for changes in all major climate phenomena relevant to Australia. This information is critical for effective risk-based planning in virtually all sectors of society. Finally, the "cycles question" deals with those changes in the energy, water, carbon and nutrients cycles that are found to be most relevant to society. This provides a framework for the monitoring of both natural and anthropogenic influences on our resources. It vitally informs food and water security for the nation.

Put together, the five priority questions provide an innovative and flexible framework for solutions-focused climate science, one that can serve the needs of Australia for the coming decade. We show how such a framework can be used to help prioritise and resource climate processes research in the medium term in section 5.

The technology challenge

Executing the ambitious science program above requires Australia's research program to stay at the forefront of both observational and modelling capabilities. Researchers in Australia are fortunate to have access to data gathered by agencies around the world (e.g., satellite observations). But the benefits of such access can only be realised if sufficient scientific expertise is present within Australia to optimally exploit these data sources in our region. Moreover, observing the Australian continent and its surrounding seas will remain our own responsibility and constitutes a major contribution to the global effort.

Agreeing on a set of priority science questions, such as those posited above, will be vital to determine the most viable and impactful observational program for Australia. A clearly articulated set of scientific priorities is required to guide the scarce resources towards the most important observations to support Australia's needs as well as global efforts. It is beyond the remit of this report to discuss future observational needs. However, it is worth noting that to succeed, climate processes research will require access to both long-term and field study observations.

In addition to observations, a world-class climate simulation and prediction capability for Australia is another critical need for a comprehensive climate processes research program. It underpins the nation's ability to independently assess and predict climate variability and change. It also provides a focus for research activities on processes and phenomena that are most critical to our regional and local climate. ESMs and prediction systems are available from other countries. However, without significant local expertise in model design and application it will be difficult to ensure their effective use in research and prediction and to enable predictions to be effectively applied to decision making at all levels of society.

A current strength of the Australian climate research program is its modelling capability embodied in ACCESS. ACCESS is a set of modelling components that can be combined to provide predictions systems and science tools for a wide range of spatial and temporal scales. ACCESS underpins Australia's numerical weather and seasonal prediction capability as well as providing an Earth System Model for future climate projections.

While originally envisaged as seamless modelling tool using a small set of components, the ACCESS system has experienced a diffusion of efforts through the adoption of diverse model components for different applications across organisations. This has significantly impeded the community's ability to collaborate. The absence of dedicated support and resources for a well-defined set of ACCESS core model components reduces the ability of climate processes researchers to meaningfully engage with the modelling program. The recently proposed

ACCESS National Research Infrastructure (NRI), being considered under the National Collaborative Research Infrastructure Strategy, could provide a strong foundation for both simulation and prediction in Australia if adopted. Without it, the community will likely scatter and return to sub-critical modelling efforts with significant consequences for our ability to predict weather and climate at the world standard. Our community consultation revealed strong concern for the negative impacts on climate processes research if a national modelling system is not adequately supported.

Underpinning the simulation and prediction efforts described above are critical systems of supercomputing and big data. Here, our research efforts, especially in atmospheric modelling for climate, have fallen well behind those that lead the world, in part because of a lack of computational power and data storage. Reversing this trend is essential and will require a coordinated program of growing both research and technological expertise, which could be initiated with a resourcing approach like the ACCESS NRI proposal.

The community challenge

Individual climate process can be, and often are, successfully studied in small teams. However, to have impact, the knowledge gained in this research must be synthesised into a more complete understanding of climate phenomena and incorporated into the modelling systems used for weather and climate prediction. This requires uniting a community that is usually divided into those who study processes, those who study phenomena and those who work on tools (both observational data sets and modelling systems).

Compelling science questions and a set of common tools can provide the glue that brings the community together. For example, a common observations platform, such as the Research Vessel (RV) “Investigator”, unites the atmospheric and ocean communities to study processes critical to coupled phenomena over the oceans. Observational networks organised through collaborative NCRIS funding, such as the Terrestrial Ecosystem Research Network (TERN) and the Integrated Marine Observing System (IMOS), provide focal points for researchers, as do reanalyses such as Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia (BARRA). A common modelling system, such as ACCESS, provides a framework for transferring process knowledge into simulation and prediction tools.

Ultimately, success in rising to the science challenges, and thereby providing society with the information it requires, hinges critically on a well-coordinated national climate science effort. Such an effort must integrate the strength of each of its partners. The following section analyses the current state of climate processes research in Australia setting the scene for the discussion of potential future solutions that meet the above challenges.

3 A stocktake of current activities

This section provides an analysis of the current activities in climate processes research in Australia. Its results are based on a community-wide survey of activities that was conducted in mid-2019 with census dates encompassing the period 1 July 2018 to 30 June 2019. The survey was targeted at research group leaders in all major organisations involved in climate process research. We received 108 responses for staff (representing 561 staff FTE) and 44 responses for students (representing 121 PhD students). The response rate was around 85%. For a copy of the survey questions please see Appendix 4. This section focusses on the main findings of the survey.

The workforce

The total workforce reported by survey participants encompassed 561 FTE of staff time and 142 PhD students engaged in the community. Importantly, of those, **345 staff FTE and 121 PhD students are dedicated to research activities**. The total number of staff is significantly higher than that reported in the Australian Climate Science Capability Review (419 FTE). However, the research FTE of 345 staff is lower. The reduction by one third from total to research FTE is a result of many researchers engaging in other activities, most prominently research administration, teaching, and the support of operational systems. Combining students and staff results in 466 FTE engaged in climate research. Of those, 39% constitute staff in government organisations, 35% are staff employed by universities and 26 % are PhD students.

Of the 345 staff FTE, 149 (43 %) are directly funded by the employing organisation. This includes staff on appropriated funding in government organisations as well as academic staff at universities. The remaining 196 are externally funded. Of those, 80 (23%) are funded by the Australian Research Council and 89 (26%) by government funding other than ARC grants. The remaining 27 FTE (8 %) are funded from industry (14) and international (13) grants.

Following on from the general overview, survey participants were asked to assign their teams' research FTE to sets of categories. First, they were asked to divide their effort into major research activities. They were then asked to repeat the process for major climate processes and, finally, climate phenomena. These sets of categories are independent; a given research activity (e.g., model evaluation) may be focused on a particular process (e.g., atmospheric dynamics) and also applied to a particular phenomenon (e.g., heat waves). The results of this categorisation are summarised in the following three subsections, followed by an illustrative case study.

Major climate research activities

Figure 2 summarises the major research activities undertaken by staff and students in climate research in Australia. Of the total 466 FTE, 98% are engaged in the broad activities covered in the survey. 40% of the research effort is dedicated to the collection and analysis of observations, 40% is engaged in modelling activities (using as well as developing models), 13

% addresses forecast system development and verification, with the remaining 7% dealing with theoretical (5%) and laboratory (2%) studies.

