NATIONAL MARINE SCIENCE COMMITTEE

National Marine Science Plan

Infrastructure Theme

White Paper

Research Vessels, Experimental Facilities, Observing Systems and e-Research

a. Abstract

In order to have in place infrastructure that is critical to meet the grand challenges set out in Marine Nation 2025 and elaborated in other theme white papers, the Australian marine science community needs to do two difficult but important things. We need to rise above institutional and disciplinary perspectives and get behind the concept of national facilities that can be used by the whole community through appropriate management and access arrangements. And we need to prioritise the infrastructure investments being advocated in order to maximise our chances of success in what is likely to remain a competitive environment for publicly funded marine science. A small number of critical requirements have therefore been identified in this white paper, focused on securing, utilising, and accessing the infrastructure required.

b. Background

Who does this work in Australia, how mature is it, how does it rate internationally, who funds this work?

Marine Nation 2025 recognises that infrastructure is critical to marine science. It recommends that the concept of national facilities be expanded to include all significant national marine science infrastructures, and that infrastructure investment be prioritised in line with the marine science required to address grand, national challenges. Confronting and dealing with these challenges will underpin substantial economic and social benefit for Australia in coming decades.

Research infrastructure is defined as comprising the assets, facilities and services which support marine science, including staff and technical capability. It is not just about capital investment. It is about holistic funding to build, operate and maintain the infrastructure required. National infrastructure is defined as being on a scale generally requiring operation and use by multiple institutions, supporting collaborative research, and regarded as part of the national research capability. Definitions are provided in Attachment 1.

The scope of infrastructure covered by this white paper includes:

Infrastructure categories	Sub-categories
Vessels	Bluewater, Polar, Shelf scale (tropical, temperate)
Experimental Facilities	Research Aquaria, Research Stations, Analytical Facilities
Observing Systems	*In situ*, Earth Observation from Space
e-Research	Data, Computing, Modelling

Some of this infrastructure is quite specific to marine science e.g. research vessels, marine observing systems, aquaria, island research stations. In other cases, marine scientists require access to national infrastructure that serves a broader science base e.g. satellite remote sensing, data storage, high performance computing, and some analytical facilities. We must be cognisant of this distinction when thinking about expanding the concept of national facilities and prioritising investment around the grand challenges to be addressed by marine science.

In terms of marine specific research infrastructure, this white paper will consider but not be limited to:

- The Marine National Facility (MNF[1]) (http://www.marine.csiro.au/nationalfacility/) which includes the recently commissioned research vessel (RV) *Investigator* operated by CSIRO;
- The research and supply vessel *Aurora Australis* (http://www.antarctica.gov.au/living-and-working/travel-and-logistics/ships/aurora-australis) operated by the Australian Antarctic Division (AAD), noting that the process to build a new ice-breaker has commenced;
- The nine shelf scale research vessels capable of operating to 200 nautical miles, operated by eight different research organisations, state agencies and universities;
- The National Sea Simulator (SeaSim) at the Australian Institute of Marine Science (AIMS) (http://www.aims.gov.au/seasim);
- Island Research Stations on the Great Barrier Reef (GBR) i.e. Heron, One Tree, Orpheus, Lizard, operated by Universities/Museums in the Tropical Marine Network;
- Antarctic research stations (Mawson, Casey, Davis and Macquarie Island) operated by AAD (http://www.antarctica.gov.au/living-and-working/stations);

[1] For a list of all acronyms see Attachment 9

- IMOS, the Integrated Marine Observing System (http://imos.org.au/); and
- AODN, the Australian Ocean Data Network (http://portal.aodn.org.au/aodn/).

Other research infrastructure to be considered will include:
- The National Earth Observation from Space (NEOS) ground network, calibration and validation network, and storage processing and delivery backbone;
- NCI, the National Computational Infrastructure (http://nci.org.au/); and
- Other National Collaborative Research Infrastructure Strategy (NCRIS) Capabilities – see https://education.gov.au/national-collaborative-research-infrastructure-strategy-ncris .

Further background is provided in Attachments 2 to 7 under the following headings - Research Vessels, Experimental Facilities, IMOS and AODN, Other marine observing, Earth Observations from Space (EOS), and e-Research.

It is important to note that national capability in marine technology underpins the development, operation and maintenance of vessels, experimental facilities and observing systems. Investment in infrastructure should contain a balance between the development of the underlying capability, and the acquisition of assets (see Marine Technology capability, Attachment 8).

Research infrastructure is currently operated through a variety of access and management arrangements. Access arrangements include institutionally determined, independently assessed, and open access. Management arrangements include owned by an institution, hosted by an institution, and distributed across institutions. Research infrastructure can therefore be classified as follows:

ACCESS				
Open access	*Island stations*		*IMOS, AODN, EOS*	
Independently assessed	*Aurora Australis, SeaSim, Antarctic stations*	*MNF,NCI*		
Institutionally determined	*Shelf vessels*			
	Owned	**Hosted**	**Distributed**	**MANAGEMENT**

The MNF is Australia's most mature marine national facility. It was established in 1984 with commissioning of the oceanographic research vessel *Franklin*. The MNF has always encompassed not just a vessel platform, but also the technical capability to work safely and effectively at sea, a pool of specialised scientific equipment, and a data centre to describe and provide ongoing access to voyage survey data. The MNF's scope was broadened considerably in 2003 when *Southern Surveyor* was transferred into the MNF and upgraded with swath mapping and sub-bottom profiling capability. At this point the MNF became the national blue water research platform not just for oceanography, but also for fisheries and marine ecosystem science, and marine geoscience. The MNF is entering a new era with the $120 million *Investigator* commissioned in September 2014. The scope of disciplines supported has been further expanded to include atmospheric science, the spatial and temporal range has been significantly extended (both in terms of days at sea and ability to go to the ice edge), and scientific complement almost trebled to support the large, multidisciplinary teams required to conduct modern marine and climate science at sea. The MNF has well developed access arrangements, which call for applications that are internationally peer reviewed and assessed on the basis of science quality, track record, and national interest. The MNF is undoubtedly a world class research infrastructure with *Investigator* in commission, though the fact that it is a single vessel operating 180 days per annum means Australia does not yet have the world class blue water research vessel capability required of its status as a marine nation.

IMOS is now a mature marine national facility, with ~$145 million of Australian Government investment committed over the decade from 2006-16. Having gone through an establishment phase in 2006-9 and a significant (80%) growth phase in 2009-11, the current configuration of IMOS has been in operating mode since around mid-2011. IMOS has well-developed science and implementation planning processes (which include international peer review), cutting edge open data access arrangements, and established systems for monitoring uptake and use. IMOS is widely recognised as a world leading national marine observing system, and has recently been formally accepted as a Global Ocean Observing System (GOOS) Regional Alliance.

