Dealing with Climate Change: Tropical Oceanography Research in Australia

Abstract

Tropical oceans are an integral element of the climate system. Changes in ocean circulations in the tropical Pacific and Indian Oceans are both a manifestation and cause for climate variability, which significantly impacts on Australia's environment, economy, and society. While tropical oceanography research in Australia is already mature and world class, there are still many aspects of the science that need to be further investigated, with new phenomena continuously being discovered. To anticipate what the future has in store, we need to sustain intensive research, extend the presently short observational record, and address shortcomings in climate models that are used for predictions and for understanding complex processes.

Background

Tropical oceanography underpins much of the Australian climate. The northern half of the Australian landmass is flanked by tropical Indian and Pacific Oceans. Rich meanders of ocean currents within the tropical belt transport heat, salt and affect nutrient distributions that sustain the health of Australia's marine habitat. The tropical Indian and Pacific Oceans are also home to some of the Earth's most prominent climatic phenomena, such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), which influence weather patterns and ocean currents not only around Australia but also far beyond the tropics. Many of the severe droughts and floods experienced in Australia are associated with ENSO, the IOD, or their concurrences.

As the globe is expected to warm with increasing emission of atmospheric greenhouse gases (Stocker et al. 2013; Kirtman et al. 2013), our current expectation is that the tropical climate system will undergo significant changes. Yet, our tools for understanding the issue are still far from perfect (Brown et al. 2011; Irving et al. 2012), and there are still many aspects of the tropical climate system that need to be understood. However, thanks to sustained research efforts, further insights and discoveries of new phenomena have continuously emerged. An improved knowledge in the context of past and present-day climate supported by enhanced reliability of observational and modelling tools, will allow us to better understand the ways the complex tropical system would respond to the increasing influence of future greenhouse effect.

Research in this diverse range of research topics is conducted by scientists at various academic and government institutions across Australia. Given the subject diversity, short-term employment (postdocs on 1-3 years contracts), and the fact that the topics are also often investigated by researchers outside the field of oceanography (e.g., mathematicians and statisticians, environmental engineers), it is difficult to pin down the exact number of scientists working in this area. However, a large group of these scientists are networked under the umbrella of the Australian Research Council (ARC) Centre of Excellence for Climate System Science (ARCCSS), which includes five universities (UNSW, ANU, Monash University, Univ. of Melbourne, and UTas) in partnership with the Bureau of Meteorology and CSIRO. This group alone comprises about 40-50 scientists (excluding graduate students) who are actively working in various aspects of tropical oceanography. Given the different nature of the academic and government institutions, research efforts across the different institutions complement one another.

Australian research in this field of science is mature and recognised internationally. Many of world-leading scientists in the field reside in Australia, and they are active members and leaders of CLIVAR Indian Ocean and Pacific Ocean panels. CLIVAR (http://www.clivar.org/) is an international project under the World Climate Research Programme that aims to understand the inner working of the climate system through facilitating observations, analysis and predictions. The Bureau of Meteorology is also a member of the World Meteorological Organization (WMO). The Bureau, CSIRO and universities have had a long and important involvement in the Intergovernmental Panel on Climate Change reporting process, including the most recent report. In addition, the volume and standard of our research output are high as evidenced by the large number of research papers published in leading international journals (e.g., Power et al. 2013, *Nature*; Santoso et al. 2013, *Nature*; Cai et al. 2013, *Nature Geoscience*; Cai et al. 2014a, *Nature Climate Change*; Cai et al. 2014b, *Nature*; England et al. 2014, *Nature Climate Change*; Kim et al. 2014, *Nature Climate Change*; McGregor et al. 2014, *Nature Climate Change*, Risbey et al. 2014, *Nature Climate Change*).

