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Coastal Climate Services:

A Review of Needs for Coastal, Marine and Offshore Applications

Kathleen McInnes, Jules Kajtar, Neil Holbrook, Mark Hemer, Vanessa Hernaman

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Contact

Enquiries regarding this report should be addressed to:

Kathy McInnes

CSIRO

kathy.mcinnes@csiro.au

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REPORT SUMMARY

Coastal climate services: A review of needs for coastal, marine and offshore applications

A review of information needs and services available for the coastal sector, the marine sector and maritime and offshore industries has been undertaken as part of the NESP Earth Systems and Science Hub. The purpose of this review is to assess the expected information requirements of these three sectors. This information has been used to tailor the work undertaken in the Hub Project 5.8: Marine and coastal climate services for extremes information. It will also provide relevant guidance for the production of case studies that present relevant information for stakeholders within Project 5.8. Although the review is primarily informing this project, the findings are valid and useful more widely.

Coastal services for land management, planning and adaptation

Sea-level rise projections have been the most established and widespread of the climate change information used for coastal land-use and adaptation planning and in many cases, this is the dominant factor, so is rightly given prominence. Additional information required to develop actionable information from sea-level rise projections included the development of sea level allowances (i.e. how high do coastal defences need to be raised to afford the same protection in the future that they provide presently), changes to extreme sea level heights and frequencies and land-elevation data, but their availability and accuracy depended on location. Projected changes to extreme sea levels caused by storm surges and waves are important for determining sea level extremes and inundation (e.g. wave overtopping of sea walls) and shoreline changes through erosion, but are not as widely available in Australia as they are elsewhere. While projections of storm surge and waves exist, uncertainties have not been fully evaluated and the processing required to deliver projections to stakeholders has not been undertaken. Sea-level rise can also influence salt-water intrusion into rivers, lakes and groundwater systems affecting infrastructure, groundwater quality, the efficacy of drainage systems and wetland ecologies. Specific information on the effect of sea-level rise on groundwater systems is limited and therefore is not addressed in this review.

Tools and services supporting coastal management and planning are well established in Australia at the national scale. Information relating to extreme sea levels and associated coastal impacts are available in specific locations where targeted studies have been undertaken. The provision of coastal climate information at the national scale presents an opportunity for Project 5.8.

Marine services for aquaculture, fisheries and management

For the marine sector, a high priority has been to better understand coastal ocean physical processes at higher spatial resolution. The way in which changes to physical processes affect ocean ecology is poorly understood, and it was concluded that more research on impact thresholds are deemed necessary.

Services for marine industries are limited and tend to focus on providing data over short outlook periods. While some information on longer (decadal to multi-decadal) timescales is available, this is limited to changes in averages of physical variables such as ocean temperatures rather than extremes that would be more meaningful for determining ecological impacts. However, further work is required to establish whether and how marine sectors would utilise such data if it was made available.

Marine services for maritime and offshore industries

The information requirements for offshore industries focusses on met-ocean variables (e.g. winds, waves and currents) over forecasting to seasonal time scales for operational applications. Whilst maritime and offshore industries contribute significantly to Australia’s economy, particularly through the ports, shipping and oil and gas sectors, the application of climate information for adaptation planning and its integration into practical decision-making processes is at an embryonic stage, despite near decade long calls for greater information to support these sectors. Consideration of climate change driven risks are increasingly relevant for offshore project planning with 30+ year time horizons.

Examples of services for offshore industries focus on providing climatological data for a range of offshore activities, including the marine renewable and traditional offshore fossil energy sectors, shipping and ports. Further work is required to establish whether and how these sectors would utilise longer term climate projections data if they were made available.

1 Introduction

Climate services transfer climate information from research to users, helping them manage and communicate the risks and opportunities of climate variability and change (Le Cozannet et al., 2017). In addition to providing underpinning climate data, climate services may also provide guidance on how to use climate data in decision making as well as tools that deliver data to inform decision making. Services that relate to the coastal and marine sector are emerging but are generally less advanced than climate services in general (Le Cozannet et al., 2017).

Within the Earth Systems and Climate Change (ESCC) Hub, it is timely to undertake a review of coastal and marine services. The findings of this review have not only informed the ongoing work under Project 5.8 but are also of relevance to Project 5.3 in developing recommendations for the Next Generation climate projections for the Australian region.

