Dealing with Climate Variability and Climate Change

Abstract

While the presence of long-term warming and an anthropogenic cause are clearly observed, well understood[1] and widely accepted within the scientific community[2] the knowledge required to *deal with Climate Variability and Change* and manage future risks to Australia still constitutes a significant scientific challenge. Climate impacts are experienced on global to local scales and often manifest via extremes, so our science must be able to inform at these scales. This requires considerable advances in observations, modelling and technology and improved structures for cross-disciplinary, multi-institutional collaboration. This paper summarises key outstanding challenges and requirements to realise the highest national priorities for dealing with climate change.

Background

Marine-focussed climate variability and climate change science occurs across a number of geographically dispersed publicly-funded research agencies (PRFAs) and universities. Primary amongst the PRAFs are the CSIRO, the Australian Antarctic Division (AAD), the Australian Institute of Marine Science (AIMS), and the Australian Bureau of Meteorology (BoM). The major ocean climate research universities include UTas, UNSW, ANU, among others (Table 2). In addition, focussed joint research programs across multiple institutions exist, including the Antarctic Climate & Ecosystems Cooperative Research Centre (ACE CRC: CSIRO, AAD, BoM and UTas) and the Australian Research Council Centre of Excellence for Climate System Science (ARCCSS: ANU, UNSW, UTas, UMelb, Monash, CSIRO, BoM). These cross-institutional collaborations have proved highly successful, creating critical mass within the relatively small Australian science community.

Research infrastructure requirements are underpinned by the National Computational Infrastructure (NCI) high-performance computational facilities, the Marine National Facility (MNF), the Integrated Marine Observing System (IMOS) and logistic support from the AAD (RSV *Aurora Australis*, Antarctic Bases). There is no significant private investment and the scope for tapping into this is too limited to represent a viable strategic option.

Funding for marine climate research comes directly to institutions from the government with additional external funding through the Australian Research Council (ARC), the ACE CRC, the Australian Climate Change Science Program (ACCSP) – which will end in June 2016 – and the Australian Antarctic Science Programme (see Table 3, for details).

Despite having a relatively small number of researchers in the marine climate field, Australia has a high international research profile publishing prolifically in leading academic journals and with membership and significant leadership roles on virtually all of the most influential international committees and working groups of the International Council for Science (ICSU), the World Meteorological Organisation (WMO) and the United Nations Educational, Scientific and Cultural Organisation (UNESCO). Leadership and active participation at the international level ensures that science priorities important to Australia are addressed. As an example Australia provided 38 lead or contributing authors to the 2014 IPCC report and Australian led research was highly cited[1].

Relevance

Climate variability and change impacts all aspects of society and the marine and terrestrial environment. Heat, water, carbon and nutrients are the fundamental elements of the climate system and the ocean is the dominant reservoir for all four constituents. To understand the climate system and its impact on society and the natural environment, we must be able to observe and model its oceanic branch including the storage and transport of heat, freshwater, nutrients and carbon in the ocean, and their exchange to the atmosphere and marine and terrestrial ecosystems, at global, regional and local scales.

As the Earth's climate enters a new era where it is forced by human activities, it is critically important to maintain a world-class Australian marine science capability that is able to detect, monitor, and predict regional and global marine climate variability and change. Australia is already highly vulnerable to extremes in climate[3] that are intimately linked to the state of the ocean[4], even without future climate change. Australia is also critically dependant on marine resources and services. Interpretation of past changes, monitoring and understanding the present climate and projections of future extremes, variability and change depends on understanding ocean circulation and ocean properties. Australian marine climate research needs to (and does) span the equatorial to polar regions, the Indian, Southern and Pacific Oceans and reaches from the coastal margins and boundary currents to the vast abyssal ocean of the Southern Hemisphere. This region covers well over half the volume of the global ocean, and is influenced at the surface by major climate oscillations[5] including the El Nino-Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Southern Annular Mode (SAM), and the Interdecadal Pacific Oscillation (IPO), all of which directly impact Australia's terrestrial and marine environment. The marine climate research undertaken in Australia covers the full spectrum from fundamental to applied science.