The Australian government has been the backbone driving research in this area. ARCCSS, for example, is one major initiative funded by the Australian government through the ARC. Other major federal and state government funded initiatives include the Australian Climate Change Science Program (ACCSP, focussing on Southern Hemisphere climate), the former Pacific Australia Climate Change Science and Adaptation planning Program (PACCSAP), the Western Australia Marine Science Institution (WAMSI, for Indian Ocean Research), the Goyder Research Institute Climate Programme, and the Indian Ocean Climate Initiative (IOCI). Tropical climate and oceanography has also comprised a large part of the research of the Centre for Australian Weather and Climate Research (CAWCR), a partnership between CSIRO and the Bureau of Meteorology.

Relevance

Tropical climate phenomena, such as ENSO, greatly influence ocean and atmospheric circulations, rainfall, streamflow, crop production (e.g. Power et al. 1999), and the number of tropical cyclones making landfall (e.g., Callaghan and Power 2011). This impacts on Australia's environment and socio-economy. For instance, rainfall reduction and risk of agriculturally damaging winter frosts, summer heat waves, dust storms and bushfires over the more densely populated eastern regions are enhanced during El Niño (e.g., Williams and Karoly 1999). On the other hand, the risk of tropical cyclone, marine heatwaves off Western Australia coast, and floods in eastern Australia is heightened during La Niña events (e.g., Diamond et al. 2013). The extended costs of damages associated with major extreme weather events (e.g., the 1983 Ash Wednesday, 2010 Queensland floods, Cyclone Yasi in 2011) are often of the order of billions of dollars. Coral reefs, fisheries, and marine ecosystems of the Western Australia coast had been significantly impacted by the 2010/11 marine heatwave dubbed Ningaloo Niño. Several lines of evidence suggest that global warming will only increase Australia's vulnerability to climate variations with potentially devastating consequences.

Given the significant impacts, intensive research on the tropical climate system is crucial, and is of interest to a wide range of industries that are heavily dependent on the state of the ocean, weather and climate, such as the Australian Navy, fisheries, tourism, marine park and transport, farming, water resources management, renewable energy industries, real estate, and insurance. The global extent of these impacts means that tropical climate variability ultimately affects the overall stability of Australia's financial systems, national defence, food security, and the wellbeing of the general public.

An enhanced capacity in anticipating the impacts of climate variability in the backdrop of a changing climate is crucial for how we manage risks and resources. Better multi-week to seasonal rainfall forecasts would allow farm management strategies to be implemented to conserve water and diversify crops. The value of these forecasts can exceed $50/ha in the grains industry, and can have a payoff time (the time for a forecast to be highly certain of bringing such benefits) of just a few years (Asseng et al. 2012). Long-term management would certainly benefit from better decadal climate forecasting and improved future projections. An agricultural enterprise located in a region projected to dry in the future may have to decide when to change crop, or when to move to a better location. A fishing enterprise may have to decide when to change target species or move to a different home port. A mining enterprise may have to decide on major development of infrastructure. Many health issues are directly related to climate, such as food security, safe drinking water, heat related stress and death, and spread of disease. Adaptation to climate change in addition to climate variability will need to be implemented during the next decade or two. This means that the interplay between decadal climate variability and global warming has to be taken into account. A potential for decadal climate prediction - a new research frontier - has already been demonstrated (Meehl et al. 2014), and if operationally feasible, may provide useful information to support the timing of adaptation decisions.

For end-users to fully reap the benefit of this research, communicating the science is crucial (e.g., Power et al. 2005, 2007, 2012). Over the past decade, communication between scientists and grain farmers has been instrumental in increasing the mutual understanding of weather and climate forecasts, and guiding development of new and targeted forecast products (e.g., McIntosh et al. 2006). Seasonal forecasts have been shown to benefit the extensive rangelands grazing industry in northern Australia by strategically increasing stocking rates without increasing top-soil loss. Recent engagement with the cotton industry will explore the value of short-term temperature forecasts in helping determine planting time, season extension, and defoliation prior to harvest.