The AODN should in theory be as or more mature than IMOS given that it was formally created in 2005. At one level it has been quite successful with 13,412 metadata records available in September 2014, of which 77% come from sources other than IMOS. However for the vast majority of these additional metadata records you cannot directly access and download the data. As such, the AODN is still well short of being the world class infrastructure it aspires to be.

Earth Observation from Space (EOS) is mature globally, with reliable sea surface temperature (SST) records going back to 1981, and sea surface topography (altimetry) back to 1993. The international EOS community is continually pushing the boundaries and so this type of infrastructure is continuously evolving. Without an independent, national satellite capability Australia cannot claim to have world class EOS infrastructure. With strategic investment in ground networks, calibration and validation facilities, and a storage/processing/delivery backbone, Australia can play a vitally important role in the Southern Hemisphere that enables our researchers to engage on international mission teams and undertake world class science using the global satellite constellations.

Australia's Antarctic infrastructure is very mature. Mawson Station was established in 1954. The research and supply vessel *Aurora Australis* has just celebrated its 25th anniversary, and the process to build a new ice-breaker has commenced. That said there are some significant issues to take into account when assessing the maturity and international standing of Australia's Antarctic research infrastructure. Access is guided by the Australian Antarctic Strategic Science Plan 2011/21 and driven through a highly competitive project application process. With the *Aurora Australis* having research and supply responsibilities, the number of marine science days available is actually quite limited and has been so for many years. If ice conditions preclude access to bases for resupply, or incidents occur that threaten the health and safety of crew or expeditioners, marine science programs can be heavily curtailed or completely cancelled. A new Australian Research Council (ARC) funded Antarctic Gateway Partnership is being established ($24M over three years, 2014-16) to assist researchers in gaining access to the Southern Ocean, ice zone, and Antarctic continent. A national review of the Strategic Importance of Antarctica in the 21st Century by Dr Tony Press as Head Inquirer has been released (October 2014). The review will result in a 20 Year Australian Antarctic Strategic Plan, and addressed terms of reference including "Committing to undertaking nationally and globally significant science", with specific terms to "Scope the future high priority research for Australia in Antarctica and the Southern Ocean, and its delivery through the Australian Antarctic Science Strategic Plan; and Consider Australia's role in driving and participating in international collaborations on science of global significance." The Government is considering the report recommendations and will provide a formal response in the coming months.

The National Sea Simulator (SeaSim) is a new $35 million research facility, owned and operated by AIMS and located near the GBR. SeaSim was designed to enable sophisticated experiments on tropical marine organisms under a broad suite of simulated environmental conditions. In recognition of the potential for SeaSim to provide a quantum step in understanding of the complex interactions between stressors on tropical marine ecosystems, AIMS is making up to 50% of SeaSim capability available to scientists and research institutions from around Australia and the world to work on collaborative research projects with AIMS staff. Access guidelines have just been released. SeaSim is clearly a world class infrastructure and the mix of institutional ownership/use and collaborative access is an important development in the context of this white paper. It has the potential to catalyse a paradigm shift in thinking about management and access with respect to marine experimental facilities.

Most of Australia's shelf scale RV capability across the tropical north is provided by AIMS. *Cape Ferguson* and *Solander* are institutionally owned and operated, with collaborative access provided through project level engagement and co-investment. Their area of operation covers Commonwealth waters as well as State waters of Queensland, NT and WA. There is currently no coordinating mechanism for shelf scale RV capability across the temperate south, nor is there a single institution with a national mandate in this region. Research/training/survey vessels are owned and operated by CSIRO, University of Tasmania (UTAS) and James Cook University (JCU), as well as State Fisheries/ Environment Departments in SA, WA, Queensland and NSW. In summary, while shelf scale RV capability is very mature, it would be difficult to assess Australia as having world class capability under current arrangements.

The GBR is the world's largest coral reef system, and Island Research Stations on Heron, One Tree, Orpheus, and Lizard provide a world class infrastructure for teaching and research. The stations are openly accessible through booking systems run by the host institutions. The Tropical Marine Network is a joint program of the University of Queensland (Heron), the University of Sydney (One Tree), JCU (Orpheus) and the Australian Museum (Lizard). It links the island research stations together and offers courses in tropical marine science that use the network.

The National Computational Infrastructure (NCI) is Australia's national research computing facility, providing world-class services to Australian researchers, industry and government. NCI is home to the Southern Hemisphere's fastest supercomputer and file systems, Australia's highest performance research cloud, and one of the nation's largest data catalogues.

Specialist analytical facilities dedicated to marine science are few, and recently developed. They are mostly targeting animal health and biosecurity as end uses, and bio-molecular sciences (e.g. genomics) in terms of capability. The contribution of these facilities on a national scale is nascent, but growing.

Much of the research infrastructure under consideration in this white paper is funded by Australian Government, either through institutional budgets (Publicly Funded Research Agencies, Departments, Universities), or through programs (such as NCRIS), which then provide funds to host and assist participating institutions. State Governments also invest in research infrastructure, including through co-investment in Commonwealth programs like NCRIS. In a number of areas addressed in this white paper, there is scope for creation of more effective mechanisms enabling multi-jurisdictional approaches to national marine research infrastructure development. Shelf scale RVs and research aquaria are two examples. There is also potential for Government-Industry partnerships to be considered, noting that for national scale research infrastructure there is likely to be a 'market failure'. The 2012 National Research Investment Plan noted that market failure occurs when "*in the absence of government investment in research, neither the business nor non-business sectors are likely to carry out the amount of research necessary to sustain national wellbeing*".

c. Relevance

Who are the users who benefit/will benefit from this research (directly and indirectly), evidence indicating end user engagement?

As outlined in Marine Nation 2025, infrastructure is relevant to all aspects of marine science in some way. Undertaking science in the marine environment requires the ability to:

- discover the unknown through observation, sampling, analysis and identification;
- undertake studies of marine processes at a variety of scales, from aquarium to open ocean;
- collect observations of essential marine and ocean variables and build them into time series that inform the study of ocean variability and change; and
- develop, test and run numerical models of marine systems, validate their output, and improve confidence in their ability to forecast future trends and states.