Given the diversity of marine climate variability and change research undertaken in Australia the end-users also span a diverse group from international non-government organisations, international, national, state and local governments, national defence organisations, tourism, agriculture, fisheries and aquaculture, off-shore oil and gas and renewable energy industries, marine parks and regulatory authorities. The research undertaken by this science community underpins development of climate products and services needed by industry, the public and policy makers[6–9].

Science needs

To tackle the full breath of marine research required to "Deal with Climate Variability and Climate Change" seven key areas were identified that underpin understanding of one or more climate impacts identified in Marine Nation 2025[10]:

- Pacific-Indian tropical oceans
- Polar and mid-latitude oceans
- Australian coastal and shelf oceans
- Paleoclimate
- Ocean biogeochemical cycles

- Sea level and ocean heat and freshwater content
- Marine Extremes

These themes examine specific science challenges that are affected by climate change and climate variability. Seven full white papers developed under each of these topic areas and with contributions from ~100 scientists across over 20 institutions, are provided as attachments. Here we provide a distilled list of the key science questions identified under each research area:

Pacific-Indian Tropical Oceans: Just north of Australia, the 'Indo-Pacific warm pool' is the engine for low-latitude atmospheric circulation and a key driver of global climate variability. It supports the existence of many climatic phenomena including ENSO and IOD on interannual time scales, and the Interdecadal Pacific Oscillation (IPO) on decadal time scales. Understanding these phenomena is critical for improved forecasting[5,11] and long-term projections of regional climate around Australia. Key science gaps include:

- Improved understanding of the physical drivers of tropical climate phenomena on various time scales, their interactions, teleconnections and physical impacts,
- Improved knowledge on the link between the Pacific and Indian Oceans and what controls the variability of the Indonesian Throughflow and its influence on climate, ,
- Improved dynamical understanding of multi-scale air-sea interaction processes within the Indonesian Seas and across the Maritime Continent.

Polar and mid- latitude oceans: The mid- and high-latitude oceans influence climate change and variability by storing and transporting vast quantities of heat, freshwater, nutrients and carbon dioxide. Moreover, interaction between the Southern Ocean and the Antarctic Ice Shelves are key to understanding future rates of sea-level rise. On decadal timescales the mid-latitude ocean-atmosphere system also influences Australian water availability and agriculture. As a result polar and mid-latitude research is vital for enhancing our ability to predict climate at decadal and longer timescales. Key science gaps include:

- How will the ocean's overturning circulation change in the future?
- How and why is Antarctic sea ice coverage changing?
- To what extent do interactions between the ocean, atmosphere, sea ice and the Antarctic ice shelves control the rate of Antarctic ice loss?
- How will regional currents, including the East Australian Current and the Leeuwin Current, change in the future?
- How is mid-latitude climate variability influenced by oceanic processes?

Australian Coastal and Shelf Oceans: In Australia, over 20 million people live within 10 km of the coast. Understanding coastal processes and changes are vital for translating large-scale changes in the climate system down to local impacts. The impact of climate variability and change on the coastal ocean environment is still highly uncertain. Key science gaps include:

- The role of sub-mesoscale ocean processes in coastal circulation
- The drivers and mechanisms of ocean-shelf exchange
- Drivers of coastal ocean warming and stratification changes on the shelf circulation and impact of changes in boundary currents

- Improved understanding of the bio-physical interactions and the response of coastal marine ecosystems to physical changes.

Palaeoclimate: Past climate reconstructions are an important means for estimating climate sensitivity and therefore how the planet will respond to anthropogenic changes in the long-term. Examination of analogue climatic periods in the past (with rapid rises in greenhouse gases) provides clues to our potential future climate and can be used to test and calibrate present-day climate models. Key science challenges are:

- Understanding of the climate history of the Australasian region
- Evolution of Southern Hemisphere climate modes and links to past climate
- Ocean control of atmospheric carbon dioxide (CO_2) during past warming events
- Adaptability of marine organisms and marine ecosystems to climate variations
- Previous global climate - carbon cycle - ecological dynamics and feedbacks