This review of coastal and marine climate services has been divided into three broad categories that comprise the following three sections. Section 2 considers coastal climate services and the information needs relating to land management, planning and coastal adaptation. The physical variables of primary interest for these mainly land-based activities involve sea-level rise and ocean processes that drive extreme sea levels, including storms and waves. Seption 3 addresses information needs for marine and coastal ocean industries including aquaculture, fisheries as well as marine management. The physical variables of concern relate mainly to ocean temperature (including ocean temperature extremes, in particular marine heatwaves) although ocean chemistry including oxygenation and acidification are also of potential relevance. Section 4 addresses marine coastal and offshore industries such as renewable and traditional offshore energy, ports and shipping for which key variables of interest are met-ocean variables such as winds, waves and weather systems.

Each section reviews relevant national and international information such as peer-reviewed literature, reports and stakeholder surveys. Where available, online tools for the delivery of information have also been reviewed. A regional perspective is then offered at the end of each section. The presentation of material in each section is structured in a way that best represents the available information.

The concluding section presents a discussion and synthesis of the information reported, and the recommendations for the development of new information products for Project 5.8.

2 Information and services for land management, planning and adaptation

Coastal services that evolve from the needs and priorities of end-users involved in planning, management and adaptation are influenced by many factors ranging from geophysical to socio-political. In this section, stakeholder needs are discussed based on a review of reports and peer-reviewed literature. This is followed by a review of coastal services from a selection of countries. The services reviewed include those pertaining to short time scales (coastal services) as well as those applying to longer time scales using climate information (coastal climate services).

2.1 Review of stakeholder needs

Researcher needs

Physical science

Researcher needs for coastal climate information can differ considerably from the needs of other users of coastal climate data in terms of its context, format, language, spatial and temporal resolution (ECLISEA, 2019).

Researcher knowledge gaps and future research priorities for Australia in relation to sea level and coastal extremes were identified and discussed in McInnes et al. (2016), while research priorities for coastal relevant weather systems were discussed in Walsh et al. (2016).

The recommendations included more work on the following topics:

- Improvements in the resolution of sea level projections through higher-resolution, horizontal eddy-resolving ocean models that are capable of resolving shelf dynamics (e.g. Zhang et al., 2017).
- Improved understanding of local vertical land movements supported by an enhanced network of ongoing geodetic observations such as continuous GPS observations. This in turn would support projections of relative sea-level rise for adaptation activities.
- Trends in extreme sea levels around Australia are relatively poorly understood owing to the few long-term tide gauge records. Efforts are needed to lengthen records through data digitisation and to analyse extremes and their contributing factors (e.g. Hoeke et al., 2017).
- Further work to develop projections of waves including wave heights, periods and directions and their uncertainties, with consideration of morphological driven changes in wave conditions in the nearshore and coastal environment (e.g. Morim et al., 2018; Morim et al., 2019).
- Further work to develop storm surge projections (e.g. Colberg et al., 2019) and their uncertainties at the continental scale including causal weather systems such as tropical cyclones and east coast lows (Walsh et al., 2016).

In addition, newly available research needs to be taken into account to update projections where available. Examples include new assessments of the role of dynamical sea ice loss from Antarctic in sea level projections since this process has the potential to significantly increase estimates of future sea level rise (e.g. Oppenheimer et al., 2019) and efforts to model future changes in storm tides at the global scale (e.g. Muis et al., 2016).

Coastal Impacts

In addition to ongoing development and refinement of met-ocean and sea-level data in a climate change context, further research on the interactions of weather and climate variables with the geomorphology and coastal landform is also seen as a research priority (McInnes et al., 2016) such as further research on the following topics:

- Understanding how the coastline will respond to sea-level rise, storm surges, and waves through erosion or deposition, which additionally requires high resolution geomorphological data, high resolution topographic and bathymetric data and models capable of simulating geomorphological change over multiyear to decadal timescales (Ranasinghe et al., 2013).
- Understanding interactions and dependencies in space and time of tide, surge, wave setup and riverine flooding particularly in complex coastal systems such as estuaries.
- Salt-water intrusion into water rivers, lakes and groundwater systems is an important consequence of sea-level rise. It can have detrimental impacts on groundwater resources, reduce the efficacy of drainage systems, increase corrosion of subsurface infrastructure and also alter the ecology of low-lying wetland areas. While sea-level rise, rainfall and evaporation data are key inputs to understanding the changes on groundwater systems, groundwater observations and modelling studies are limited within Australia and so this topic is not addressed further in this review.

Management needs

Coastal land management in Australia typically involves local and state government. Traditional Owners of the land also have an important role in managing and caring for the Australian coast, including the Torres Straits (Morgan et al., 2019).