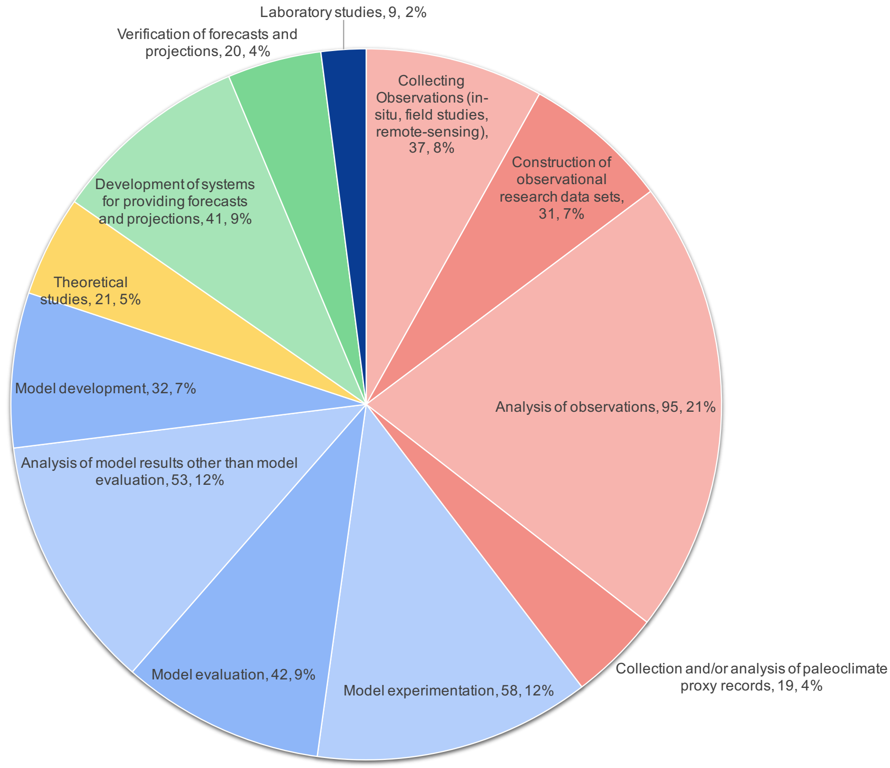

Figure 2 - The Australian climate research effort by major research activity. Numbers reflect FTE and percentage of the total effort. Colours represent overall areas: red – observations, blue – models, yellow – theory, green – prediction systems, dark blue – laboratory studies

In the observational part of the research conducted in Australia, about half is dedicated to the analysis of observations, about one fifth is dedicated to the collection of data and the construction of research data sets, respectively, with the remaining 10% devoted to paleoclimate data specifically.

Most of the modelling research (~83 %) is dedicated to the use of models, involving model experimentation and the analysis of model results, including model evaluation. Only 17% of the total modelling effort and 7% of the total research effort are dedicated to model development.

Research activities on major climate processes

Figure 3 shows the research effort divided into climate processes. About 70% of the overall climate research FTE in Australia is associated with climate processes research. 40% of Australia's processes research is dedicated to the ocean, about half of this amount devoted to the study of ocean dynamics at various scales.

Roughly 30% of the processes research effort deals with atmospheric processes. Again, about half of the atmospheric processes research effort studies atmospheric dynamical processes, with the other half spread across physical processes and chemistry. Sizeable efforts exist in atmospheric convection and chemistry, with other areas receiving only very limited attention.

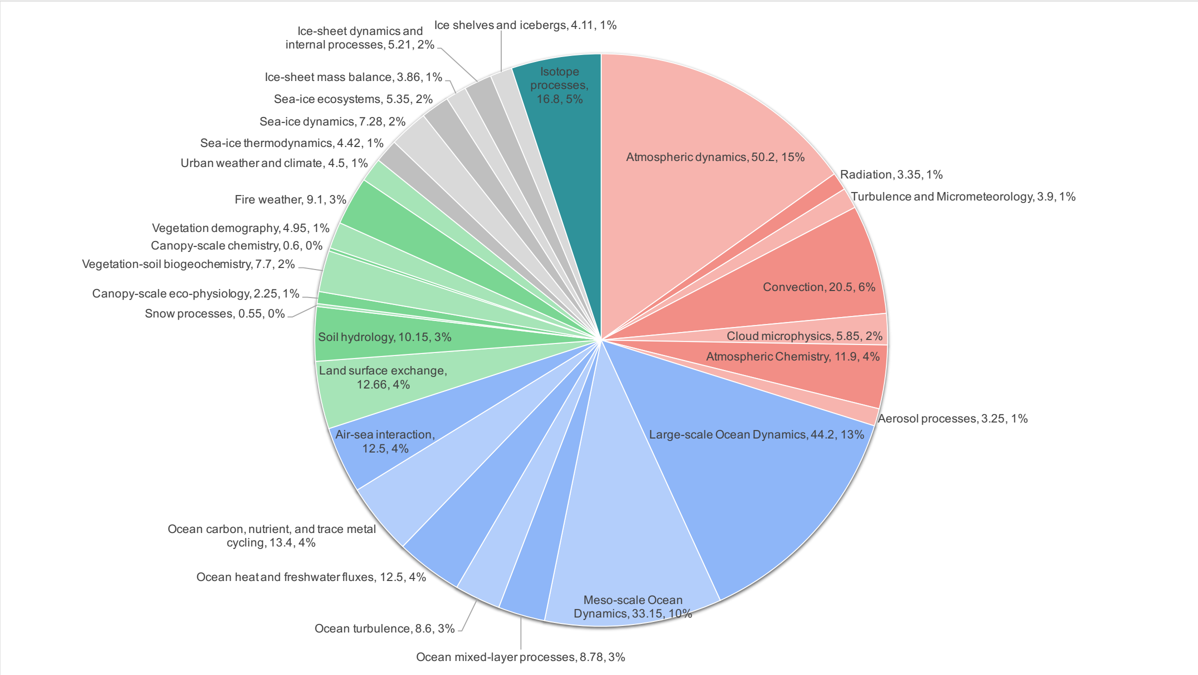

Figure 3 - The Australian climate research effort by climate process. Numbers reflect FTE and percentage of the total effort. Colours represent overall areas: red – atmosphere, blue – ocean, green – land, grey – ice, dark green – isotopes.

Land processes research accounts for 17% of the climate process research, with mostly small efforts across a range of topics. A number of small efforts exist in cryospheric processes, summing to a total of 8% of the overall climate processes research.

A key feature of Figure 3 is the significant fragmentation of process research into small efforts. With the exception of a few areas, most notably atmospheric and ocean dynamics, many key processes are not covered extensively. Some, such as turbulence, radiation, aerosol processes, snow and canopy processes attract only very small efforts, with less than 4 FTE devoted to each of them.

Research activities on major phenomena

Figure 4 provides a summary of the Australian research activities dedicated to specific phenomena relevant to Australian climate. About 77% of the total research effort is dedicated to climate phenomena. It is evident that there is a large variety of phenomena studied in Australia. While there are no major standout areas, the largest efforts are dedicated to extremes (18%), Australian climate drivers (17%) and the Global and Southern Ocean (15%). The remaining half of the research effort is distributed across a number of phenomena with about equal efforts dedicated to land phenomena, feedbacks, the cryosphere and paleoclimate (~6-8% each).

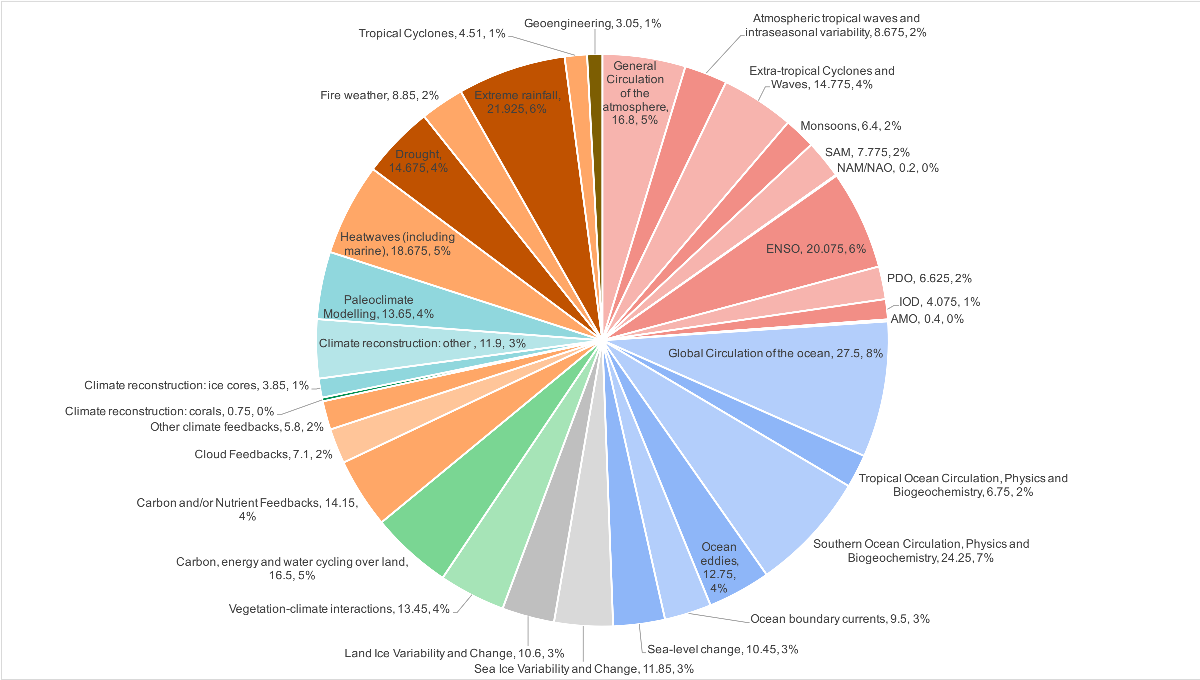

Figure 4 - The Australian climate research effort by climate phenomenon. Numbers reflect FTE and percentage of the total effort. Colours represent overall areas: red – atmosphere & coupled, blue – ocean, green – land, grey – ice, orange – feedbacks, cyan – paleoclimate, brown – extremes, dark brown – geoengineering.