Biogeochemical Cycles: Ocean biogeochemical research is central to determining the capacity of Australian regional seas and the Southern Ocean to take up and store carbon, supply oxygen to the deep sea, control biological productivity and biomass, and for determining the sensitivity of these processes to changing climatic conditions. Characterisation of ocean biogeochemistry provides critical information on the exposure of Australia's marine ecosystems to ocean acidification. Key science needs are:

- Quantification of the role of the ocean in global biogeochemical cycles and carbon-climate feedbacks.
- Detection of ocean acidification and other chemical changes and their impact on marine ecosystems.
- Improved determination of linkages and controls of marine biogeochemical cycles on food security and marine ecosystem resilience.

Sea level and ocean heat and freshwater content: The sensitivity of the climate system and the hydrological cycle to increasing greenhouse gas concentrations (and other human activities) directly impacts the amount and distribution of warming, changes in precipitation, winds, and air-sea fluxes of heat and freshwater, and as a result impacts both global-averaged and regional sea-level change. Changes in ocean heat and freshwater content are an important priority both for understanding sea level rise and other oceanographic processes. Key science gaps that Australia is positioned to pursue include:

- Improving estimates of past rates of sea-level change.
- Narrowing uncertainties around heat sequestration into the ocean interior.
- Quantification of regional patterns of historical and projected sea-level change.
- Better constraints on ice sheet contributions to long-term sea-level
- Improved estimates of vertical land motion
- More rigorous attribution of observed global and regional sea-level change
- Understanding the discrepancies between current projections and those from semi-empirical models

Marine climate extremes: Marine extremes research acts as a vital bridge between global / regional scale climate research and the much smaller scales that are relevant to many stakeholders. Australia is a coastal nation making extreme sea-level and waves, storm surges, and ocean heat waves a particular concern for many communities and ecosystems. Significant physical, environmental and socioeconomic impacts are realised through extreme events and so improved understanding of many aspects of extreme events is needed to address the significant risks they pose to the Australian community. Key science gaps include:

- Improved estimates of historical changes in extreme sea levels and waves
- Causes of extreme impacts arising from multiple events need to be better quantified
- Improved understanding of severe weather events (e.g. tropical cyclones and East Coast Lows) in the context of climate variability and change.
- More robust projections of future changes to waves and surges and marine temperature extremes
- Improved quantification of the effect of mean sea level and extreme events on different shoreline types

Summary

There are many cross-linkages amongst the key science questions identified by different sectors of the marine climate research community. It is clear that there is a need for fundamental understanding of many phenomenon spanning global scales (e.g. melting of Antarctic ice and its link to global sea level rise, ocean uptake of heat and CO_2 – pivotal for our understanding of climate sensitivity), regional impacts (e.g. ENSO, IOD and their complicated inter-basin interactions), and local impacts (e.g. tropical cyclones, storm surges, ocean acidification). This fundamental understanding is essential if we are to manage the marine environment wisely and reduce uncertainty in future projections.

Perspective

The key science gaps of the 7 research areas have intertwined science priorities. Here we specifically consider these in a holistic framework around the marine science priorities for "dealing with climate variability and change."

1. <u>Enhanced understanding of ocean-cryosphere-atmosphere-biogeochemical variability and controls on interocean and ocean-atmosphere exchanges by wind, heat and freshwater fluxes.</u>

Australia is uniquely situated with respect to the global ocean as it straddles two major inter-basin exchange routes via which climate variability may be propagated. North of Australia the Indonesian seas are the only major low-latitude connection in the global oceans. This connection permits the transfer of Pacific waters into the Indian Ocean, known as the Indonesian Throughflow. The Indonesian Throughflow and low latitude Pacific and Indian Oceans have a major influence on both the regional and global climate. The Indonesian Throughflow provides a pathway for the transfer of climate signals and their anomalies around the world's oceans. While the heat and fresh water budget of the tropical ocean-atmosphere are known to influence the regional climate on seasonal to long-term time scales the tropical ocean-atmosphere circulation is not yet sufficiently observed and simulated in seasonal prediction and climate models.