Coordination needs

The development of the National Climate Change Adaptation Research Facility (NCCARF) CoastAdapt tool involved a rigorous process that included strong collaboration with a wide range of stakeholders (Webb et al., 2019). In the first of a two-stage process, input was sought initially from numerous geographic locations and sectors including natural resource, primary and secondary industry, services, development, investment, public sector and non-government organisations. In the second stage, findings and solutions were tested for coastal settlements and infrastructure since these were identified as high priority topics by the majority of stakeholders.

The tool provides physical data such as datasets on historical flooding; present-day coastal sensitivity to erosion; and future climate extremes, sea-level rise, and inundation for each coastal council together with a risk management framework that supports users through the six stages of decision making including awareness, planning, risk and options assessment, decision-making, monitoring and review (Palutikof et al., 2019a; Palutikof et al., 2019b; Webb et al., 2019). It is noted that ongoing support is needed to keep tools such as this up to date will new scientific developments.

Assessment Scales

In Australia, coastal planning at national to regional scales is shared by the federal and the state/territory governments, while local coastal planning and management is primarily the role of local governments under the direction of relevant departments of the state government. As such, information needs for management are influenced by the jurisdiction of the management authority. For example, the federal government has undertaken a 'first pass' coastal vulnerability assessment of geomorphology, sediment type, tide and wave characteristics to understand coastal hazards at the Australian national scale.

Regional or 'second pass' assessments have been carried out at the state scale with the aim of providing higher accuracy inundation assessments for state-based planning and adaptation. These assessments typically combine higher resolution extreme sea level estimates (e.g. McInnes et al., 2012a for Sydney; McInnes et al., 2013 for Victoria; McInnes et al., 2012b for Tasmania) with more accurate elevation data provided by airborne LiDAR surveys (e.g. Lacey et al., 2012 for Tasmania; Lacey and Mount, 2011 for Victoria; McInnes et al., 2012a for Sydney) to provide inundation maps of extreme sea levels.

However, for localised decision making, 'third pass' assessments are often required in which high resolution projections of physical data (e.g. sea level rise, waves and storm surges) are developed together with detailed localised information such as elevation data, shoreline geomorphological classifications, orthorectified historical photogrammetry. Ideally, such data are combined in geographical information systems (GIS) allowing users to view and overlay a range of data sources to aid in coastal planning and adaption decision making.

Such a system is presently under development for Port Phillip Bay in Victoria as part of the Port Phillip Bay Coastal Hazard Assessment (McInnes et al., 2019) following the guidelines outlined in (DELWP, 2017). Funded by the State Government of Victoria, this tool will support state and local government entities such as the Department of Environment, Land, Water, and Planning (DELWP), Melbourne Water, the Port of Melbourne Corporation, the Environmental Protection Authority (EPA), as well as the various coastal councils around the bay with information on how sea level rise will influence inundation, erosion and groundwater change. The level of resourcing and the data requirements for such detailed assessments are considerably higher than first pass national scale first pass assessments. However, first pass assessments provide the foundational steps towards more detailed assessments.

Engagement needs

User needs

Efforts to develop climate services require understanding of the information needs of users, which may include councils, state or federal governments, consultants, insurance companies and so on. With regard to sea level rise information, Hinkel et al, (2019) used a decision analysis approach to determine that four types of information are needed by users:

(i) Probabilistic predictions for short-term decisions when users are uncertainty tolerant.

(ii) High-end and low-end sea level rise scenarios chosen for different levels of uncertainty tolerance.

(iii) Upper bounds of sea level rise.

(iv) Learning scenarios derived from estimating what knowledge will plausibly emerge about sea level rise over time.

They note that probabilistic scenarios can only be achieved in the short term (next 20 years) before there is strong divergence of different emission scenarios and hence sea level rise estimates. Upper bounds of sea level rise cannot be practically estimated from a physical basis because of large uncertainties in the various components that contribute to rising sea levels and high- and low-end scenarios require both user and expert judgements even though information on upper bounds is often sought for high-risk applications.