Knowledge of various aspects of tropical climate variability has been widely communicated to various other stakeholders through collaborative research projects, invited presentations and end-user oriented workshops (e.g., IOCI Science Update, presentations at Insurance Australia Group), and to the general public through the media (e.g., newspapers, television programs, radio, *The Conversation*, etc.). Each institution also has their own websites accessible to the public that contain science updates, climate predictions, data access, and educational purposes (e.g., http://www.bom.gov.au/climate/).

Science needs

Just north of Australia, the Earth's largest and warmest pool of ocean water straddles across the Maritime Continent. This 'Indo-Pacific warm pool' fuels rigorous atmospheric convection that drives the atmospheric Walker Circulation within both the tropical Pacific and Indian Oceans. The warmth of the tropical oceans facilitates strong air-sea interactions that support the existence of many climatic phenomena across a spectrum of time scales, such as ENSO, the IOD on interannual time scales, the Interdecadal Pacific Oscillation (IPO) on decadal time scales, and the Madden Julian Oscillation (MJO) on intra-seasonal time scales.

Research over recent decade has provided a realisation that climate phenomena across ocean basins can interact with one another via the atmosphere (e.g., Dommenget et al. 2006; Santoso et al. 2012). One example is the eastward propagation of atmospheric MJO signals from the Indian Ocean into the Pacific which influences the evolution of ENSO and thus its predictability (Wheeler and Hendon 2004; Hendon et al. 2007). The evolution of ENSO is also influenced by the IOD via atmospheric teleconnection (Luo et al. 2010), as well as variability outside the tropics (e.g., Terray 2011). Recent research has suggested that taking the IOD into account can extend the predictability of ENSO events from six months to fourteen months (Izumo et al. 2010). While such knowledge has raised some hope for better predictions, it also highlights the complexity of the system in that to understand the evolution of a certain climate phenomenon we need to take into account processes occurring outside its source region. Their complex interplay on rainfall for instance (Risbey et al. 2009; Cai et al. 2009) underlines the difficulty in attributing and anticipating the associated impacts. The behaviour of climate phenomena is also influenced by the warming background climate in ways not at present fully understood (e.g., Kociuba and Power 2014), complicating the issue even further.

While the associated atmospheric teleconnection mechanisms are still being intensely investigated, recent studies (Yuan et al. 2011, 2013) have suggested that inter-basin interactions can also occur via the oceanic channel across the Indonesian Archipelago. Consisting of slightly more than thirteen thousands islands, the Indonesian Archipelago is a complex tropical channel that allows a voluminous flow of water from the Pacific into the Indian Ocean, thus termed the Indonesian Throughflow. Changes in the Indonesian Throughflow impact on the heat and freshwater budget in the Pacific and Indian Oceans and thus have important ramifications for climate (Wijffels et al. 2008; Sprintall et al. 2014). Yet our understanding of the Indonesian Throughflow and its variability is still incomplete, due to the difficulty in measuring it and representing it in climate models. The challenges primarily lie on the complex bathymetry of the Indonesian Archipelago which makes it difficult for any observing systems to fully sample the spatial and temporal characteristics of the flows through the narrow straits. At present, the issue is studied using high-resolution ocean models that can resolve the narrow passages within the Indonesian Seas (e.g., van Sebille et al. 2014). Since they sit within the Indo-Pacific warm pool, the Indonesian Seas are an important component of the climate system. Their role in air-sea interactions, cloud formation, and climate variability on regional and global scales can only be properly studied using high-resolution fully-coupled atmosphere-ocean-land models. Due to presently expensive computational cost for running such models, their role in variability longer than inter-annual time scales remains to be not fully understood.