The following table summarises critical, national infrastructure dependencies identified by theme, with further detail provided in the text below:

	National Security/ Hazards	*Energy Security*	*Food Security*	*Bio-diversity*	*Climate Change*	*Optimal Resource Allocation*	*Urban Coasts*
Vessels							
• Bluewater (MNF)	Critical	Critical	Critical	Critical	Critical		
• Polar (AAD)	Critical		Relevant	Critical	Critical		
• Shelf – tropical	Relevant	Critical	Relevant	Critical	Critical		Relevant
• Shelf - temperate	Relevant	Critical	Critical	Critical	Critical		Relevant
Experimental Facilities							
• SeaSim		Relevant	Relevant	Critical	Critical	Relevant	Critical
• Other research aquaria		Relevant	Critical	Critical	Critical	Relevant	Critical
• Analytical facilities	Relevant	Critical	Critical	Relevant	Relevant	Relevant	Critical
• Research stations			Relevant	Critical	Critical		
Observing Systems							
• *In situ* – IMOS	Critical	Relevant	Critical	Critical	Critical	Relevant	Critical
• *In situ* - other	Critical	Critical	Relevant	Relevant	Critical	Relevant	Relevant
• Earth Observation	Critical	Critical	Critical	Critical	Critical	Relevant	Critical
e-Research							
• AODN	Critical	Critical	Critical	Critical	Critical	Critical	Critical
• Other data, tools	Critical	Critical	Critical	Critical	Critical	Critical	Critical
• NCI	Critical	Critical	Relevant	Relevant	Critical	Relevant	Relevant
• Other compute, n/works	Relevant	Relevant	Critical	Critical	Relevant	Critical	Critical

■ = critical dependency, ■ = relevant

Australia's fleet of RVs ranges from large, to small. Large vessels are the multi-disciplinary blue water vessel *Investigator* (94m), and the specialist ice-breaker *Aurora Australis* (95m). Smaller vessels include shelf scale (~20-35m) and coastal (~15-20m). Full details are included in Attachment 2. On a per capita basis, Australia's RV capability is modest. It is within the mid-range on an international scale, being on par in terms of size, number, and capability with nations such as Argentina and Brazil. It is dwarfed by traditional powerhouses such as the USA, Japan, Germany and Russia. And we have been rapidly overtaken in recent years by China, and to a lesser extent India. It is important to note that while the term "fleet" is used throughout the white paper, Australia's complement of RVs does not currently operate as a fleet, a point addressed later. Relevance to users is obviously correlated to vessel capability - polar, blue water, shelf and coastal, tropical and temperate. With a single polar vessel (highly constrained in terms of support for marine science) and a single blue water vessel (just coming into commission), there is no question as to relevance. With nine vessels collectively providing a mere 15 minutes of ship time per annum per kilometre of coastline, shelf/coastal capability is certainly not in oversupply. Commercial vessels (merchant vessels, ferries, fishing vessels) are used as Ships of Opportunity and there is potential to grow their contribution, noting that decisions about access and use will be driven by commercial imperatives and not research need. Where appropriate, taking national security and other issues into account, consideration should also be given to strengthening relationships between marine science and Government Agencies operating and chartering vessels for other purposes e.g. hydrography, surveys, buoy servicing etc.

Marine research aquaria are being transformed across Australia as experimental marine scientists strive to better replicate nature in their experiments. The demand for such studies is driven by the requirement to understand the impacts of interactions between different environmental parameters as they fluctuate through time (both short- and long-term). Previously, research aquaria had simply strived to maintain water quality and conditions at a standard to ensure that organism health during experiments was sufficient not to confound effects caused by other manipulations. Now we are able to nearly replicate conditions and vary them to reflect natural cycles and anthropogenic impacts (e.g. temperature, lighting spectrum and intensity, salinity, pCO_2, turbidity). Most research aquaria are operated by universities and State agencies with ready access to seawater, although several transport seawater from distant sites into their facilities which then operate in a closed, recirculating mode. Users of research aquaria are mostly scientists employed by the owner/operators of the aquaria. Projects are often to satisfy contracted research and development (R&D) so results are of critical interest to the contracting party, industry and government. They include aquaculture/hatchery experimental facilities which have strong end user engagement from an industry that contributes over a billion dollars per annum to the Australian economy[2]. Projects using research aquaria can also be collaborative, enlarging their footprint beyond the owning/operating organisation.

Australia's complement of offshore research stations are on islands scattered throughout the GBR, and in Australia's Antarctic Territories, with some organisations having coastal offshoots to allow colocation of researchers with the marine environment (e.g the National Marine Science Centre of the Southern Cross University). Providing research facilities and accommodation for both visiting researchers and station staff, these outposts allow long-term observations and colocation of experiments in high priority ecosystems. They extend the reach of Australian marine science in line

[2] The AIMS Index of Marine Industry, June 2014 (http://tinyurl.com/AIMS-Marine-Index-2014)

with the respective mandates of their operating institutions, and provide a platform for national and international collaborative research in areas of natural advantage for our marine nation. University owned stations service their own research and teaching needs (with the latter dominating their use in some locations), but also provide bases for other university researchers from throughout Australia and an increasing number of international researchers. Long term observational records maintained by research stations of their immediate and nearby locations provide a powerful context against which to conduct other research projects and experiments. Island locations also support other marine research infrastructure such as observing systems, extending their reach by acting as base stations for distributed networks and station staff providing basic support when observing systems fail or are impacted by severe weather.

Specialist research and analytical laboratories committed to marine science are often collocated with aquarium facilities where their parent organisation is sited near the coast or is a base for an RV. Specialist marine laboratories include the Centre for Marine Microbiology and Genetics at AIMS, the Australian Animal Health Laboratory at CSIRO, the NCRIS Algae and Biofuels Facility and South Australia (SA) Aquatic Biosecurity Centre at the SA Research and Development Institute (SARDI), Antarctic krill aquarium at AAD, and a series of specialist laboratories at the Australian Maritime College (UTAS). These specialist laboratories have been developed in response to existing or forecast user need. For example, the aforementioned biosecurity laboratories enable rapid research and incident response for aquaculture disease outbreaks. These high quality institutionally-owned laboratories often provide services for a fee with different pricing tiers that increase relative to the relationship of the customer with the organisation hosting the laboratory (i.e. lower fees for internal users and often collaborators, with fees increasing for non-partner organisations and even more for commercial customers). Most use of the facilities is therefore by employees of the owner-operator and collaborators who obtain discounted services.