Presentation of information

Although dedicated coastal climate services are in their infancy (Le Cozannet et al., 2017), a European Union and national institution-funded project, the European advances on CLImate Services for Coasts and SEAs (ECLISEA) project (ECLISEA, 2019) has completed a comprehensive review of climate information needs for stakeholders across multiple European countries and sectors and the key findings of that review relevant to this section are presented here (note that some of the reviewed sectors are also discussed in Section 4 of this report that deals with offshore industries). Information needs for climate services identified in Germany for the coastal protection sector and the municipalities and regional policy sector are discussed here. These studies were funded by the German Federal Ministry of Education and Research (BMBF) through the research program 'Klimzug – Managing Climate Change in the Regions for the Future' (https://edoc.sub.uni-hamburg.de//klimawandel/frontdoor/index/index/docId/568), which develops innovative approaches to climate change adaptation.

Climate information is required for the development of adaptation measures and strategies to climate change such as coastal and flood protection structures, for analysing the effectiveness of coastal protection structures, and performing vulnerability analyses. Information is also required on a range of climate variables such as sea level rise, storm surges, local wave climate and wave setup together with morphodynamical information such as sediment transport and sediment availability, erosion and coastal protection levels in a future climate. Information was also identified from scientific studies into coastal protection and included historical storm surge and measured water level data, water inflow and runoff data, sea level rise scenarios and wind fields.

Stakeholder feedback included examples of where climate information was difficult to work with such as the large uncertainties on sea level rise projections. Stakeholders also indicated that extreme event attribution to anthropogenic climate change was not particularly important for their work, being more concerned about how extreme events would change rather than understanding why they had changed (ECLISEA, 2019), although this finding may be specific to the particular stakeholders surveyed.

There was a requirement for more socio-economic data to accompany climate projections to enable an assessment of risk although it is noted that access to data may depend on whether the data is in public or private ownership. Applied information relating to the performance of infrastructure was also deemed important, such as what level of sea level rise would compromise pumping stations or render the drainage network ineffective.

2.2 Review of services for coastal applications

This section reviews the types of information that are available as well as the delivery systems through which information is delivered to stakeholders. The first section reviews services that are available both nationally and internationally. This is followed by a brief synthesis of examples from overseas.

Coastal services in Australia

Coastal planning at the national to regional scale is shared by the federal and state and territory governments, whereas local coastal planning and management is mainly the role of local councils under the guidance of state policy. Most coastal climate services in Australia have been developed through federal funding for the whole of the Australian coast, although there are examples of more localised services. The following discusses the various tools and websites that have been identified in this review. These have, for the most part, been developed independently. However, they generally address different niches and as such complement each other.

In terms of short term predictions of met-ocean variables (i.e. the combination of meteorological and physical ocean variables such as winds and waves), tide height predictions are provided by the Bureau of Meteorology (http://www.bom.gov.au/oceanography/projects/ntc/ntc.shtml). The Bureau also provides national forecasts of waves (Durrant et al., 2009; Zieger et al., 2018) and storm surges based on an operational storm surge forecast model (Allen et al., 2018). There are ongoing efforts to develop inundation forecasting by linking forecast sea level thresholds with urban inundation extents (Hague et al., 2019), similar to efforts being developed in the US (Sweet et al., 2018).

As part of a national release of climate projections for Australia, regional sea level rise projections and their uncertainties up to 2100 were delivered as a national climate service by CSIRO at https://www.climatechangeinaustralia.gov.au/en/ (McInnes et al., 2015). In addition to sea-level projections, sea-level allowance based on Hunter et al. (2013) were also developed, which provide guidance on the height that coastal defences would need to be upgraded to ensure their level of protection in the future remains at present day standards (McInnes et al., 2015). While a useful concept, it should be noted that this allowance takes into consideration only the present-day extreme sea level likelihoods (e.g.

return periods) and its formulation does not readily allow for the inclusion of projected future changes to extreme sea levels. In addition, the derivation of the allowance is highly sensitive to how the sea level rise uncertainty is defined such that the larger the sea level rise uncertainty, the larger the allowance. Potential ambiguity in defining uncertainties in sea level rise projections is discussed in McInnes et al. (2015).

The sea level rise projections and allowances were subsequently provided at the scale of the approximate 255 coastal councils around Australia together with other tools and guidance material to support coastal council adaptation needs on the 'CoastAdapt' web site (https://coastadapt.com.au/). CoastAdapt also provides tools such as inundation mapping software and local coastline morphological information to inform erosion potential.

The inundation mapping software is also separately available at http://coastalrisk.com.au/. This software incorporates an interactive map tool designed to communicate coastal inundation associated with sea level rise to the year 2100. The underpinning digital elevation models (DEMs) have been constructed using airborne LiDAR technology, which are then combined with 'bucket-fill' inundation modelling to create the map-based visualisations.