4 Strengths, weaknesses and gaps in Australian climate processes research

Strengths

The overall size of the research effort identified in the previous section provides a solid foundation for meeting current and future climate science challenges. Particular strengths in climate processes research are:

All the major organisations involved in climate research have a sizeable effort in climate processes research. The stocktake outlined in the previous section identified a considerable workforce within Australia dedicated to climate science research. Importantly, 70% of this effort is associated with climate processes, demonstrating the centrality of climate processes research to the overall research effort. Since climate processes underpin both understanding of the climate system as well as prediction at all scales, it is important to maintain expertise in climate processes across organisations with different foci and responsibilities within the climate science enterprise. It should be noted, however, that not all of the research associated with particular climate processes is explicitly aimed at increasing our understanding or ability to model that process. Ensuring that such detailed process studies remain prominent in the effort is a challenge moving forward.

A very strong, world-leading effort in observing and modelling the oceans, with particular strength in Southern Ocean research. The strength of the ocean research within Australia is evidenced by the large fraction of climate processes research that is focussed on oceanic processes in Figure 3 (larger than any other area), as well as the consensus among participants in the community consultation (both among researchers engaged in oceans research and those that are not). Furthermore, infrastructure such as the RV investigator allow Australia to provide a globally significant contribution to the global effort toward observing the oceans. Australia's geographic location puts it in an ideal position to lead Southern Ocean research, and strength in this area should therefore be seen as a strategic use of resources that should be maintained.

A good range of expertise across the relevant spheres. Figure 3 shows significant research efforts in processes related to the atmosphere, the ocean, the land, and the cryosphere, reflecting the broad interests within the community. As described further below, this presents a challenge for coordination, given the relative fragmentation of some these efforts in different institutions and locations.

World leading capability in the development of prediction systems and provision of prediction services (oceans, atmosphere, and coupled). The ACCESS coupled prediction system provides the capability for prediction across all the relevant timescales, from weather prediction, to seasonal and decadal climate prediction, up to centennial-scale climate projections. The responsibility for these different scales is split between the BoM and CSIRO but maintaining this capability must be a community-wide effort. This strength should be seen as particularly important given the community's position as one of the few major climate research hubs in the Southern Hemisphere.

A large cohort of graduate students and Early Career Researchers. The community survey identified a cohort of graduate students making up more than a quarter of the research workforce in climate science. This cohort represents the future leaders of the field and should therefore be seen as a resource to tap into in order to strengthen Australian climate processes research in the future.

Weaknesses and gaps

Despite the good foundation, there are significant gaps in Australia's climate processes research capability. Filling these in the short and medium term is important if we are to meet the challenges outlined in section 2. In this context, the most prominent and relevant gaps are:

Sub-critical mass in research efforts of aspects of atmospheric physics. The community survey revealed that certain physical processes within the atmosphere, in particular boundary layer processes and turbulence, cloud microphysics, and radiation, have very little FTE dedicated to them. Since such processes are integral to phenomena such as ENSO (see Figure 1) and heatwaves (see Figure 5), the loss of expertise in these areas represents a critical threat to Australia's ability to understand and predict such phenomena into the future. The shortage of expertise in these areas requires urgent correction.

Fragmented efforts in cryosphere processes. While a significant effort in cryosphere processes exists across the nation, a deeper analysis of the survey data reveals that this effort is particularly fragmented. This is especially true for the areas of ice sheets and sea ice, Here, efforts are made up of very small fractions of FTE (0.2-0.5) scattered across several groups. Such fragmentation presents a risk to maintaining ongoing expertise within these areas.

Limited effort in model development. While more difficult to glean in detail from the survey, there is some evidence that model development efforts in Australia are approaching critical thresholds of under-resourcing and capacity limits. Overall model development comprises 7% of the surveyed effort (Figure 2) but that constitutes only 17% of the overall modelling effort, with 83% dedicated to model applications. Given the critical role models play in predictions at all timescales, the community workshop expressed the need for gradually growing Australia's model development capability. The view among those involved in model development was that this area is insufficiently incentivised given the "publish or perish" mindset within the University sector, and the focus on services within government research organisations.

Other Challenges

In addition to the gaps identified, further challenges exist in priority setting and community organisation:

Community fragmentation. The fragmentation described for cryosphere processes above is, to some extent, a feature of all climate processes research in Australia. While substantial in absolute number, a large part of the climate and weather research effort is spread thin, with many groups reporting fractions of less than 1 FTE in most of the areas they work on. This leads to often competing sub-critical efforts in many areas.

Institutional priorities vs national interest. The community consultation revealed some concern for conflict between priorities of individual organisations and the priorities that would most encourage national collaboration. This contributes to the fragmentation of the community and inhibits the growth of a true community effort that can tackle big challenges.

A case study for Australian climate processes research strengths, weaknesses and gaps - Tropical-extratropical interactions

Recent research has shown that tropical-extratropical interactions strongly affect major weather and climate phenomena around Australia (Figure 5, Parker et al., 2013, 2014). Most prominently, tropical convection in the northern part of Australia, has been shown to exacerbate and prolong summer heatwaves in the south-east of the country (Parker et al., 2014). Enhanced tropical convection in the north, associated with the Australian monsoon, heats the atmosphere through microphysical processes. An upper-level high pressure system associated with the convection modifies the upper-level flow and in doing so strengthens the surface high-pressure system that is responsible for the summer heatwave in the southeast. Land surface processes and turbulence contribute to additional heating of the atmosphere from the ground.

While tropical convection influences extratropical heatwaves, extratropical processes themselves have been shown to strongly influence convection in the tropics. The trailing end of frontal systems can extend from the extratropics all the way to Northern Australia, where they have been shown to cause most of the rainfall bursts observed during the Australian monsoon season (Narsey et al., 2017). As they traverse eastwards, the strongest of these fronts are responsible for severe bushfire

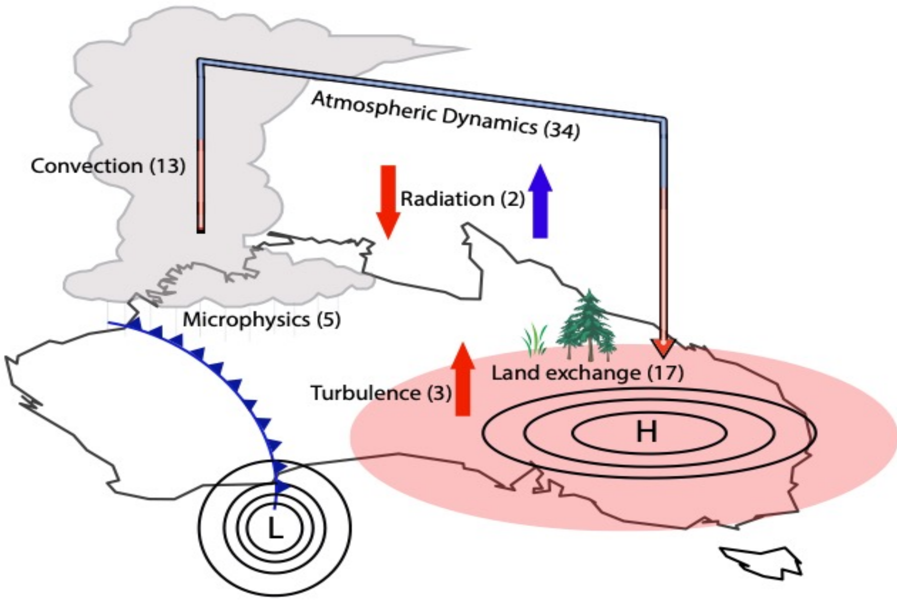

Figure 5 Schematic of the interaction of climate processes to produce Southeast Australian Heatwaves. Numbers indicate FTE staff working on each of the processes in Australia

conditions that are often associated with the end of an extended heatwave. Occasionally, the cold fronts depicted in Figure 5 take the form of atmospheric rivers (Reid et al., 2019), which transport high amounts of water vapour from the tropics to the extratropics, leading to heavy rainfall in southern Australia.