South of Australia, the Southern Ocean is a major conduit for the inter-basin exchange amongst the Atlantic, Indian and Pacific Oceans. High-latitude oceans (modulated by seasonally-varying sea-ice coverage) help to govern the ocean's overturning circulation to control oceanic heat and carbon storage on long timescales. However, the response of the overturning circulation to changes in winds, heat and precipitation remains poorly understood. A significant research challenge is to understand the dynamical interaction between the high latitude Southern Ocean and the Antarctic Ice Shelves, mediated by sea ice coverage. These interactions control the rate of mass loss from the Antarctic Ice Sheet and hence rates of future sea level rise. Inflow of glacial meltwater also influences ocean circulation and sea ice.

Separating the equatorial and high-latitude oceans are the mid-latitude Indian and Pacific Oceans. The East Australian Current and the Leeuwin Current, at the Australian continental boundary, connect the low and high latitude oceans. The variability of these major boundary currents and their control of the shelf-open ocean exchange have a profound impact on Australian shelf circulation and marine ecosystem diversity and health in Australia's exclusive economic zone (EEZ).

Key Requirements:

- Through regional programs and links to international initiatives, complete and maintain a comprehensive and sustained global ocean observing system that is capable of quantifying variability of the ocean-cryosphere-biogeochemical system on decadal to centennial time scales.
- Intensive interdisciplinary observation-modelling process studies that target key marine climate phenomena (e.g. ocean-atmosphere drivers of moist convection over the tropical regions; ocean vertical and horizontal mixing; studies of physical and biogeochemical drivers from the Southern Ocean to the tropical seas and cross-shelf ocean boundary exchanges).
- Develop and maintain a suite of integrated ocean-cryosphere-atmosphere-biogeochemical-ecosystem data assimilation and forced models that span the range of low- to- high resolution. Observational and process studies will provide information to improve parameterisation of the complex interactions required to improve model simulation and predictions from seasonal, decadal and centennial time-scales.

2. <u>Improved knowledge of the impact of increasing greenhouse gas concentrations on the complex interplay between major climate phenomena and ocean-cryosphere-atmosphere-biogeochemical dynamics</u>

Ocean warming accounts for more than 90% of the extra heat energy stored by the planet since 1970. Measurements of ocean heat content are therefore essential to quantify the earth's energy budget and to track the evolution of climate change. The ocean is an important sink for anthropogenic CO_2, accounting for uptake of about 25% of annual emissions and about 40% of the ocean uptake occurs in the Southern Ocean. Changes in processes that regulate the size of the ocean sink and the rate of ocean heat and carbon uptake could significantly alter the earth's heat and carbon budgets with important implications for world climate including ocean acidification and sea level rise.

Human induced warming by greenhouse gases interacts with the ocean's natural variability, mainly driven by the key climate phenomena_- ENSO, IOD, SAM, IPO. The interaction between anthropogenic climate change and the ocean's natural variability is highly non-linear. Therefore it is essential to understand and correctly model the interaction between natural variability and human-induced climate change because adaptation to climate change will depend in a critical way on decadal to multi-decadal prediction.

While observational and modeling studies provide information on the current and potential future state of the climate system, paleo-oceanographic data and paleoclimate modelling provide an insight into the earth past climate history. Paleo-reconstructions and modeling can provide benchmarks against which to assess current and future changes in climate. In particular paleoclimate studies provide guidance of the response of the earth system to previous ocean warming and high atmospheric carbon concentrations and the impact of ocean acidification and melting of ice caps on marine ecosystems (including biodiversity and health) and global and regional sea levels.

Key Requirements

- Develop and maintain full-depth ocean temperature, salinity, carbon and nutrient observations to quantify the thermosteric and halosteric contributions to sea level rise, assess changes in the global water cycle and ocean carbon budget and acidification, respectively.
- Develop and maintain integrated ocean-cryosphere-atmosphere-biogeochemical-ecosystem data assimilation and climate models that improve the reliability of seasonal-to-decadal-to-centenary prediction of the climate system.
- Advance observational systems and models of key palaeoclimate era to understand variability of the ocean-atmosphere system for assessment of potential future variability of SAM, ENSO and IOD and reconstruction of the deglacial history of Ice Sheets over Antarctica, and their impact on sea-level.