One of the many implications of interactions between the tropical Indian and Pacific climate systems is the Ningaloo Niño, a newly discovered climate phenomenon (Feng et al. 2013), resulting in decimation and southward migration of marine species (Pearce and Feng 2013). The discovery was preceded by an observation of extreme ocean warming off the coast of Western Australia in 2011, due to an intensification of the ocean Leeuwin Current and anomalous atmospheric circulation instigated by strong La Niña condition in the Pacific and promoted by the local air-sea interaction. The occurrences of Ningaloo Niño may be due to La Niña-like decadal trend, that is, with the IPO shifting into its negative phase. As the climate system varies on multi-decadal time scales and is expected to change under greenhouse warming, new phenomena and rare behaviour may emerge, such as the El Niño Modoki (Yeh et al. 2009), and eastward propagating El Niño (Santoso et al. 2013). This highlights the need for continuous observations far into the future to observe the full range of ENSO behaviour while also resolving multi-decadal variability and trends.

The increasing breadth of observational data available, as well as significant advances in theories and numerical modelling, has enhanced our knowledge on many aspects of tropical oceanography and climate. This has allowed future projections to be made using the latest generation of climate models. The projections show that the tropics will significantly warm with a slowdown of the large-scale atmosphere and ocean circulations (Vecchi et al. 2006; Sen Gupta et al. 2012). As a result, the behaviour and impacts of certain climate phenomena such as El Niño and the positive phase of IOD have been suggested to become more extreme and frequent (Power et al. 2013; Santoso et al. 2013; Cai et al. 2013, Cai et al. 2014a, 2014b; Chung et al. 2014).

The picture about the future cannot however be more certain without a better understanding of how and to what extent the tropical climate system behaves over decadal time scales and beyond throughout Earth's history. More certainties can only be achieved when we have longer high quality observations. At present, our understanding rests on the use of limited observations and paleo-climate reconstructions, and relatively coarse-resolution state of the art climate models which are not yet capable in properly simulating many aspects of the real system. Even though these tools are still in need of improvements, it is important that more effort over the next 5-10 years is still spent on even more thorough investigations using the existing tools, despite their shortcomings, coupled with innovative experimental designs and theoretical considerations. This will serve as a benchmark for future studies in the next 20 years when past results need to be revisited and verified. It is also important that activities in model evaluation on many aspects of the tropical climate system are sustained and enhanced.

In summary, there are still many aspects of the tropical climate system that we do not yet fully understand. This includes: the limits of ENSO and IOD predictability, inter-basin interactions, the drivers of multi-decadal variability, variability of the Indonesian Throughflow, air-sea processes within the Indonesian Seas. Our lack of understanding is largely due to the limited observations and models that are still too coarse to explicitly represent important processes. As observations and models advance over the next 20 years, our knowledge and future projections of the tropical climate system need to be reassessed. Questions that can be answered with high-resolution numerical models include understanding the role of stochastic forcing and meso-scale variability on multi-decadal climate variability, as well as climate impacts on regional scale. Future research will also need to get away from focussing on what we take to be modes of climate variation and change, (i.e. ENSO, IOD, IPO, etc), studying each mode separately, but rather understand the global climate system as a whole.

It is only by resolving these gaps and challenges that our capacity in predicting tropical climate variability and its impacts will be truly enhanced. This will then improve our capacity in managing risks and resources in a future climate that is expected to change significantly. Improved projections of the tropical climate variability can enhance Australia's ability to become 'climate-proof.'

Perspective

To meet those key challenges we need to expedite the following science priorities over the next 5-10 years:

The need to identify the mechanisms that link climate phenomena between ocean basins: This includes, for example, understanding how the IOD and Ningaloo Niño interact with ENSO as well as the IPO through both the atmospheric bridge and the Indonesian Throughflow. This requires an understanding of moist convection and cloud formation in the entire tropics and subtropics, as well as the dynamics of the Indonesian Throughflow. Work in this area has started to progress, requiring intricate experimental designs using coupled atmosphere-ocean models. However, there is still plenty of scope for properly assessing all possible mechanisms for all climate phenomena in the tropics and their interactions within the tropics and beyond.