IMOS was established with the explicit objective of being relevant to a very broad base of marine and climate scientists and users of that science. It is guided by science and implementation planning undertaken by Nodes that engage both the scientific and user communities. IMOS is integrated across spatial and temporal scales, supporting blue water and climate science, science at continental shelf scale, and marine coastal science. It has observing assets in Australia's tropical north, in temperate regions (east, west and south), and in the Southern Ocean down to the Antarctic shelf. It is integrated across disciplines, providing observations and data for studies of ocean physics, biogeochemistry, and marine biology and ecosystems. Increasingly, IMOS is being used by ocean modellers as well as by observational and experimental scientists. The focus is on data, in near real time where appropriate, but always in delayed mode, quality controlled, so as to build the long time series of Essential Ocean Variables (EOVs) required. All of the data are openly accessible to the entire marine and climate science community and its stakeholders. IMOS has established multiple pathways for uptake and use, from peer reviewed publications to operational forecasting systems. It has also established multiple partnerships with major research projects and programs in Australian marine and climate science that are delivering on government and industry priorities, in order to provide clear pathways to impact. Evidence of end user engagement is provided through regular updates, communications and reports (see http://imos.org.au/), including the recently released IMOS Strategy 2015-25[3].

[3] http://imos.org.au/plans.html#c1956

In situ operational observing systems are also relevant in a research infrastructure context. Operational marine observing in Australia is largely implemented through the Bureau of Meteorology (BOM), relevant State marine authorities, and sometimes in partnership between them e.g. tide gauges, and wave buoys. The Royal Australian Navy (RAN) has operational responsibility for hydrography and provision of met-ocean services to the defence forces. Geoscience Australia (GA) undertakes marine surveys to provide pre-competitive information on energy resources, and to determine Australia's marine jurisdiction under international law. The Australian Maritime Safety Authority (AMSA) operates systems relating to navigation, safety and oil spill monitoring and surveillance. Collectively these *in situ* operational observing systems are relevant to the *Sovereignty, security, natural hazards* theme (through operational oceanographic forecasting, as well as hydrographic data and charts), the *Energy security* theme (through mapping and modelling), and the *Dealing with climate change* theme (contributing to understanding, mitigation and adaptation to sea level rise, increase in ocean heat content, carbon cycling and ocean acidification).

State and Territory Governments undertake a wide range of other bio-physical observing/monitoring programs to meet their legislative and policy requirements, however there is currently no comprehensive national picture of this activity.

Other foundational datasets are required, including bathymetry (underwater depth and topography) and ocean reanalysis (providing descriptions of past states and time series showing trends and changes). These also need to be systematically built into national resources by responsible agencies such as GA and BOM, who must ensure the datasets are openly accessible to the marine science community and other users.

Sensors on satellite platforms orbiting the Earth provide a unique advantage when observing the ocean's surface and its dynamics, given their ability to automatically record large areas, rapidly, and frequently. They observe ocean phenomena that cannot be practically sampled with the necessary spatial or temporal resolution by any other means. In general, remote sensing provides direct observations of the surface (or very near-surface) of the ocean. Integrated quantities such as variation in ocean mass can also be derived from space gravity missions, providing a valuable information source for bathymetry. EOS is therefore relevant to virtually all NMSP themes. However the fact that Australia does not have an independent, national satellite capability means that we cannot directly control user relevance. This needs to be managed by strategic engagement with international civil space-based Earth observation programs, focused in areas where Australia can make both a globally relevant contribution and extract national benefit[4].

The use and relevance of research data infrastructure is now pervasive in the scientific arena globally. Australia is a foundation member of the global Research Data Alliance (https://rd-alliance.org/) focused on "research data sharing without barriers". The Australian Research Data Infrastructure Strategy (TARDIS)[5] is about to be released by the Federal Education Department, setting out a clear plan to optimise Australian Government's existing and future investments in research data infrastructure with a vision of having "Excellent Australian research data infrastructure fostering

[4] An Australian strategic plan for Earth observations from space, Australian Academies of Science (AAS) and Technological Sciences and Engineering (ATSE) (https://www.science.org.au/publications/australian-strategic-plan-earth-observations-space)

[5] Reference being sought from the Education Department

globally significant research". Open access research data infrastructure is where things are heading, and the Australian marine science community is currently seen to be quite advanced, both nationally and internationally. However user relevance of the AODN and other foundational datasets is still well short of where it could and should be. This is perhaps the biggest opportunity we have in responding to Marine Nation 2025's call for expanded national facilities, prioritised in line with grand, national challenges. To capture every precious measurement and observation we take in the marine environment, and treat the resulting data as an asset that will appreciate through use and reuse.

The use and relevance of research computing infrastructure is even more pervasive than for research data, though there is clear delineation according to scale. High performance computing (HPC) is national scale research infrastructure of broad utility that is required for some specific aspects of marine and climate science. The relevance of NCI for high end computation and data handling is clear, and end users such as BOM, GA and CSIRO are directly engaged. At the other end of the scale, access to a significant level of computing resource is now mandatory at the institutional level and does not require further attention in this white paper. The requirements for national computational research infrastructure at the intermediate level are an issue under consideration within the e-Research domain. In summary, this is a national research infrastructure question that the marine science community need to engage with at the appropriate level, rather than being specific to marine research infrastructure.

Developments in observations, data and computing are creating many new opportunities for marine science, but it has become apparent that we often lack an experimental context within which to bring them together in an efficient and effective way. This has given rise to the concept of virtual laboratories (VL) to create the software tools and collaboration resources required to make this happen. A Marine Virtual Laboratory (MARVL) is currently being established (http://www.nectar.org.au/marine-virtual-laboratory). Other VLs being established that may be relevant to marine science include Geophysics, Genomics, and Climate and Weather. This is an exciting area for future investment.

d. Science needs

Crisp articulation at a high level of the key science gaps/needs/challenges, and key outcomes/national benefit that would flow from investment in this area (perhaps separated into 5, 10, 20 year horizons)

Australia requires its marine science community to explore, understand and monitor our marine estate at a high spatial resolution so as to enable effective management, and plan for future R&D. Our marine territory is highly complex, being home to deep-sea canyons, undersea mountains, and the world's largest coral reef, to name but a few critical ecosystems. The operating environment extends from sub-zero to tropical temperatures and is subject to weather extremes such as cyclones and intense polar storms. Much remains unexplored and little understood because this ocean territory covers many millions of square kilometres, and is over seven kilometres deep in places, a scale beyond our current capability to explore and monitor.

Australia's capacity limitation is partly driven by there being little redundancy in our RV fleet both in geographic scope of operation as well as functionality e.g. only one each of an ice breaker, a multi-purpose blue water vessel, and a coastal vessel operating throughout the GBR. With a large Antarctic Territory, Australia requires at least one purpose-built icebreaker. It is not practical to repurpose the same vessel to undertake blue water research in the temperate/tropical Pacific or Indian Ocean. Our single blue water vessel is therefore covering the entire Australian EEZ. Vessel size also limits the capability that our national fleet can deliver. The smaller vessels cannot support deep water exploration and oceanography. For example, RVs operating on the GBR and in SA coastal waters are not currently capable of supporting research in the adjacent Coral Sea and much of the adjacent Great Australian Bight (GAB), areas of high national interest.