As in the El Niño case above (see section 1), many different climate processes combine to produce several high-impact phenomena. Some of these processes are well-researched in Australia, most notably atmospheric dynamics. However, efforts in several key processes, such as cloud microphysics, turbulence and radiation are well below the critical mass required to sustain research efforts, making it challenging to fully understand as well as accurately simulate South-East Australian heatwaves, monsoon rainfall bursts, fire weather and heavy rain in the southern half of the country. Given the large impact of these events, advancing research into tropical-extratropical interactions must be of high priority.

5 Priorities and resourcing for future climate process research in Australia

Having identified the challenges ahead and analysed the current effort, this section uses this information to identify priorities for the medium-term future of climate processes research in Australia. It also outlines options for tackling the major challenges in an effective community-wide research effort.

An important conclusion of the community consultation is that the overall research effort is significant and has the potential to address the key issues if it is well coordinated. However, the consultation also identified some weaknesses in that coordination. First, there is a large fragmentation of the community, supported by funding models that reward competition over collaboration. Exceptions to this do exist but are rare. Where they are successful, they are driven by funding models that strictly enforce collaboration, a lesson to keep in mind when searching for solutions. Second, there are a number of critical gaps that, if not addressed, will inhibit Australia's climate science ability to understand and simulate key climate phenomena. Most prominently these gaps exist in atmospheric physics and cryosphere processes.

A first, short-term priority then, is to fill some of the critical gaps outlined above. This is likely going to be a gradual process. It requires the recognition of the gaps identified in this report by the major research organisation and the direction of future recruitment into the critical areas. There is evidence for the success of such an approach in recent decades. Tropical convection had become a sub-critical area in the early 2000s after much research success in the 1980s and 1990s. Targeted recruitment in both the government and university sector has yielded a now strong effort (20 FTE, Fig. 3) of high international repute.

Notwithstanding the critical gaps, a main conclusion of a workshop held in support of this report was that for additional investment in climate processes research to be effective, a transformation of the climate science community into a more collaborative structure is required. We note that this does not imply the formation of new organisations, such as CAWCR in the past. Instead, we recommend *a stepwise transformation from a loose but well-supported research network to targeted small collaborative efforts to a national research approach over the next decade or two*.

Looking ahead

We base our outlook on the notion that the five priority science questions posed in section 2 provide a comprehensive framework to both guide and integrate climate processes research. We stress that the question of how climate variability and change affect the planet's habitability must be central to all climate research. It is answers to this question that society demands. Encompassing both human and natural systems the question is central to the health of humans and ecosystems, food and water security. As such, it provides a framework to setting priorities in studying the physical and biogeochemical processes in the climate system encompassed by the other four science questions.

Acknowledging the need to provide society with information on possible futures of our planet we propose to organise the community efforts in climate and weather research as illustrated in Figure 6. The delivery of climate information should form the core of the effort. Each of the areas of research, guided by a central question (see above), will serve as a focal point for the research community. In this way, the wide variety of research approaches, from observations to models and processes to phenomena will directly contribute to providing solutions for Australia.

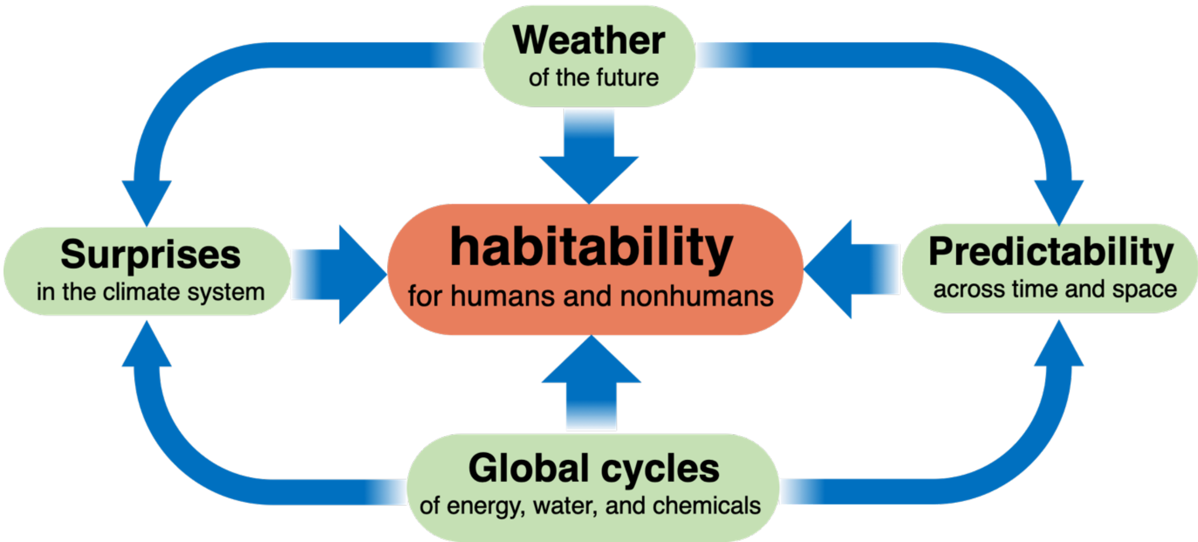

Figure 6 – Schematic of a potential future research framework informed by priority science questions.

Possible implementation pathways of the research encompassed in Figure 6 across the diverse community are discussed below. Notwithstanding the research gaps identified above, improved coordination and collaboration, supported by a strong research infrastructure, is a necessary first step towards improved research outcomes. We recommend three phases to improve community interactions in the areas required to achieve the vision discussed above. We acknowledge the challenges associated with each phase and recommend that their implementation be accompanied by close monitoring of their outcomes.

Phase 1: A research network (Start now)

An important first step in improving climate processes research efforts in Australia is to more effectively use existing resources through improved collaboration and planning. Using the five science questions as guidance and keeping the need for improved information to society firmly in mind, this could be achieved through the establishment of a moderately funded research network.

Specifically, it is envisaged that each of the five main research areas would be led by a dedicated research coordinator. Their role would be to coordinate efforts across organisations in their respective area, and in collaboration with each other, coordinate efforts across the five questions. The coordinators could report directly to the NCSAC. To be practical, this would require funding of a fraction of each coordinator's time to enable them to fulfil their role.

For the network to flourish, funding would be required for community workshops (within and across the main efforts) as well as exchanges and research visits of scientists across the different organisations involved in the network. These activities are critical to build a cross-institutional community that takes advantage of the strengths of each partner. Depending on the funding model for the research theme coordinators, the implementation of the network envisaged here would require only moderate funding of the order of $500K per annum. We note that this funding would be for coordination rather than research itself. We illustrate the vision of a flourishing research network in the hypothetical example below.

The Year 2021 in the national research network

It is 2021 and a national climate research network is flourishing. Supervised by the NCSAC and led by a part-time Director, five individuals lead the research coordination of the five major themes of the network. They represent a mix of mid-career researchers from the Bureau of Meteorology, the CSIRO and the university sector. They are funded to spend 30% of their time to coordinate the research in their theme as well as cross-theme activities in consultation with the Director.