The need to better understand ENSO: ENSO remains the most dominant mode of year-to-year climate variability. While much is now known about ENSO, there are still many of its aspects that are not yet fully understood. For example, why El Niño is not a mirror image of La Niña in terms of event growth (e.g., Santoso et al. 2013), event decay (e.g., McGregor et al. 2013), and rainfall impacts (Power et al. 2006; Cai et al. 2010). One major challenge is to observe, model and theoretically understand the complex interplay between ENSO and human induced global warming, and the implication for ENSO prediction.

The need to quantify natural variability of the tropical climate system on decadal-to-centennial scales: This requires sustaining existing observation effort that has continued for a near decade long, and an enhanced gathering and examination of paleo-proxy records. Paleo-climate studies in long-term changes of ocean surface temperatures in the tropics and their interactions with major climate phenomena are currently based on insufficient number of marine and terrestrial proxy records and are seriously lacking replication. There is a critical need to expand the geographical and temporal coverage of proxy data, particularly in the poorly sampled Indian Ocean and Indo-Pacific warm pool region. These efforts should aim to narrow down uncertainties that current proxy reconstructions and paleo-model data intercomparisons presently exhibit. Knowledge of past climate variability will improve detection and attribution of climate change signals.

The need to understand the complex interplay between climate variability and greenhouse warming on multiple time scales: Recent studies have shown that the rate of human induced global warming is altered by its interaction with ENSO (Thompson et al. 2011). The so called hiatus in global warming from 1998 to the present was caused in part by a period when ENSO favoured the occurrence of La Niña (England et al. 2014). Earlier

(1976-1998), ENSO favoured more occurrences of El Niño, and global warming was accelerated. How do natural and human-induced climate changes interact? How sensitive is local air sea coupling in the tropics to the phase shift of the IPO and greenhouse effect? It is essential to understand and correctly model the interaction of natural and human induced climate change because adaptation to climate change will depend in a critical way on decadal to multidecadal prediction. It is also crucial to conduct assessment of the potential impacts of greenhouse warming on tropical climate predictability, and the associated impacts on the environment.

The need to understand the mechanisms and impacts of multidecadal variability and trends: This includes identifying the physical mechanisms underlying the Interdecadal Pacific Oscillation (IPO). Is the IPO a natural, multidecadal phenomenon as a consequence of the internal, chaotic mechanisms inherent in ENSO and its teleconnections? What physical mechanisms set the 30-40 years time scales? What is the role of ocean circulations, including western boundary currents (e.g., Leeuwin Current, East Australian Current), the relative role of internal and external forcings, Pacific-Indian-Atlantic interactions, and tropic-extratropics interactions? What controls multi-decadal variability in the Indian Ocean (Han et al. 2014)? What is the cause for the rapid warming rate in the Indian Ocean sea surface temperature (Luo et al. 2012)? The scope of research extends to determining the impacts of multidecadal variability and trends on hydrological cycle within and beyond the tropics (e.g., Power et al. 2006), and implications on ENSO predictability (e.g., Aiken et al. 2014), just to mention a few. This research will benefit from high-resolution fully coupled climate models to understand changes at regional/continental scales. Paleo-proxy records and paleoclimate modeling will also play a crucial role in benchmarking decadal to centennial scale climate variability (e.g. Huiskamp and Meissner, 2012; Phipps et al., 2013).

The need to understand Indonesian Throughflow and air-sea processes over the Maritime Continent: The Indonesian Throughflow is an important component of the global conveyor belt and it regulates the Earth's climate. It is important to monitor and resolve its interannual and decadal characteristics, to study its implications on climate variability, such as the IPO, ENSO, IOD, and MJO, and ocean circulations, such as the Leeuwin Current and East Australian Current. The Indonesian Throughflow transport appears to vary with ENSO phases (e.g., Meyers 1996; England and Huang 2005, van Sebille et al. 2014), but the details on how the two are linked are still lacking. This work requires sustained observations and high-resolution climate models, as well as. utilising paleo-reconstructions to understand its evolution in the past (e.g., Abram et al., 2014; McGregor et al. 2013; McGregor et al. 2010, 2013c; Neukom et al., 2014; Zinke et al., 2014). There is a need for developing paleo proxy records at key locations within a coordinated national effort, for example, in the south-east Indian Ocean and West Pacific at a) Indonesian Throughflow passages into the Indian Ocean and along coastal wave guide, b) the western Pacific region between 130-150E, 0-10N and c) the Central Pacific region.