3. <u>Increased understanding of the mechanisms and impacts of multi-decadal variability and longer-term trends on Australian and regional climate (including Asia and Pacific Islands).</u>

Major vulnerabilities in the future behaviour of the ocean-carbon-climate system include the effects of ocean warming, enhanced vertical stratification, strengthening and shifts of westerly winds in the Southern Ocean, and shifts in the biological carbon pump and ecosystem functioning that could alter carbon and nutrient cycling. Ocean acidification has potential to cause imminent and widespread disruption to marine ecosystems, including the coral reefs that provide food, coastal protection and tourism opportunities for Australia and our regional neighbours. These vulnerabilities are likely to have a major impact on the Australian economy and environment. Sea-level change is a major issue with 140 million people living within 1 m of the current high tide level, many in south and east Asia close to Australia, and with vulnerable populations in Pacific and Indian Ocean island nations. Climate change refugees may be a significant issue during the 21st century. Added to the sea level rise is the increased risk of marine extremes (e.g. wave and storm surges, marine heat-waves).

International and Australian government (at all levels from local to national) and industry are in urgent need of improved and continuing advice from the marine science community on the risk of future ocean acidification, sea-level rise and extreme events. Fisheries and the oil and gas industry and the emerging ocean renewables sector need to understand effects of variability and change for making sound investments and planning on the horizon of decades. Thus they require reliable decadal to longer-term climate predictions. At these time-scales, the ocean is the major driver of climate predictability.

Key Requirements:

- High resolution coastal/shelf data to provide a better understanding of the characteristics of natural climate variability including societal-relevant extreme events and frequency of such events.
- Long, continuous time-series of vertical land movement at all (~40) climate-related tide gauges within Australian territories (including island sites and Antarctica) and adjacent regions.
- A wave monitoring observational system for the Australian coastline
- Reliable coastal response models, which can accurately forecast future shoreline positions under rising sea-level scenarios and increased extreme events. These models need to include the complexities and feedback processes that characterise coastal sedimentary systems.

4. International Engagement

The World Climate Research Programme (WCRP) coordinates climate research internationally and it is vital that Australian research continues its strong engagement with WCRP to maximise the value of Australian investment and to ensure international activities target issues of relevance to Australia.

The Australian research community is strongly involved in the Global Ocean Observing System (GOOS), a component of the Global Climate Observing System, including Argo, GO-SHIP, XBT, Global Ocean Acidification-Observing Network, and OceanSITES. It is vital to Australia's maritime interests that we continue and expand our contribution to international observing programs that can leverage national and internaional investment to increase observations in the southern hemisphere oceans.

The Australian ocean and coupled climate modelling community provides world-class expertise in the development of improved models through active participation in international model intercomparison projects and via improved model physics and parameterisations. Australia is the only Southern Hemisphere nation with this capacity, leading global efforts for accurate models in our region. It is vital to the nation that this work continues.

Australia must remain a member of International Ocean Discovery Program (IODP). This enables us to build partnerships with overseas scientists, by having research proponents and co-chief scientists who can steer programs and outputs, and by early access to key samples and data. Our region is unique to address various global science problems. Being a member of IODP will help us maintain our leadership in Southern Hemisphere marine geoscience research.

Realisation

Common Challenges

- High quality observations and adequate Research Vessel access
- Global and regional ocean climate modelling of world-class standard with a Southern Hemisphere focus
- Computational & storage resources meeting the next decade's scientific needs
- Adequate and sustained research funding targeting the marine climate sector

Across the sub-themes a number of common requirements have been identified to deliver on the science priorities discussed above and to deliver the associated outcomes to end users and stakeholders.