The Cycles and Weather themes have just hosted a joint workshop on identifying the key weather features that drive the energy and water cycles over Australia. The workshop united experts in atmospheric, land and ocean physics with those in atmospheric and ocean dynamics. To ensure impact, the group decided to focus on those climate processes that are involved high-impact events. Based on this and informed by previous work, the workshop agreed on an ambitious work program for the next three years aiming at improving the ACCESS model's representation of those processes and events.

All themes are hard at work to prepare their annual workshop that will be held in conjunction with the national AMOS conference. Through funding from the network, three international experts have recently spent three months each in Australia. Several early and mid-career researchers from Australia have spent significant time overseas gaining experience in applying the latest observational and modelling tools to Australian high-impact events. By providing true collaborative opportunities, the network, while only recently established, has begun to make a real difference to the community. The next four years of assured funding will be used to build on these early successes.

Phase 2: Accelerator Institutes (Start in Year 3)

Once a national research network has been established in Phase 1, it is likely that a number of critical research-needs as well as bottlenecks for progress will emerge. A small number of those could be advanced through the establishment of targeted efforts to accelerate progress in a particular area. We envisage establishing "Accelerator Institutes" for this purpose.

An Accelerator Institute would be a short-lived (3-5 years), highly targeted enterprise with very specific goals, such as the development of new methods and tools. The institutes would draw on talent from the entire community. Staffing could be achieved through a mixture of formal secondments from the existing network partners as well as new staff funded through special research programs, similar to the ARC's special research initiatives. The size of an Accelerator Institute is envisaged to be moderate (10-20 staff) and hence the funding required would likely be on the order of $5 Mill per annum for the duration of each institute. Examples for Accelerator Institutes could be an Institute for Next-Generation Climate

Modelling (scaffolded on the ACCESS NRI), an Institute on Tropical-Extratropical Interactions in Australian Climate, or an Institute for Dynamic Vegetation Modelling. Once again, the following text provides an illustrative example of an Accelerator Institute.

The Year 2024 in the Accelerator Institute for Tropical-Extratropical Interactions in Australian Climate

There is a buzz in the Accelerator Institute for Tropical-Extratropical Interactions. Now in its second year, the twelve staff have just hosted their first international workshop and have developed several collaborative projects with a number of overseas institutions. Formed in 2023, the institute is focused on discovering the role that two-way interactions between the tropics and extratropics play in Australian weather and climate. It is staffed through two secondments each from the Bureau of Meteorology, CSIRO and the University sector as well as six new appointments of postdoctoral research fellows. Building on previous work on the role of tropical convection in heatwaves, atmospheric rivers for heavy rain events, and decadal tropical variability on sea-ice and ice-sheet processes around Antarctica, the institute's staff are determined to unravel the underlying interplay of physical and dynamical processes in the atmosphere and ocean.

The staff are enjoying their new office surroundings at the Bureau of Meteorology. Using their networks within Australia and across the world, they interact with the community on questions of predictability and prediction of high-impact events. They are advising on strategies for climate modelling. This has become more urgent by the realization that global models are needed to simulate the tropics-extratropics interactions, as the limited domain sizes of the regional approaches prohibit the models to develop realistic interactions. Bringing observations experts, modellers and process scientists under one roof has already paid dividends. The team have come up with an innovative approach to diagnose parametrization errors, which they have just applied to the ACCESS model. They discovered the need for improving the representation of convection and in collaboration with Bureau and CSIRO colleagues have developed a new approach that is currently undergoing testing in both the NWP and climate versions of ACCESS. Early results point towards a much-improved simulation of convection in the tropics with major impacts on the simulation of several high-impact phenomena in the extra-tropics.

Phase 3: A National Research Centre (Begin considerations in Year 5)

If Phases 1 and 2 are assessed to have been successful, a final phase of enhanced collaboration could be the establishment of a national climate research centre that unites all current efforts under one roof. The establishment of such an institute would provide a new focus and an unprecedented level of coordination to solve the critical problems outlined above. However, history shows that the community is currently not ready for such an approach, preventing the transformation of the current community into such a central effort in the short term. We therefore suggest that this option should be seen as a possible long-term solution, whose viability (or lack thereof) could be established through execution and continuous assessment of the previous, lower risk, two phases.

Other considerations:

In addition to the longer-term strategy, there are some more immediate opportunities in research coordination to improve outcomes on relatively short timescales.

1) The establishment of ACCESS as a National Research Infrastructure through the National National Collaborative Research Infrastructure Strategy (NCRIS) would provide an immense opportunity for both simulation science and the delivery of more informative predictions of weather and climate to the Australian community. Harnessing this opportunity purely through the existing research structure will not make optimal use of the new capabilities. Hence it is important to supplement the infrastructure funding though a dedicated program of research, such as an Accelerator Institute for Next Generation Climate Modelling.

If the ACCESS NRI is not funded, our ability for community collaboration will be severely diminished, as one of the key drivers for collaboration - a common modelling and simulation system – would be lost. There is evidence for a divergence of modelling systems being already underway. The community uses at least two ocean models for global modelling. There are two global land-surface models used across different systems and there are first signs of a different global atmospheric model being used. In regional modelling there are many different systems in use across organisations and states, leading to potentially inconsistent information being provide to users. In the absence of the ACCESS NRI underpinning a unified tool development, these trends will likely accelerate.

2) Acknowledging the central need of connecting the outputs of climate research with the communities that use climate information in decision making accelerating research in this area could be transformative. A practical short-term option to achieve such acceleration is to use the next round of the NESP process to establish a NESP Hub that addresses the habitability question as the focal point for the research network proposed above. This Hub would naturally continue the work of the current NESP Earth Systems and Climate Change Hub as the conduit to the stakeholder community.

6 Summary

This report responds to a request of the NCSAC to provide input into deliberations on strategies for the future of climate processes research in Australia. The report's results and recommendations are based on a wide community consultation effort that included a survey of current efforts and a workshop to identify gaps and priorities.

Climate processes are the fundamental building blocks of the climate system. As a result, the understanding and prediction of critical climate phenomena, such as ENSO or sea-level rise, critically depends on the understanding of climate processes and the successful translation of this understanding into prediction tools.

The report concludes that the overall climate processes research effort in Australia is substantial. Critical gaps exist in the areas of atmospheric physics, cryospheric processes and model development.

While important and in need of addressing, these gaps are accompanied by inefficiencies that result from a lack of organisation of the community into a nationally coordinated climate processes research effort. The report proposes to overcome this issue with two major initiatives. First, the report highlights the importance of a scientific framework that prioritises research to maximise the delivery of solutions for Australian society whilst encouraging collaborative world-leading research. The report proposes such a framework. Second, the report recommends supporting the scientific framework through a moderately funded research network, that implements the science framework with a focus on collaboration and science delivery into climate services.

The report also recommends the establishment of small and short-lived Accelerator Institutes that target specific high-priority research needs. These institutes, partially staffed through secondments from the partners in the research network, will serve as both nuclei of long-term collaboration and ignition charges in areas of immediate critical service needs. The report recommends establishing them after the research network has been successfully established.

The report concludes that a transformation of climate processes research into a community working collectively towards national goals in a common science framework is essential. Given the underpinning role of processes research for all other climate research this transformation provides the foundation for providing solutions to the climate-related societal challenges ahead.