The need to discover and understand new climate phenomena and their impacts: The future tropical climate changes may lead to new phenomena that are unrelated to any pattern of variability we currently know of. The more frequent emergence of Central Pacific El Niño (El Niño 'Modoki') in recent decades has been suggested to be a consequence of greenhouse warming (Yeh et al. 2009). El Niño Modoki exhibits distinct impacts from the classical El Niño (Ashok et al. 2007; Taschetto et al. 2009; Power et al. 2013). The emergence of eastward propagating El Niño events in 1982 and 1997 has been attributed to the slowdown of the equatorial currents and is projected to occur more frequently under greenhouse warming (Santoso et al. 2013). More observational data are required to further investigate such rare phenomena, and thus it is crucial that observing systems are sustained far into the future and paleo studies to be supported. This will allow us to understand, for instance, how stable the Ningaloo Niño and ENSO are over time (Zinke et al. 2014; McGregor et al. 2013), and what role different multi-timescale interactions plays on such phenomena.

The need to leverage international investment: Australian scientists contribute to international projects in many topics of the above science priorities, such as Southwest Pacific Ocean and Climate Circulation Experiment (SPICE), and Northwest Pacific Ocean Circulation and Climate Experiment (NPOCE). These priorities highlight the need to sustain and improve observations, climate models, and proxy reconstructions – 3 core aspects in which Australian scientists are also actively contributing to and participating in many international programs.

On the observation front, our scientists have actively participated in international programs. For example, Australia was one of five participating nations in INSTANT, a major international project to directly measure the Indonesian Throughflow from 2004-2006. Since then Australia has contributed to the throughflow measurement via the Integrated Marine Observing System (IMOS; http://imos.org.au/waimos.html). Australia has also become a major international player in development of the Global Ocean Observing System (GOOS), particularly with regard to the programs to profile oceanic temperature and salinity with Argo floats, to monitor the climate-critical Indonesian Throughflow as an adjunct to the international Tropical Atmosphere Ocean (TAO) project. Relevant questions to be considered include: To what extent does the Argo program support seasonal climate prediction? Would a few air-sea interaction moorings north of Australia improve predictions of intraseasonal variability (MJO)? What is the best way to enhance biophysical observing? What very long term observing system will be required to address adaptation to climate change?

On the modelling front, the Australian community have improved coordination of modelling efforts over recent years, especially through the CAWCR partnership between CSIRO and BoM and the delivery of the Australian Community Climate and Earth System Simulator (ACCESS) and its uptake by the university community through ARCCSS. Increasing the sophistication of models requires dedicated technical support, which has been facilitated through the National Computational Infrastructure (NCI). Australia has a long track record of contributing model outputs to support all past IPCC assessments. More recently it has contributed through the World Climate Research Program (WCRP) Coupled Model Intercomparison Project (CMIP). Further international coordination in climate modelling comes through representation on CLIVAR panels (OMDP, GSOP, basin panels) and the WCRP Working Group on Coupled Models (WGCM). The ACCESS Ocean Model participates in Coordinated Ocean-ice Reference Experiments (COREs) through the CLIVAR Ocean Model Development Panel. Ocean nowcasting/forecasting through BLUElink delivers the operational products that support stakeholder needs. Toward the 20-year horizon, modelling activities should aim to conduct systematic and coordinated experiments using eddy-resolving climate models to revisit past results, further study variability on timescales beyond decades, and to determine how it can be modulated by the greenhouse effect.