Central to all climate science is **high quality observations**. As this is a science of change, observations taken over multi-decadal time scales are required in order to detect climate change from a backdrop of climate variability. In addition, targeted process studies are needed to identify the physical mechanisms that must be understood if we are to predict future change and its impacts. Key requirements:

- A long-term commitment of support and gradual expansion of IMOS, which underpins Australia's observational capabilities. This long-term commitment is required to maintain IMOS programs over periods sufficient to resolve decadal variability and climate change. In addition the current IMOS portfolio needs further expansion to incorporate emerging technologies for improved monitoring in poorly observed but climatically important areas (e.g. under ice, and in the deep ocean and along coastlines). Sustained biogeochemical monitoring severely lags behind observations of the physical environment and needs to be enhanced as a priority.
- Access to greater ship-time is critically needed to facilitate marine science voyages on the continental shelf, open ocean and in ice-covered seas. *RV Investigator* provides a more capable ocean-going vessel than previously available in Australia, but operations must be expanded from the presently funded 180 days/year to 300 days/year to meet the demand from Australian researchers. The *RSV Aurora Australis* and a future Australian icebreaker are crucial for work within the sea-ice zone, and sufficient funding to support marine science must be included in the Australian Antarctic Division budget.
- Incorporation of a coastal vessel accessible to different institutions into the National Marine Facility to facilitate coastal zone observations and coordination of the national effort.
- Australia's national capacity for observations of ocean–ice interaction is limited. As some of the largest uncertainties in projections of future climate and sea level rise result from poor understanding of ocean–cryosphere interactions, enhancements to the high-latitude observing system are needed. Coordinated international deployment of autonomous platforms and moorings in key regions has the potential to revolutionise our understanding of the remote, challenging and under-sampled under-sea ice and –ice shelf environments. Continued access to satellite data is also crucial, and Australia has a leading role to play in algorithm development and calibration and validation of derived geophysical quantities.

- Australian marine scientists must have access to new technologies for coordinated ocean and sea ice sampling. These include "deep Argo" floats capable of profiling the full ocean depth; profiling floats with new biogeochemical sensors; and ice mass-balance buoys providing simultaneous measurement of sea ice dynamics and growth/melt.

Seasonal scale forecasting, decadal prediction and long-term projections require world-class **numerical models** of the climate system validated against long-term observations from multiple regions. It is only recently that computational power has reached a level that we can start to look beyond large scale projections, to space and time scales that are directly relevant to stakeholders. However this is a major challenge as new processes must be accounted for and validation must also occur using observations at much finer scales.

- Maintain and extend the capabilities of BLUElink. This product provides important services for various stakeholders (e.g. in navy, tourism, marine transport)
- Support existing and new modelling efforts covering timescales from seasonal to decadal prediction to centennial scale projections, prioritising improved physical parameterisations and a move towards mesoscale/submesoscale modelling
- National effort in palaeoclimate modelling (e.g. through the development of a palaeo-version of the ACCESS model), fostered by greater collaboration between the paleoclimate and modelling communities
- Ocean model development in Australia is currently an *ad hoc* arrangement between the university community (focussed via ARCCSS) and PFRAs such as CSIRO, BoM and AAD. National (and international) coordination of these efforts is focussed on individual applications (e.g. ocean forecasting, climate prediction, ocean-ice interaction). Australia's oceanographic contributions would be enhanced by better coordination of these efforts, allowing the benefits of investment in each area to be spread across the community. Crucially, there is a major gap in Australia's current sea-ice modelling and ice-sheet modelling capabilities.

Long term observational data and new modelling efforts that can adequately resolve local scale impacts and short time scales, within the context of long-term change, will require ongoing large increases in **computational storage and power** and a massive ramp-up in short-term storage and long-term archival facilities

- Improved supercomputing and storage capability is needed to meet the massive growth in computational power and storage that will be required for future modelling
- Ocean modelling has been limited by computational power, and this will continue to be a constraint for the foreseeable future. Continued secure funding for the current NCI, which entails a national approach to high-performance computing, is a necessity for Australian marine science. NCI facilitates both the research (through provision of computing power) and provides a common environment to facilitate collaboration between different parts of the research sector. In addition, in-house expertise within NCI provides invaluable high-level technical services to the sector. Modelling groups need to prepare for the significant increase in both storage and computing needs for running next generation coupled climate

models and processing of satellite observations, including porting code to new types of computer architectures and maintaining state-of-the-art capability.