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Appendix 1: List of acronyms

AAD:	Australian Antarctic Divison
AAS:	Australian Academy of Science
ACCESS:	Australian Community Climate & Earth System Simulator
ACCESS NRI:	ACCESS National Research Infrastructure
ANTSO:	Australia's Nuclear Science and Technology Organisation
ARC:	Australian Research Council
BARRA:	Bureau of Meteorology Atmospheric High-resolution Regional Reanalysis
BOM:	Bureau of Meteorology
CSIRO:	Commonwealth and Scientific Research Organisation
IMOS:	Integrated Marine Observing System
NCSAC:	National Climate Science Advisory Committee
NESP:	National Environmental Science Program
TERN:	Terrestrial Ecosystem Research Network

Appendix 2: Glossary of terms

Here we present definitions of the *climate processes* and *climate phenomena* used in the stocktake questionnaire and referred to in this report. As defined in the report, climate processes represent the building blocks of the climate system, while climate phenomena represent the confluence of a number of processes that produce a particular influence on the climate. For example, the phenomenon of El Niño is influenced by a number of processes, such as air-sea interaction, convection, microphysics, radiation, and atmospheric and oceanic dynamics at various scales.

Many of the process listed below actually represent a set of processes that are commonly studied together. The definitions were not given to survey participants, but they are constructed to reflect the common understanding of these terms within the climate research community as much as possible. Note that there is some overlap between different the processes and phenomena; survey participants were instructed to assign their research effort as sensibly as possible given any ambiguity.

Climate processes

Aerosol processes: the set of processes that govern the emission and production of aerosols (microscopic liquid or solid particles suspended in the atmosphere), chemical or physical transformations of aerosols within the atmosphere, and the eventual removal or aerosols from the atmosphere, either by dissolution into cloud droplets and eventual precipitation (wet scavenging) or through direct deposition on the surface (dry deposition).

Air-sea interaction: processes that govern the exchange of heat energy, freshwater, chemicals, and momentum between the ocean and atmosphere. See also: *ocean heat and freshwater fluxes.*

Atmospheric chemistry: the set of processes governing the composition of the atmosphere, including emission of pollutants or other gases and chemical reactions in the atmosphere (including chemical reactions that happen when chemical species dissolve in cloud droplets or raindrops). See also: *aerosol processes.*

Atmospheric dynamics: the set of processes that governs the movement of air in the atmosphere (i.e., winds). Such motions occur at scales ranging from a few metres (e.g., turbulence around an aircraft wing) to the scale of continents (e.g., the Australian monsoon). See also: *turbulence & micrometeorology*, *convection*.

Canopy-scale chemistry: Processes that govern the emission of chemical species from vegetation, including the biological processes that produce different chemical species and the chemical reactions that happen within the vegetation canopy (rather than in the atmosphere above).

Canopy-scale eco-physiology: processes governing the physiological response of plant functions (photosynthesis, respiration, growth, and transpiration) to environmental conditions (e.g., temperature and humidity) within the vegetation canopy.

Cloud microphysics: the set of processes governing phase changes in the atmosphere, the creation of cloud droplets, and the growth of cloud droplets into raindrops and snowflakes which may eventually fall to Earth.

Convection: the set of processes that contribute to rapid vertical air motions in the atmosphere that often produce clouds. Convection may be “dry” if no cloud is produced, “shallow” if clouds are produced in the lower atmosphere and only weak precipitation is produced, or “deep”, if clouds spaning the depth of the troposphere are produced in association with strong precipitation.

Fire processes: processes that govern how fires spread within a landscape. This includes land-surface processes such as those that govern fuel load and atmospheric processes that govern the meteorological conditions that determine the spread of a fire.

Ground water and soil hydrology: processes that govern the transport of water through the land surface. This includes transport through the root-zone and the sub-surface soil layers and interactions of ground water with an aquifer.

Ice-sheet mass balance and surface temperature: processes that govern the growth and decay of ice sheets (e.g., Antarctic ice sheet, Greenland ice sheet) largely at their upper surface due to their interaction with the atmosphere, but also at the rock/ice interface (via geothermal heat flux).

Ice-sheet dynamics and internal processes: processes that govern the flow of ice sheets and their internal structure.

Ice shelves and icebergs including calving: processes that govern the behaviour of floating ice shelves that protrude into the ocean from glacial (flowing) ice sheets. This includes the production of icebergs, which are parts of ice shelves that detach from the parent ice sheet by a process called calving.

Land surface exchange of energy and water: processes that govern the transport of energy and water from the land surface to the atmosphere. For example, evaporation and precipitation transport water from the surface to the atmosphere and from the atmosphere to the surface, respectively.

Large-scale ocean dynamics: the set of processes that govern the movement of water masses in the ocean (i.e., ocean currents) on large scales. Large-scale motions are those that produce phenomena of sizes greater than a few hundred kilometres across. See also: *mesoscale ocean dynamics*, *ocean turbulence*.

Mesoscale ocean dynamics: the set of processes that govern the movement of water masses in the ocean on mesoscales. Mesoscale motions are those that produce phenomena of sizes between ten and a few hundred kilometres across. See also: *large-scale ocean dynamics*, *ocean turbulence*.

Ocean carbon, nutrient, and trace metal cycling: processes that contribute to transport of different chemical species through the ocean. This includes transport of chemicals by ocean currents, physical processes that exchange chemicals between the ocean and the land/atmosphere, and biological and chemical processes that transform nutrients chemically.

Ocean heat and freshwater fluxes: processes governing the transfer of heat energy and freshwater into the ocean.

Ocean mixed-layer processes: processes in the ocean that govern the behaviour of the uppermost layer of the ocean, generally a few tens of metres thick. This layer of the ocean is strongly affected by the interaction between the ocean and atmosphere (including drag between the ocean and atmosphere and the transport of energy and water between the ocean and atmosphere).

Ocean turbulence: processes associated with chaotic (unpredictable) motions of water within the ocean. There are different types of ocean turbulence that occur at different scales, from a few metres in the mixed layer to hundreds of kilometres in mesoscale eddies. See also: *mesoscale ocean dynamics*, *large-scale ocean dynamics, ocean mixed-layer processes*.

Snow processes: processes associated with the effects of snow on the land surface. For example, processes that govern the effect of snow cover on the behaviour of vegetation or processes that govern the effect of snow cover on the reflectivity (albedo) of the Earth's surface.

Radiation: processes relating to the propagation, absorption, scattering, and emission of electromagnetic waves. This includes processes relating to solar radiation incident on the Earth from the sun and terrestrial radiation emitted by the Earth, oceans, and atmosphere.

Sea-ice dynamics and circulation: processes that govern the movement of sea-ice in response to the movement of the air above and ocean below.

Sea-ice ecosystems: Polar sea ice provides a stomping ground for a wide range of organisms, from tiny organisms living in the brine within the sea-ice matrix to larger fish or animals which seek the sea-ice as a refuge or feeding ground. Sea-ice ecosystem processes refers to the collection of biological and physical processes that govern this ecosystem.

Sea-ice thermodynamics and growth/melt: processes that govern the growth and melt of sea ice due to its interactions with the atmosphere above and ocean below.

Turbulence and micrometeorology: processes associated with the behaviour of the atmosphere at the scales of a few metres to a kilometre. Such processes are often particularly important in the atmospheric boundary layer (roughly the lowest kilometre of the atmosphere) which is strongly affected by the properties of the land surface (such as the vegetation or urban landscape).

Urban processes: processes associated with the microclimates produced by cities. For example, processes governing the urban heat island effect and thermal comfort of city-dwellers. See also: *micrometeorology.*

Vegetation demography: processes that govern the growth and death of vegetation and how plants allocate resources to different functions depending on environmental conditions. Vegetation demography also seeks to account for how environmental conditions affect the distribution of vegetation communities across the Earth's surface, with each species filling its ecological niche.

Vegetation-soil biogeochemical processes: processes that govern how plants use and produce different nutrients, and how these nutrients are transported between the root-zone and the vegetation.

Climate phenomena

AMO (Atlantic Multidecadal Oscillation): A phenomenon associated with changes in the sea-surface temperature pattern in the Atlantic Ocean. The AMO appears to undergo one cycle over a few decades, but the shortness of our observational record limits our ability to characterise it with precision. See also: *PDO*

Atmospheric tropical waves and intraseasonal variability: weather systems in the tropics that propagate around the globe and influence the tropical rainfall distribution on timescales from hours to months. See also: *Madden-Julian Oscillation.*

Carbon and/or Nutrient Feedbacks: A climate feedback occurs when an initial change in the climate is either amplified (positive feedback) or diminished (negative feedback) by the internal workings of the climate system. Carbon/nutrient feedbacks are climate feedbacks associated with the carbon cycle or other nutrient cycles. For example, anthropogenic global warming may cause melting of Artic permafrost, and this melting may release methane, a greenhouse gas. The additional methane emissions contribute to further global warming, resulting in a positive feedback. See also: *cloud feedbacks, other climate feedbacks.*

Carbon, energy and water cycling over land: The uptake of carbon, energy and water by the land surface (including vegetation) and their release back into the atmosphere.