The Australian paleoclimate community is world-class and has made globally significant contributions to understanding the tropical ocean-atmosphere interactions. Australia's palaeoclimate research contributes to several international working groups of IGBP-Past Global Changes (PAGES; e.g. Ocean2k, Aus2k, 2k-Network, Sea-Ice Proxy and IMPRESS), of the International Union for Quaternary Research (INQUA; e.g. SHAPE), and PMIP (the Palaeoclimate Modelling Intercomparison Project). It has also contributed to the Intergovernmental Panel for Climate Change (IPCC) assessment reports (e.g. AR5 working group 1, Chapter 14: *Climate Phenomena and their Relevance for Future Regional Climate Change*). Australian palaeoclimatologists are representatives on many international governing, scientific and technical boards related to IODP (International Ocean Discovery Program) and international collaborative science programs (e.g. BIOTRACERS, ECORD, IMPRESS, PAGES, SCAR).

These three activities and research in the core science priorities should be sustained toward the 20 year horizon if Australia wants to remain a major international player in this field and reap the benefit of a far greater international investment.

Realisation

Addressing these challenges requires sustained investments in the observational systems, numerical models, computational resources, data management and analysis, and technical skills. Substantial investments on the technology for monitoring and modelling the tropical circulation and its changes will significantly speed up the progress toward answering the key scientific questions over the 20 years horizon.

Observations

Observation and description of the role of the ocean in the climate system is essential for higher level research on climate change. The observational infrastructure has improved tremendously during the past seven years as a consequence of National Collaborative Research Infrastructure Strategy (NCRIS). Established under NCRIS in 2007 and later enhanced under the 2009 Super Science initiative, the Integrated Marine Observing System of Australia (IMOS) has been one of the key infrastructure investments in Australia over the past five years, to monitor multi-decadal ocean change, climate variability and weather extremes, major boundary currents and interbasin flows, continental shelf processes, and ecosystem responses. IMOS facilities include Argo floats, ships of opportunity, ocean gliders and radar, underwater vehicle, and Australian Ocean Data Network, to name a few. IMOS contributes to many international programs such as Global Ocean Observing Systems (GOOS), Southwest Pacific Ocean and Climate Circulation Experiment (SPICE), CLIVAR, and international ARGO project. It is necessary to emphasise that while the breadth of ocean observational network has improved over recent decades, it is crucial that the spatial and temporal coverage must be extended, in particular in order to resolve future decadal variability. Thus, whilst IMOS is developing its ten-year plan into the future, it is important for IMOS to strive to monitor the long-term state of the ocean. There is a strong international consensus that GOOS, TAO (equatorial Pacific), RAMA (tropical Indian Ocean), and IMOS (Australian regions) are high priority programs that must be maintained and enhanced.

Due to the US budget cuts, the TAO array, developed in response to the 1982/83 Super El Niño, has been operating only at 40% capacity since 2012 (Tollefson 2014). The TAO moored buoys provide high-frequency real-time measurements that Argo free-floating buoys cannot, as well as weather data (e.g., air-sea fluxes) important for seasonal forecasting and benchmarking models. With the frequency of extreme El Niño and Indian Ocean Dipole events projected to increase in the future, Australia must consider supporting the future of the TAO network and extending support to the more recently installed RAMA network in the tropical Indian Ocean, for better monitoring and forecasting of extreme events. Future funding toward observational infrastructure should also be aimed to enhance the spatial coverage of the currently limited ocean observations off the north-west Australia and in the vicinity of the Maritime Continent through installation of mooring arrays. In complementary with international efforts in maintaining and extending mooring arrays, this would greatly benefit our research in understanding the regional impacts of tropical climate variability and teleconnection.