Australia's marine estate interacts with, and is influenced by those oceans that surround our EEZ. If we are to prevent a knowledge deficit developing in our region of responsibility relative to the rest of the world, Australia needs to maintain pace with neighbouring nations as they increase their exploration and understanding of the oceans. A growing gap in capability will erode our current leadership position in different marine science disciplines.

There is also a critical need to better explore our deep marine estate and Australia must invest in more submersible technologies and tools. Autonomous and semi-autonomous systems allow marine science to go places inaccessible to scientists themselves and operate over timeframes beyond human capacity (e.g. night-time and all day underwater operations). Our underwater science tools are few and far between, comprising only several shallow-water autonomous underwater vehicles (AUV) and remotely operated vehicles (ROV). The *Investigator* may eventually be home to one research-grade deep water ROV, but this will be insufficient to meet the demands we face over the next 10-20 years. Submersible technologies are also critical for shallow water marine science, enabling better monitoring of complex topographies such as reefs and seamounts, and improving understanding of Antarctic under-ice ecosystems which will help Australia maintain its scientific leadership among Antarctic Treaty nations. The national RV fleet needs to be complemented by an autonomous and semi-autonomous vehicle fleet (both for surface and sub-surface observations). This will also deliver an innovation dividend to Australia by our involvement in submersible and autonomous vehicle development, providing powerful platforms on which to trial and develop sensing systems and technologies that can be used within other Australian maritime sectors (e.g. offshore resources, defence). This need has already been recognised with the aforementioned ARC Antarctic Gateway Program aiming to invest $6-7M over the next 3 years to develop a long-range AUV system tailored to polar environments, but more attention is needed to enable adoption of these technologies in shallow and non-polar systems.

Undersea exploration is also aided by cutting edge technologies, often carried by research vessels, that enable accurate mapping and compositional analysis of the seabed surface as well as penetrating deep into the seafloor. Maintaining technological currency and maximising the area covered by these explorations is important as it provides the geological context for our biological understanding and documents geological events that have occurred throughout history and shaped our marine territories.

A systematic program of multi-beam data capture and analysis is needed to continue to build foundation knowledge of marine environments. Only 28% of Australia's marine estate is mapped with any detail through multi-beam echo-soundings and benthic samples, yet this foundation data is the basis for discovery and inventory of seamounts, canyons, deep reefs and even moraines, knowledge of which informs all other NMSP themes. Coordination of shelf and blue water vessel surveys is a logical and cost effective first step toward this outcome as well as consideration of new capability to be deployed on these vessels to increase the geoscientific knowledge of our marine estate.

Experimental facilities enable the Australian marine science community to better answer questions at multiple scales: local, regional national and global. They also allow replicating future scenarios (e.g. in research aquaria) to then measure the likely impacts and potential resilience of an ecosystem and the biodiversity within it (e.g. in analytical facilities). These same purposes can be satisfied at research stations which not only provide bases for observations but also the conduct of *in situ* experiments, with the added benefit that these experiments are in locations of intense national interest. A more integrated approach using large scale and long-term experiments at these locations will generate an increasingly national view rather than locally/regionally applicable knowledge. For example, research in the southern GBR does not necessarily translate to knowledge and relevance for the northern GBR or to temperate reefs. Research conducted at different locations using the same protocols on different marine biodiversity not only builds knowledge about impacts at the site of the research but can be integrated more broadly across ecosystems and latitudes.

The ability to conduct far more complex experiments than before demands sophisticated experimental design not previously required. Now that marine scientists can conduct complicated experiments varying numerous parameters that better reflect natural cycles and the real world, the almost infinite degrees of freedom allowed in experimental design demands vastly improved quantitative skills and statistics. This will result in easier translation of results obtained in experimental facilities to our understanding of the natural world and how it may respond to challenges.

Some of the issues faced by our marine estate and our management of it are also being confronted around the world, particularly cumulative impacts from multiple users (i.e. fisheries, aquaculture, shipping, oil/gas exploration). Australian marine science needs to be integrated into this global picture. This is enabled by direct comparisons of data and research outputs from Australia with those from our international partners and collaborators, requiring increasingly common data standards, harmonised QA/QC and the ability to obtain measurements of a quality recognised internationally. This also promotes confidence in results obtained and their interpretation. Building networks around these experimental facilities will allow sharing of protocols and standards. Presently, these networks are informal and nascent. Investment is required to make them more formal and considerably more active. Transfer of data and knowledge can be promoted by mobility grants and funding which needs to be resourced appropriately so financial burden is not placed solely on host organisations.

IMOS has articulated high level science needs and gaps through a comprehensive approach to science and implementation planning[6]. The needs have been identified under five major themes of research, along with the EOVs to be observed and the facilities/platforms/sensors to be used for collecting observations required at appropriate time and space scales. The major research themes, as described below, are tightly coupled with the grand challenges in Marine Nation 2025 i.e.

1. multi-decadal ocean change
    - global energy budget, hydrological cycle, ocean circulation, and carbon cycle;
    - Pacific, Indian and Southern Oceans.
2. climate variability and weather extremes
    - inter-annual and intra-seasonal;

[6] http://imos.org.au/plans.html#c1210

- modes of climate variability (El Niño Southern Oscillation, Indian Ocean Dipole, Southern Annular Mode), cyclones, East Coast Lows.

3. major boundary currents and inter-basin flows
    - fluxes, drivers, dynamics;
    - East Australian Current, Leeuwin Current, Indonesian Throughflow.
4. continental shelf and coastal processes
    - eddy encroachment, upwelling/downwelling, cross-shelf exchange, coastal currents, wave climate.
5. ecosystem responses
    - productivity, distribution and abundance;
    - nutrients, microbes, plankton, nekton, apex predators;
    - benthic and pelagic.

Various national planning and consultative processes have identified the need to grow IMOS capability beyond its current scope. Major gaps are in the deep ocean, the ice zone, and in areas of the coastal zone where high social/economic/environmental value justifies intensified effort[7].