Cloud Feedbacks: Climate feedbacks (either positive or negative) that result from a change in the character of clouds owing to climate change. See also: *carbon and/or nutrient feedbacks, other climate feedbacks.*

Drought: A period of unusually dry conditions persisting for at least a few weeks, but up to a few years. Dry conditions may be defined as simply a lack of rainfall (meteorological drought), a lack of soil moisture or stream flow (hydrological drought) or it may include factors that are of particular importance to crop development (agricultural drought). See also *heatwaves (including marine).*

ENSO (El Niño-Southern Oscillation): A coupled ocean-atmosphere phenomenon that is associated with a change in the patterns of sea-surface temperatures and winds over the Pacific Ocean, but that affects weather patterns around the globe. ENSO affects the climate through El Niño events that bring drier than average conditions to parts of Australia and La Niña events that bring wetter than average conditions to parts of Australia. ENSO varies on interannual timescales, so El Niño events occur every few years. See also: *PDO, IOD.*

Extreme rainfall: The upper tail of the rainfall distribution, corresponding to the most intense rainfall or strongest rain events one can expect. Extreme rainfall may be defined as rainfall that exceeds a given accumulation over a given period of time, or one may define extreme rainfall relative to the distribution of rain at a given place (e.g., the 99th percentile of daily accumulations).

Extratropical cyclones and waves: weather systems in the extratropics that propagate around the globe and produce cold fronts and other phenomena associated with precipitation.

General circulation of the atmosphere: the planetary-scale wind systems on the Earth including the major overturning cells (Hadley, Ferrel & polar), the jet streams, and the trade winds. See also: *general circulation of the ocean.*

General circulation of the ocean: the planetary-scale ocean current systems on the Earth including the large-scale ocean currents driven by winds (e.g., the gyres in each ocean basin and the Antarctic circumpolar current), and the large-scale ocean currents driven by temperature and salt concentration differences in the ocean (e.g., the thermohaline circulation). See also: *general circulation of the atmosphere.*

Geoengineering: Deliberate modification of the large-scale climate of the planet either to reduce the impacts of climate change or otherwise improve its habitability for humans or other life. For example the injection of sulfate aerosols into the stratosphere to reduce the solar radiation absorbed by the Earth and thereby cool the climate.

Heatwaves (including marine): A period of unusually high temperatures persisting for at least a few days. Heatwaves may be defined in absolute terms (e.g., a given temperature threshold) or relative to the seasonal and location specific climatology. Marine heat waves correspond to unusually high ocean surface temperatures in a given region. See also: *drought.*

IOD (Indian Ocean Dipole): A phenomenon that is associated with a change in the patterns of sea-surface temperature over the Indian Ocean, but that also affects weather patterns over Australia. The IOD varies on interannual timescales. See also: *ENSO*.

Land ice variability and change: Changes in the extent and thickness and volume of ice on land either due to weather and climate variability or due to long-term climate change. This includes ice sheets (Antarctica and Greenland), ice shelves (floating), as well as mountain glaciers. See also: *sea ice variability and change*.

Monsoons: Continental-scale wind systems that blow in one direction in summer, producing wet conditions, and blow from the other direction in winter, producing dry conditions. Monsoons occur over the majority of tropical continents. The largest monsoon is the Asian monsoon, which is associated with heavy rainfall over the South and East Asia in the Northern Hemisphere summer months (Jun-Nov). The Australian monsoon brings wet weather to the Northern part of the continent in the Australian summer (Dec-Mar), and it gives relatively dry weather for the remainder of the year.

NAO (North Atlantic Oscillation): A phenomenon characterised by a north-south wobbling of the storm track in the North Atlantic. See also: *SAM*.

Ocean eddies: Current systems in the ocean that are a few hundred kilometres across and act much like weather systems in the atmosphere; they move around and change from week to week. See also: *ocean boundary currents.*

Ocean boundary currents: Fast flowing currents that occur on the western boundary of ocean basins. The Gulf stream (in the western North Atlantic) and Kuroshio current (in the western north Pacific) are the largest examples. The East Australian Current, flowing south along the east coast of Australia is an example from the Southern hemisphere. See also: *ocean eddies.*

Other climate feedbacks: Climate feedbacks not categorised as either cloud feedbacks or carbon/nutrient feedbacks. A climate feedback occurs when an initial change in the climate is either amplified (positive feedback) or diminished (negative feedback) by the internal workings of the climate system. For example, global warming may reduce the area of ocean covered by sea ice, thereby decreasing the albedo (reflectivity) of the planet and triggering further warming.

Paleoclimate modelling: The use of models of the climate system to simulate past changes in Earth's climate (strictly speaking, not a climate phenomenon). These simulations may be compared to evidence of past climates based on proxies derived from e.g., coral and ice cores. See also: *reconstruction of climate from coral records, reconstruction of climate from ice cores, reconstruction of climate from other proxy records.*

PDO (Pacific Decadal Oscillation): A phenomenon associated with changes in the sea-surface temperature pattern in the Pacific Ocean. The PDO undergoes one cycle over one to two decades.

Reconstruction of climate from coral records: Developing understanding of how the climate has varied in the past by studying the composition of coral skeletons (strictly speaking, not a climate phenomenon). Coral are very sensitive to environmental conditions, having fairly specific temperature and depth requirements for their growth. By sampling and dating different parts of a coral reef, one can therefore derive information about the local climate in the time period in which the coral grew. See also: *reconstruction of climate from ice cores, reconstruction of climate from other proxy records.*

Reconstruction of climate from ice cores: Developing understanding of how the climate has varied in the past by studying the composition of ice cores (strictly speaking, not a climate phenomenon). Ice cores contain a record of the composition of the atmosphere in bubbles that form within the ice, and they contain information about the climate within the composition of the ice itself. For example, the ratio of different isotopes of oxygen within the water molecules in ice can provide information on global ice volume, providing an indication of global climate. See also: *reconstruction of climate from coral records, reconstruction of climate from other proxy records.*

Reconstruction of climate from other proxy records: Developing understanding of how the climate has varied in the past using proxies other than those based on coral or ice cores, including proxies based on pollen grains within sediments, the composition of stalagmites and stalactites (collectively called speleothems) in caves, and the skeletons of organisms such as foraminifera. See also: *reconstruction of climate from coral records, reconstruction of climate from ice cores.*

SAM (Southern Annular Mode): A phenomenon characterised by a north-south wobbling of the southern hemisphere storm track. The storm track is a region of enhanced weather activity (i.e., a region with many extratropical cyclones, fronts and other precipitation producing weather systems). A shift in the storm track thereby alters the regions that are more likely to be affected by such weather activity. The wobbling associated with the SAM happens primarily on a timescale of a few weeks. However, longer term shifts in the SAM may occur as a result of climate change and variability.

Sea-level change: Change in the height of the sea surface averaged over the tides. Sea-level change happens at a global level due to thermal expansion of the ocean and melting land ice, but it is also expressed differently in different regions due to variations in ocean currents and the effects of continental uplift and sinking.

Sea ice variability and change: Changes in extent, thickness or volume of sea ice either due to weather and climate variability or due to long-term climate change. See also: *land ice variability and change.*

Soil biogeochemistry: The uptake and release of nutrients into the soil and atmosphere by vegetation and how this depends on environmental conditions and characteristics of vegetation.

Southern Ocean circulation, physics and biogeochemistry: The system of ocean currents in the Southern Ocean, including the interaction of these currents with biological and chemical processes, and the resultant transport of chemicals around the ocean.