About $120M allocated through the 2009 Super Science initiative has been used to build RV Investigator, a new ocean-going research vessel for the Marine National Facility. Currently being fitted with $7M equipment on top of the state-of-the-art devices already on board, the ship is designed for an all-year full-time operation. The ship has 40 berths and must be manned by two crews for full time operation. However, funding is currently committed to support only 180 days/year ship time. Half time operation of the Australian research vessel was started more than 30 years ago during a period of tight funding. This has not been turned around in the succeeding years for no particular reason. We now have a mature marine research community that every year puts forward many more proposals to use the ship than can be supported in 180 days. Maintenance of GOOS/IMOS also requires more ship time than is presently available. RV Investigator is one of the most technically capable research vessels in the world and should be used to the full extent of its capability to support GOOS and IMOS.

Data assimilation

The vast area of the ocean surface means that direct observations are not sufficient to provide high-definition spatial information needed to understand the full extent of ocean variability, or to fully realise the predictability of ENSO and the IOD. To bridge this gap, ocean data assimilation systems are required. BLUElink is a major infrastructure supported by the Australian government for this purpose, in particular to synthesise and interpret the enormous amounts of data into a coherent and accessible user database. Its products, in the form of information on ocean conditions and forecasts, are widely used (e.g., naval, tourism, marine transport). BLUElink uses complex data streams from a number of different sources (observations from satellite, ships, Argo profilers, weather predictions) to create a comprehensive suite of ocean forecasts that predict all types of marine weather scenarios, from local beach conditions to oceanic interactions on a global scale. The BLUElink global ocean modelling effort represents Australia's contribution to GODAE OceanView, an international collaboration that aims to provide access to accurate and up-to-date ocean observations and forecasts for the benefit of the wider global community. BLUElink is an essential infrastructure that must be sustained.

Modelling

Modelling integrates observation, theory and understanding, and ultimately provides the capability for prediction. Modelling capability to simulate key climatic modes (ENSO, the IOD) will remain essential to Australia's climate information needs over increasingly higher resolution spatial scales and at all timescales (NWP, seasonal to decadal prediction, and climate projections). Additional processes with increasing complexity will be added to models over the next decade with the realisation of carbon cycle, chemistry, and Earth System models. Model biases and drift remain critical impediments to progress (e.g. Kirtman et al. 2013). Key biases remain in modelling of the tropical thermocline and SST, which are fundamental to ENSO and IOD simulation. Priorities for model improvement include better parameterisation of horizontal and vertical ocean mixing, improved parameterisation of mesoscale and submesoscale processes, and over the next one to two decades the implementation of higher resolution models that are truly eddy resolving. International modelling coordination also needs to be maintained through WCRP, WGCM, and CLIVAR. These efforts will ensure that Australia stays current with emerging science in the fields of oceanic physics, chemistry and biology.

It is also important that a national effort in palaeoclimate modelling (development of a palaeo-version of the ACCESS model) is needed. We must ensure that Australia maintains access to world- class palaeoclimate modelling capacity – including not just the development of the tools themselves, but also ongoing maintenance, training and investment in personnel. On this note, paleoclimate research needs to be funded as well (see paleo white paper) and collaboration between paleoclimate researchers and the modelling community needs to be fostered.

Computing

Coordination of technical and computing resources will need ramping up to meet the challenges of distributed computing on massively parallel architectures. We will need to build on the existing community approaches such as with the ACCESS model and the NCI facility. Australian computing resources are a long way behind those of our scientific equivalents overseas, and continued investment in computing upgrades is essential. The NCI facility is undoubtedly one major infrastructure that needs to be sustained. The facility has provided strong pillars for the modelling community to progress by providing high-performance computing and data storage facilities through Research Data Storage Infrastructure (RDSI). For this research area continue to advance, the key infrastructures above will need to be supported, for instance through maintaining investments into major initiatives such as the NCRIS and Super Science Initiative, which has supported the NCI and IMOS. However, these infrastructures would not be able to be fully utilised without the capable scientists who conduct the measuring, analysis and interpretations. Long-term commitment in funding research centres both at government and academic institutions is crucial to support the current and future scientists who will advance this research. This can be facilitated by ensuring sufficient funding is available through the ARC and federal and state government initiatives.

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