Additionally, although IMOS is well-regarded for including physical, chemical and biological observing in the one national program, the challenge remains to scope, design and implement an ecological observing system. The current IMOS approach is to take sustainable observations at specific trophic levels that may then be considered individually or synergistically in models of ecosystem change. However this is an area of growing scientific interest at the international level. GOOS has established new biogeochemical, and biology and ecosystems panels to define ecosystem EOVs, establish requirements, and assess readiness for inclusion in the global ocean observing system. Complementary work on ecosystem-EOVs is being undertaken by multi-national ocean observing programs in the Southern Ocean (via the Southern Ocean Observing System, SOOS) as well as a Deep Ocean Observing System GOOS pilot project. IMOS will need to keep well-engaged with these activities in order to evolve towards the long term goal of sustained ecological observing.

Although *in situ* operational observing systems are not driven by science need, the observations and data they produce can be used to address science needs and gaps. As noted in the previous section, high level drivers are the requirement for operational oceanographic forecasting, hydrographic data and charts, mapping and modelling of energy resources, and contributing to climate change understanding, mitigation, and adaptation.

The high level science need for EOS derives from the fact that the ocean is a globally connected system, and Australia's marine estate is the third largest on the planet. Ocean phenomena with characteristic sizes of 10's to 100's of km^2, changing continuously over such a scale, cannot be practically sampled with the necessary spatial or temporal density by any other means. Satellite remote sensing data and products required for marine science include SST, ocean colour, ocean surface topography (altimetry), gravity, sea surface salinity (SSS), sea ice, waves and winds. In reality, articulation of EOS needs and gaps happens within the mechanisms for international coordination of civil space-based Earth observation programs, in which Australia is a very minor player. This means it is vital for us to have a tightly coordinated and clearly focused national effort around the contributing

[7] IMOS Strategy 2015-25, p8

infrastructure investments we can make, in ground networks, calibration and validation facilities (including through IMOS), and storage/processing/delivery (including through NCI and related e-Research infrastructure). The national benefits to Australia from EOS, including through marine science, are significant. A 2010 economic study on the value and benefits of earth observation from space found that the EOS sector made a $1.4 billion direct contribution to Australia's GDP in 2008-09, providing an additional $1.9 billion in related productivity benefits to the Australian economy in the same period ($3.3 billion minimum economic impact)[8]. This study is in the process of being updated.

High level science needs for research data and computing infrastructure (including tools and collaboration resources) derive from the fact that marine and climate scientists now have the opportunity to make use of a vast amount of information from vessels, experimental facilities, *in situ* observing systems, satellite constellations, other data sources and numerical model outputs. New means of gathering, collecting and generating data in increasingly complex forms means that data-and-compute-intensive marine and climate science is now a critical aspect of the cross-disciplinary approach required to address Australia's grand challenges. That said we need to remember that for many parts of the marine environment the observational base will remain very sparse, particularly sub-surface. Collection, access, use and reuse of relatively low volume data sets will continue to be important in the marine domain. Open data access is an overarching issue, requiring adoption of common data standards and approaches through AODN and related initiatives.

N.B. An assessment of 5, 10, 20 year horizons has not been provided for the Infrastructure theme in isolation. These will very much depend on the science horizons assessed by other NMSP themes, and will be dealt with in later phases of the process.

e. Perspective

Specific science priorities for the next 5, 10 20 years, should include accounts of how we link to international efforts in these areas and/or why Australia needs to do this work if we're not already world class

Knowledge about Australia's marine domain is not just critical to Australia but also for global understanding. However, other countries will not invest in deploying research infrastructure to understand our marine territories. Most international RV's are occasional visitors to our waters rather than regular operators, and Australia cannot depend on these visits to build our knowledge base. Australia is uniquely positioned to be a leader in marine science as the custodian of globally significant systems, such as the Southern Ocean and GAB, the GBR, Ningaloo Reef and the North-West Shelf. Being able to conduct science in these locations gives us a place at the table in international initiatives and also ensures we remain competitive under those international obligations dependent on science leadership (e.g. the Antarctic Treaty). As a developed nation, the international community expects Australia to play its part and invest in building greater knowledge of our oceans which will be significantly enhanced by greater blue water and polar research vessel capacity. There is a need to expand our capability at the large end of the vessel spectrum to ensure access to the substantial fraction of our waters that are deep and inhospitable. Furthermore, while a number of our vessels are multi-purpose, single vessels cannot do everything. Increased capability and diversification of available functionality within the national vessel fleet, especially at the mid-size vessel range, will ensure all regions within Australia's domain are accessible as and when required.

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[8] http://www.acilallen.com.au/projects/9/geospatial/111/the-economic-value-of-earth-observation-from-space

Traditional areas of marine science and end use (e.g. fisheries, biodiversity) are now becoming increasingly focussed offshore as resource exploration activities intensify e.g. in the GAB. These locations are also among our least known and most expensive areas of operation outside of the Antarctic. The Australian marine science community is not yet at a point to be able to be conduct science *in situ* at these locations on a regular basis. While we now have the *Investigator,* currently it will be moored for half of each year, highlighting the need for greater engagement with government and industry end-users to better define how they might utilise and invest in the RV fleet.

Development of a fleet of autonomous and semi-autonomous vessels will be a major undertaking for Australia but is increasingly critical to the future of marine science in Australia. Our current capacity and capability is internationally weak and we mostly depend on other nations, putting us at the beck and call of their priorities and schedules. This makes it difficult to incorporate these devices onto our science cruises and even if we are successful in doing so, prior to the cruise their use is at risk of redeployment if the priorities of the collaborating country/foreign agency changes.

International usage of experimental facilities is usually on a project-by-project basis rather than in a programmatic form. There is a need to engage strongly with existing international networks, or build and potentially lead an international network where there is a gap. For example, recent steps by some island research station operators to engage with the World Association of Marine Stations will capitalise on the benefits of shared knowledge but also promote our existing stations, benefiting their owner-operators and the marine science community in general. There is currently no international network for high quality research aquaria, a gap that needs filling and an opportunity for Australia to catalyse and provide leadership. International effort on various analytical networks for marine science usually focuses on specific issues or parameters (e.g. water quality proficiency testing, acidification technical networks). The most active field in recent years has been acidification which has seen an explosion of activity. Acidification is a critical marine science issue which will not wane in intensity and the marine science community needs to rapidly expand its participation in proficiency networks to ensure decision-makers can be confident in the results. This is also needed to maintain and grow our international credibility and profile which can attract global investment of intellectual capital and funding.