While **funding** is the limiting factor for all research initiatives, certain funding priorities have emerged that resonate across the themes, together with certain structural funding impediments that limit progress:

- Long-term funding of the *RV Investigator* at 300 days per year is critical to meet the high demand for ship time across the themes
- A challenge common too many facets of ship-based marine science is the lack of coordination between funding for ship-time through an application to the MNF and funding for the research (e.g. salary, travel, equipment and analysis costs). Better coordination of these funding rounds would maximize use of resources, reduce time wasted on multiple funding applications and ensure the best science is properly supported.
- Most of the pressing scientific projects require longer (>3-5 years) time scales than is common for many funding schemes and funding cycles. As such longer-term and increased funding options are required, including a long-term commitment to IMOS and the ACCESS climate model.
- The Australian marine and climate science communities are relatively small and split across the university sector and PFRAs. It is essential that scientists in the two sectors collaborate effectively. At present, the shortage of funding sources that can support collaborative work between scientists based at universities and at PFRAs on the same project is a major impediment to collaboration. Continued investment in personnel in both sectors and a joint postdoctoral scheme is needed to maintain Australian expertise.
- Long-term logistics support for fieldwork is essential for monitoring slow changes at critical locations. Provision of such support needs to be funded as part of core funding to the agencies operating research vessels and other infrastructure, and not out of the funds available to support research. Such provision would allow the university sector to make meaningful contributions to field-based research, while also providing the long-term monitoring capacity that is essential for understanding and projecting climate change

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Appendices

Appendix 1: Institutions

Table 2. Make up of the Australian Climate Community (NB this is not a complete list, but represents a large component of community activity)

Institute	Activity
BGC	
CSIRO (Hobart, Brisbane, Perth and Melbourne)	observing system development, biogeochemical cycling of carbon, nutrients and oxygen, ocean-atmosphere carbon and oxygen exchanges, coastal-offshore linkages, phytoplankton ecology, satellite oceanography and modelling projections of change
IMAS UTAS & ANU	trace element chemistry and micronutrient availability
IMAS, CSIRO, CU, AAD, UQ, UTS, UNSW	marine primary production, satellite oceanography, and microbial ecology that can influence biological carbon and nutrient cycling
ACECRC	BGC of high latitude waters
AIMS, ANU, CSIRO, CU, FU, GA, JCU, SCU, SU, UA, UNSW, UQ, WU, UWA	biogeochemical cycling in coastal and reef regions
SEA LEVEL	
CSIRO OnA, UTAS	Sustained open ocean observations, SO satellite observations
NTC BoM, various regional and port authorities	Tidal measurements
CSIRO OnA, UTAS and ACE CRC	Data quality control
ANU, UCan, CU, UWA	Paleo sea level
CSIRO OnA, UNSW	Mechanisms, Projections
ANU, UTAS	Land movement
GA, CU, UNSW, ANU	radar interferometry
ANU, UTAS	Gravity measurements
ANU, CU, UTAS, CSIRO	Sea-level contributions
ACE CRC and AAD	ice-sheet/ocean interactions
EXTREMES	
CSIRO O&A, ACE CRC, UNSW WRL, BoM, Griffith U, UWA UQ, Macquarie Uni	Coastal Sea-Level Extremes including storm surge, coastal sea level, inundation
CSIRO O&A, Swinburne, UWA BoM, Macquarie, UNSW WRL	Wind-Waves
BoM, CSIRO O&A, U Melb, UWA, UTAS, Macquarie	Tropical Cyclones
U Adelaide, CSIRO L&W	Compound (including coincident) Extremes
BoM, Macquarie Uni	Tasman Lows
CSIRO O&A, UNSW WRL, UQ Macquarie Uni	Coastal Erosion
U Melb, UNSW, CSIRO O&A, UWA IMAS	Ocean Temperature Extremes and impacts
CSIRO L&W; CSIRO O&A, U. Sunshine Coast, NCCARF UNSW WRL, Macquarie Uni	Coastal Adaptation
TROPICAL	
ARCCSS, CSIRO, BoM	Research in diverse aspects of tropical oceanography is undertaken at a large number of institutions. 40-50 scientists (excluding graduate students) at the named institutions