Tropical cyclones: Rapidly rotating storms that form over warm ocean waters in the tropics and produce strong winds and heavy rainfall. Tropical cyclones are typically between a few hundred to a few thousand kilometres across, and they are often associated with extreme weather including coastal and inland flooding and high winds. See also: *extreme precipitation*

Tropical ocean circulation, physics and biogeochemistry: The system of ocean currents in the tropics, including the interaction of these currents with biological and chemical processes, and the resultant transport of chemicals around the ocean.

Appendix 3 – Report Terms of Reference

1) To implement the National Climate Science Advisory Committee's recommendation, the Department requires a consultancy to:
   a) Review the main processes researched in Australia and their associated analyses, including:
      (1) atmospheric processes
         (i) Controls on atmospheric chemistry
         (ii) Atmospheric processes and feedbacks
         (iii) Radiative forcing
         (iv) Cloud formation
         (v) Convection
      (2) oceanic processes
         (i) Sea-level change
         (ii) Deep and intermediate water-mass formation
         (iii) Ocean mass transport
         (iv) Heat transport
         (v) Sea ice formation
         (vi) Atmosphere-ocean gas exchange
         (vii) Ocean carbon, nutrient, and trace metal cycling
      (3) land processes
         (i) Antarctic ice sheet dynamics
         (ii) Surface forcing and feedbacks
         (iii) Boundary layer dynamics / micrometeorology
         (iv) Terrestrial biogeochemistry
         (v) Evapotranspiration
      (4) Dynamics of ocean-atmosphere modes of variability, including:
         (i) El-Niño Southern Oscillation
         (ii) Southern Annular Mode
         (iii) Indian Ocean Dipole
      (5) Analysis of climate observations
         (i) Analysis of ice-core records
         (ii) Analysis of coral paleoclimate
         (iii) Analysis of isotope / tracer observations
         (iv) Uncertainties
         (v) Integration of historical climate observations

   b) Undertake a stocktake of current (2018/19) Australian research activities, including:
      (1) Identification and description of the key processes under investigation;
      (2) the dependent activities for these investigations;
      (3) the physical and digital research infrastructure requirements and needs for these investigations; and
      (4) highlighting any particularly critical areas of research activity where resourcing/effort needs to be maintained and the rationale for this.

c) Identify where there are gaps in understanding or areas of uncertainty which affect climate predictability and climate projections for Australia and the surrounding regions.

2) The report should also consider prioritisation and resourcing needed to address these gaps in knowledge and research efforts in Australia over the next 10 years. This should
   a) include consideration of how existing resources could be re-prioritised to deliver better outcomes; and
   b) identify any dependencies and consider how any new activities should be phased or sequenced
3) Consistent with NCSAC's request, the report should be developed in consultation with climate-relevant research agencies and institutions including the CSIRO, Bureau of Meteorology, GA and AIMS and collaborative programs including the National Environmental Science Program-Earth System and Climate Change Hub (ESCC Hub) and the World Climate Research Program WCRP.

Appendix 4

Questionnaire for stocktake – Draft 1

The National Climate Science Advisory Committee (NCSAC) is seeking community input into its strategic planning process. The NCSAC has tasked the ARC COE for Climate Extremes to provide input into this process by providing a report that assesses the current state of ***research on climate processes*** in Australia. This is but one of several inputs into the committee's planning process.

This questionnaire has been designed as the key ingredient to the data collection for the report. It is intended to be filled in by research group leaders. It focusses on staff only, with a separate, but very similar, questionnaire sent to university research groups to cover students.

The questionnaire has four main parts. First, it seeks overall information on the size of your research group and its composition. It also aims to give a very rough overview of the sources of funding for the research you carry out.

This is followed by three parts that each aim at identifying where the main research effort is directed. In each of the three parts we ask participants to assign how much of their groups FTE is directed at what effort. Please note that:

- Each of the three parts is independent of the other. This means that each group member's FTE can be assigned three times, once in each part. However, it is not likely, nor is it expected, that all FTE of each group member is fully assigned in each part (see next point).
- It is expected that in Parts 2, 3, and 4, the assigned FTE is smaller than (and ***only occasionally*** equal to) the overall FTE of the group reported in Part 1. This is because we expect significant research in each group to be directed at activities not covered by this questionnaire.
- The purpose of this exercise is to present an honest picture of the ongoing effort. There is no judgement of effort intended, nor will the data be used beyond this report.
- The categories chosen here will not always be perfectly matched to your activities. When in doubt, please apply common sense in assigning activities to the categories provided.

With these points in mind, please enter the required information as accurately as possible based on the last 12 months (1 July 2018-30 June 2019) of activity.

Part 1

Name

Organisation

How many staff (including yourself) are in your team? This can be people you manage and/or supervise.

What gender do they identify with?

Male
Female
Other
Prefer not to answer

What career level are they at?

Senior (>20 yrs since highest qualification)
Mid-career (8-20 yrs since highest qualification)
Early Career (<8 yrs since highest qualification)

How many of your team's total FTE are spent on research?

How is your team's research FTE funded?

Internal funding (e.g., Bureau/CSIRO core funding; University Academic Staff)

External funding - ARC

External funding - Government other than ARC (e.g., funding from various departments in federal, state or local government)

External funding - non-government (e.g., industry grants)

External funding – international (e.g., US or European grants)

Part 2

Please assign how much of your group's FTE is spent on the following categories

Collecting Observations (in-situ, field studies, remote-sensing)

Construction of observational research data sets

Analysis of observations

Collection and/or analysis of paleoclimate proxy records

Model experimentation

Model evaluation

Analysis of model results other than model evaluation

Model development

Theoretical studies

Development of systems for providing forecasts and projects from minutes to centuries

Verification of forecasts and projections

Part 3

Now assign how much of your group's FTE is spent on the following categories. Please note that where climate change is not explicitly mentioned, it should be included in the respective category. For example, studying changes in ENSO should be part of the ENSO category.

General Circulation of the atmosphere

Atmospheric tropical waves and intraseasonal variability

Extra-tropical Cyclones and Waves

ENSO

IOD

Monsoons

Tropical Cyclones

SAM

PDO

NAO

AMO

General Circulation of the ocean

Tropical Ocean Circulation, Physics and Biogeochemistry

Southern Ocean Circulation, Physics and Biogeochemistry

Ocean eddies

Ocean boundary currents

Sea Ice Variability and Change

Land Ice Variability and Change

Cloud Feedbacks

Carbon and/or Nutrient Feedbacks

Other climate feedbacks

Sea-level change

Reconstruction of climate from coral records

Reconstruction of climate from ice cores

Reconstruction of climate from other proxy records (e.g., speleothems, pollen)

Paleoclimate Modelling

Carbon, energy and water cycling over land

Vegetation Demography

Soil biogeochemistry

Heatwaves (including marine)

Drought

Extreme rainfall

Geoengineering

Part 4

Finally, assign how much of your group's FTE is spent on the following categories

Atmosphere

Atmospheric dynamics

Radiation

Turbulence and Micrometeorology

Convection

Cloud microphysics

Atmospheric Chemistry

Aerosol processes

Ocean

Large-scale Ocean Dynamics

Meso-scale Ocean Dynamics

Ocean mixed-layer processes

Ocean turbulence

Ocean heat and freshwater fluxes

Ocean carbon, nutrient, and trace metal cycling

Land

Land surface exchange of energy and water

Ground water and soil hydrology

Snow processes

Canopy-scale eco-physiology

Vegetation-soil biogeochemical processes (e.g. nitrogen/phosphorus cycles, decomposition, etc.)

Canopy-scale chemistry (e.g. BVOCs, methane, dry deposition, dust emissions, stable istopes, etc).

Vegetation demography (e.g. growth, allocation, mortality)

Fire processes

Urban processes

Cryopsphere

Sea-ice thermodynamics and growth/melt

Sea-ice dynamics and circulation

Sea-ice ecosystems

Ice-sheet mass balance and surface temperature

Ice-sheet dynamics and internal processes.

Ice shelves and icebergs including calving