Australia cannot sustain many specialist high end marine experimental facilities requiring us to collaborate internationally to achieve critical mass. However, investment by Australia is necessary to maximise the likelihood that developed solutions will be applicable in an Australian setting. In a coral reef context, solutions and knowledge developed in the Caribbean may not directly translate to our management of the GBR, which is considered by many to be one of the best studied and managed reefs and marine protected areas in the world setting the standard for best practice. For Australia to maintain leadership in this field, maintaining bases in the GBR with a healthy research agenda is critical. The amount of research that can be conducted at some of the university owned stations may become more limited as the demands for use in teaching and training increase. Maintenance of research stations in the Antarctic is also critical to Australia's long-term plans as a strong science agenda and associated activity places us well among the Antarctic Treaty nations. This also requires colocation of some research infrastructure with major and relevant study sites. Research stations are experimental and observational outposts in areas of major national interest but low population density, which contributes to some of the high costs of maintaining facilities and appropriate staffing levels. Their operations enable continuation and development of long-term baselines. It is also important to ensure that experimental facilities are sited appropriately from a cost management perspective. For example, it is much more cost effective to run a research aquarium at tropical seawater temperature in Northern Australia than in Tasmania, and *vice versa* for southern temperate waters.

Specific science priorities for IMOS flow from the high level needs, gaps and challenges for each of the five major research themes in the science and implementation plans. Fundamentally there is a priority to sustain much of the current IMOS observing program so as to provide the near real time data and build the long time series required to answer questions about multi-decadal ocean change, climate variability and weather extremes, boundary currents, shelf and coastal processes, and ecosystem responses. More specifically, notable gaps and future priorities include:

- observing the deep ocean (below 2,000 metres) where sparse measurements are showing detectable change, including engagement with international efforts to develop deep-Argo;
- observing the ice zone by building on successes with animal telemetry and pilot deployments of ice-capable Argo, including engagement with new developments such as ice-capable AUVs proposed as part of the Antarctic Gateway program;
- sustaining and expanding CO_2 measurements, including into high latitudes (Southern Ocean);
- tropical flux measurements in northwest Australia to improve seasonal prediction, particularly of the Madden Julien Oscillation (MJO);
- cost effective monitoring of boundary currents (to produce reliable transport indices) using multiple platforms (including ocean gliders), focused initially on the Indonesian Throughflow and East Australian Current then moving to the Leeuwin Current;
- sustaining regional components of the observing system in areas of coastal Australia which have high social, economic, and environmental value, using a cost effective mix of moorings (including near real time), ocean gliders, ocean radars, ships of opportunity, animal telemetry, and remote sensing, and coupled with regional ocean modelling systems;
- piloting then maturing new sensor technologies to measure oxygen, pH, nutrients, and bio-optics combined with expanded use of autonomous platforms (e.g. bio-Argo);
- extracting greater value from satellite ocean colour including production of measures of phytoplankton species composition and primary productivity with appropriate calibration and validation in place;
- extracting greater value in the coastal zone from SST and ocean surface topography satellite constellations with appropriate calibration and validation in place;
- continuing to evolve ecological observing using plankton recorders, autonomous vehicles, acoustics and animal telemetry with a goal of moving towards more cost effective approaches coupled with ecosystem models;
- collecting baseline data on marine microbial diversity and function, enabling incorporation of microbial processes into ecosystem models.

With respect to active areas of research using satellite remote sensing, priorities in the medium term include the following (noting a strong overlap with IMOS, see above):

- global carbon cycle (key role for Australia in the Southern Hemisphere);

- operational ocean modelling using assimilated higher resolution SST and altimetry (coastal and open ocean) data;
- coastal water quality applications such as improved understanding of land run-off effects on aquaculture, fisheries, habitat and coral reefs;
- phytoplankton function type from ocean colour;
- development and implementation of standardised estuarine and marine habitat mapping to support decision-making at a range of scales; and
- definition and review of Australia's national maritime boundaries based on up to date, high-resolution, spatially controlled earth observation data defining Australia's coastline.

Related to the above, there is a strong argument for implementing and maintaining a vicarious calibration site for ocean colour in the Southern Hemisphere given the increasing trend in aerosol loading for Northern Hemisphere sites. A suitable ocean site for vicarious calibration of ocean colour exists in a subtropical gyre region of the SE Indian Ocean, offshore of Perth, Western Australia;

Specific science needs for research data and computing infrastructure include:

- ocean and sea-ice components of Earth system modelling (integrated sea ice-ocean-atmosphere modelling);
- a national storage, processing and delivery backbone for EOS implemented at NCI, operating at sufficient scale to manage modern satellite data sets (e.g. from geostationary satellites such as Japan's Himawari);
- a 'data cube' capability at NCI for analysis of satellite data through time, for uses such as the extraction of bathymetry from optical satellite imagery over large areas, and the characterisation and monitoring of intertidal zones and coastal vegetation;
- high resolution genomic data, noting that this issue is not confined to marine science;
- nationally agreed adoption of international data standards (and services) to facilitate data exchange and interoperability; and
- virtual laboratory environments in which to bring observations, data and computing together in an efficient and effective way.

f. Realisation

Key infrastructure and capability requirements/impediments, funding and coordination requirements/ impediments

In order to have in place infrastructure that is critical to meet the grand challenges set out in Marine Nation 2025 and elaborated in other theme white papers, the Australian marine science community needs to do two difficult but important things. We need to rise above institutional and disciplinary perspectives and get behind the concept of national facilities that can be used by the whole community through appropriate management and access arrangements. And we need to prioritise the infrastructure investments being advocated to maximise our chances of success in what is likely to remain a competitive environment for publicly funded marine science.

In the Infrastructure theme more than any other, long term commitments to funding, coordination and access are essential to enable realisation of benefits. A small number of critical requirements have therefore been identified in terms of securing, utilising, and accessing the infrastructure required:

1. Securing critical marine research infrastructure

- Build and commission Australia's next generation polar vessel, ensuring that at least 60 days per annum is available to support Southern Ocean and Antarctic marine science in line with the 20 Year Australian Antarctic Science Strategic Plan.
- Secure, sustain and develop the Integrated Marine Observing System (IMOS) in line with its 2015-25 Strategy, and National Science and Implementation Plan.
- Secure, sustain and develop the Australian Ocean Data Network (AODN) to provide national leadership in open data access, and adoption of common data standards and approaches;
- Consider options for securing a step change increase in autonomous systems capability, to provide cost effective reach across Australia's vast marine estate, especially in remote areas, under-ice and ice shelves, and in complex underwater topographies (e.g. reefs, seamounts etc.).