MID-HIGH LATITUDE	
CSIRO	Southern, Pacific and Indian Oceans Observations
AAD/ACE CRC and UMelb	Antarctic sea ice
ANU, UNSW and UTas	Ocean Modelling
ACE CRC	Ocean-cryosphere interactions
UTas, CSIRO, UWA	Indian Ocean
CSIRO, UNSW Canberra, SIMS/UNSW	Southwestern Pacific Ocean
BoM	Seasonal forecasting
IMOS	Sustained Southern, Pacific and Indian Oceans Observations
COASTAL	
AIMS, BOM, CSIRO, UNSW, UTAS,UWA, SARDI	coastal and shelf oceanography
IMOS	Observational network
UWA, SARDI, UNSW, CSIRO, BOM, AIMS, UTAS	Coastal modelling
PALEO	
ANU	main palaeoclimate data/proxy group
UWA, AIMS, JCU, UQ, UW, CU, US, UM, MU, UTAS, ANSTO, GA, AAD	Other smaller groups
UNSW, CSIRO, MU, UWA	Paleo modelling

Appendix 2: Funding Sources

Table 3. Sources of funding (NB this is not a complete list, but represents a large proportion of funding channels)

Activity	Funding Source
BGC	
Sustained monitoring	IMOS, ACCSP
High latitude research	DE, AAD, ARC, ACE CRC, ACCSP
Coastal and tropical	ARC, ACE CRC, DE, State Gov, ACCSP, Industry
Ship time	Australian Marine National Facility, ARC
Sea Level	
Observational Activities	IMOS, AuSCOPE, ASSCP
University funding	ARC, ACE CRC, AAD, former DCC
Extremes	
Coastal Sea-Level Extremes including storm surge, coastal sea level, inundation	CSIRO, DOTE (ACCSP), DFAT, State Govt, Local Govt, WAMSI, ACE CRC, BNHCRC, NSW OEH
Wind-Waves	CSIRO, DOTE, DFAT, ARENA, O&G, ARC, BoM, State Govt, NSW OEH
Tropical Cyclones	ARC
Compound (including coincident) Extremes	GA, U Adelaide
Tasman Lows	NSW OEH
Coastal Erosion	DOTE, GA, State Govt, Local Govt
Ocean Temperature Extremes and impacts	ARC
Coastal Adaptation	DOTE, CSIRO, GA, State Govt, Local Govt, NSW OEH
TROPICAL	
	Funding is primarily through various federal government schemes: ARC (e.g. ARCCCS), ACCSP, PACCSAP, WAMSI), the Goyder Research Institute Climate Programme, and the Indian Ocean Climate Initiative (IOCI)
MID-HIGH LATITUDE	

Research	ARC, ACE CRC, ACCSP/NESP, the Australian Antarctic Science Programme
Computation	NCI
RV & Antarctic bases, observations	AAD, MNF, IMOS, ACCSP
PALEO	
Australian and New Zealand International Ocean Discovery program Consortium (ANZIC)	ARC/LEIF
Australian palaeoclimate science	ARC, ARC CRS, AIMS, AAD, university fellowships and joint international programs
Research Vessel	Australian Antarctic Science Program, MNF. Internationally through the Integrated Ocean Discovery Program (IODP)
COASTAL	
Bluelink	Royal Australian Navy
Fisheries	FRDC, NSW DPI, SARDI, BP, BHP

Appendix 3: White Paper: Coastal and Shelf Oceanography in Australia

Appendix 4: White Paper: Mid- to high-latitude oceans

Appendix 5: White Paper: Ocean biogeochemistry (incl. carbon cycle, ocean acidification, marine chemistry)

Appendix 6: White Paper: Paleoclimate Research in Australia

Appendix 7: White Paper: Sea level and ocean heat and freshwater content

Appendix 8: White Paper: Ocean Extremes

Appendix 9: White Paper: Tropical Oceanography Research in Australia