2. Utilising marine research infrastructure to optimal effect

- Enable full utilisation of *Investigator* as Australia's sole blue water research platform (i.e. up to 300 days per annum), and consider options for further expanding blue water research vessel capacity over the next decade so as to better match availability with demonstrated scientific need and demand.
- Establish an alliance of shelf scale research vessel operators to provide (a) national coordination of scheduling, enhancement and reporting of collaborative research, (b) national collaboration on common issues such as cost management and operational/technical expertise so as to improve efficiency and effectiveness, and (c) national planning for fleet replacement and enhancement so as to better match capability and capacity with demonstrated scientific need and demand;
- Building on the precedent set by the National Sea Simulator (SeaSim) in making up to 50% of its capability available to work on collaborative research projects, establish a national alliance of marine experimental facilities and investigate the potential for moving other facilities from being solely institutionally managed and accessed, to being more distributed and open.

3. Accessing national research infrastructure needed for marine science

- Implement the National Earth Observations from Space Infrastructure Plan (NEOS-IP), with respect to ground networks, calibration and validation facilities (through IMOS where appropriate), and storage/processing/delivery (through NCI where appropriate);
- Sustain and develop Australia's HPC capacity at the National Computational Infrastructure (NCI), moving from petascale to exascale over the next decade;
- Develop and sustain the virtual laboratory environments required to bring observations, data and computing together in an efficient and effective way.

National capability in marine technology underpins the development, operation and maintenance of vessels, experimental facilities, observing systems, and the networks that connect them. Investment in infrastructure should contain a balance between development of the underlying capability, and acquisition of assets. This has been recognised in national facilities such as the MNF and IMOS, and it will be important to ensure this holistic approach continues as the concept of national facilities is expanded to other marine research infrastructures. It will also be essential for the marine science institutions to nurture and grow their marine technology capability to remain internationally relevant, collaborating where possible and developing niche local capability where appropriate.

With respect to key funding requirements, we estimate that to implement the 10 critical requirements outlined above will require infrastructure investment in excess of $3bn over the decade to 2025. The quantum of investment required reinforces the need for the marine science community to remain absolutely clear, focused and consistent on the critical requirements if we are to have a reasonable chance of success. Beyond the sheer quantum, other key funding impediments have been continuity of funding, and adequacy of funding for operations.

The issue of continuity can be seen in the case of IMOS. Funding was provided for five years initially, and whilst a second five years of funding has ultimately been secured, it has come in tranches of two years plus one plus one plus one. IMOS has effectively been on an annual funding cliff since June 2011. This has created significant problems in terms of maintaining data streams/time series, maintaining scientific and technical capability in the operating institutions, and maintaining co-investing partnerships. Funding timeframes for research infrastructure need to be matched to the timeframes required to manage that infrastructure effectively and efficiently.

The issue of adequate operational funding can be seen in the case of the MNF. Australian marine scientists and their international collaborators are about to have access to a world class blue water research vessel capability in the form of *Investigator*. Yet even though there is clearly demonstrated scientific demand for more than single vessel capacity on an annual basis, *Investigator* will only operate for 180 days per annum over the next three years. It makes both scientific and economic sense to enable full utilisation of funded infrastructure in line with established science demand.

Cost effectiveness is clearly a significant issue with marine research infrastructure and alternative approaches to data collection need to be considered. The potential to make greater use of commercial vessels as Ships of Opportunity, and to strengthen relationships between marine science and the government agencies operating and chartering vessels for other purposes are two examples. Citizen science is a growing area which is expected to become much more significant over the next decade as individual citizens are equipped with ever more powerful sensing and communication devices. The Reef Life Survey (RLS) project and Range Extension Database & Mapping Project (Redmap) are current examples. Other concepts are being developed e.g. citizen oceanography, equipping private vessels with ocean observing equipment including for sampling and archiving for microbial genomics. From a research infrastructure perspective, it will be important to have a focus on the quality of data produced by citizen science projects, which must be good enough to enable peer reviewed publications.

With respect to key coordination requirements/impediments, this is essentially about management and access arrangements for research infrastructure.

An overarching issue is commitment by the marine science community to open data access, requiring adoption of common data standards and approaches through AODN and related initiatives.

Requirements for management and access with respect to blue water and polar vessels, SeaSim, Island Research Stations, Antarctic Research Stations, IMOS, some aspects of Earth Observation, and NCI are considered to be in place and working.

Shelf scale vessel capability has historically been managed at the institutional level, which has provided somewhat mixed results from a national perspective. AIMS has a national mandate as Australia's tropical marine science agency, and *Cape Ferguson* and *Solander* collectively provide a capability for the tropical north that is institutionally owned and operated, with collaborative access provided through project level engagement and co-investment. However there is no equivalent institutional or coordinating mechanism with a national mandate across the temperate south. The current/projected level of available shelf scale vessel capability is inadequate to meet identified future needs across Australia's EEZ. An effective mechanism for creating an adequate, multi-institutional, multi-jurisdictional, 'virtual fleet' is required.

Australia's autonomous systems capability is currently very sparse. It comprises a small number of shallow-water AUV's and ROV's, including the IMOS AUV Facility, plus the potential for *Investigator* to house one research-grade, deep water ROV. In growing this as a national capability it will be important to pay careful attention to maximising efficiencies with respect to technical development, operational expertise, and data processing, management and delivery.

Other than SeaSim, most research aquaria and analytical facilities operate on the basis of institutional management and access. There is currently no mechanism for them to collaborate on common issues such as programmatic funding, technical skills, big science projects (that cut across latitudes, habitats, institutions, and disciplines), and coordinated approaches to proficiency testing and inter-laboratory calibration. An effective mechanism to facilitate national level collaboration across marine experimental facilities is required.

For satellite sea surface temperature and ocean surface topography, coordination is considered to be currently well organised within the relevant international frameworks (GHRSST and OSTST). Coordination of ocean colour is currently less well organised at the national level, noting that issues around open-ocean and more optically complex coastal waters are somewhat different. Future priorities outlined above indicate much higher expectations from satellite ocean colour over the coming decade e.g. in terms of reliable measurement of phytoplankton species composition and primary productivity from space. Taken together, these two statements suggest the need for an enhanced national coordination mechanism around satellite ocean colour.

World class research infrastructure requires world class skills to ensure they operate not only safely and efficiently, but also to maximise the value that can be extracted from significant capital investments. Funding to maintain and retain these skills must be included in any consideration of infrastructure investment. This will provide career paths for existing highly skilled technical staff and also be an attractor for the next generation providing successors to the current technical workforce.

Many scientists within the community have noted that there is a complete disconnect between the processes for allocating research funding and the processes for accessing research infrastructure e.g. ARC grants and MNF voyage time, to give but one example. This is not the case in other countries (e.g. the USA, UK, Canada), and there must be scope for this situation to be improved in Australia. It is recommended that this be investigated.

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