The shoreline stability information in CoastAdapt is comprised of coastal sediment compartment information and the Smartline tool. The Smartline tool is a nationally-consistent geomorphic and landform stability map developed originally by Geoscience Australia and Department of the Environment (Sharples et al., 2009) in which the coast is divided into a series of line segments where each line segment represents a section of coast with similar geomorphic characteristics (e.g. rocky cliffs or sandy shores). The characterisation of the coastline includes information about the backshore, nearshore and intertidal regions of the coastline. It is represented in a GIS line format. It provides information on the underlying landform together with its potential stability in the future due to erosion resulting from sea level rise. The information relating to each shoreline segment is stored as a set of attributes (NCCARF, 2016). Smartline is also available at https://ozcoasts.org.au/.

Smartline contains information on coastal sediment compartments, which are discrete coastal units that are characterised by broadly homogeneous features such as geology, landform types, near-shore currents, and sediment availability and movement. For each coastal compartment information on the sediment availability is given including transport of sand in both cross-shore and alongshore directions, into and out of river and estuary entrances, and into dune fields. It also contains guidance on the sensitivity of the shoreline to erosion (NCCARF, 2016).

Climatologies of extreme water level information for the Australian coast have been generated using hydrodynamic models to simulate weather and tide-induced sea level variations. Once generated for an historical time period spanning recent past decades, the modelled data can be used in statistical models to estimate return periods of extreme sea level exceedances for engineering applications. The first national modelling study of this kind for Australia was undertaken by Haigh et al. (2014) providing information on extreme sea levels at a coastal resolution of around 10 km, therefore providing greater coastal coverage of extreme sea level information than can be provided by the national tide gauge network.

Recently, models of higher spatial resolution have been developed for the Australian coast (Pattiaratchi et al., 2018). while such model data sets can be used to investigate how sea level rise combines with extreme sea levels to cause inundation, they do not provide information on how the causes of extreme sea levels may change under climate change. A hydrodynamic modelling study by Colberg et al. (2019) investigated at national scale the effect of climate change on extreme sea levels using forcing from an ensemble of simulations from four climate models by comparing the difference in extreme sea levels over the late 20th and early 21st century. The small ensemble of climate models investigated in that study, which was due to the computational cost of running large hydrodynamic model ensembles, means that the uncertainty space is poorly constrained.

Extreme water level information provided either by tide gauges or via hydrodynamic models has been provided through a tool called Canute3.0 (https://coastalextremes.shinyapps.io/canute3_0/). This tool updates the original Canute2 tool developed by the University of Tasmania available at http://www.sealevelrise.info/ by including sea level projections based on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report and extreme sea level information from additional hydrodynamic model simulations such as Haigh et al. (2014) and Colberg et al. (2019). In future developments of Canute3.0, the extreme sea level data set will include estimates of wave setup based on O'Grady et al. (2019).

A localised coastal climate service is presently under development by CSIRO for Port Phillip Bay in Victoria as part of the Port Phillip Bay Coastal Hazard Assessment (McInnes et al., 2019). Funded by the State Government of Victoria, this tool will support state and local government entities such as Melbourne Water, the Port of Melbourne Corporation, Victorian EPA and DELWP as well as the various coastal councils around the bay with information on how sea level rise and climate change more generally will influence inundation, erosion and groundwater change.

Coastal services in the United States

In the United States (US), climate change services are provided by a range of entities including federal government agencies, academic institutions, and nongovernmental organisations. Of the federal government agencies, the National Oceanographic and Atmospheric Administration (NOAA) is responsible for flood monitoring, warning and near-real-time local hazard mapping. The US Federal Emergency Management Agency (FEMA) has the responsibility for developing information on longer climate change timescales through hydrodynamic modelling and hazard mapping to support disaster prevention, preparedness and recovery. The US Army Corps of Engineers (USACE) is responsible for developing infrastructure including structural, non-structural, natural, and nature-based solutions for coastal adaptation and risk reduction. The US Geological Survey (USGS) has the responsibility for assessing impacts to geomorphic systems such as coastal aquifers, shorelines and active coastal zones (Le Cozannet et al., 2017).

A non-government example of a US CCS is inundation mapping provided by Climate Central (https://sealevel.climatecentral.org/maps/), which provides maps of inundation for the US based on LiDAR-derived DEMs and bathtub inundation methods. It also provides a global product that is based on an improved method for deriving satellite-based topography compared to the older Shuttle Radar Topography Mission (SRTM) elevation dataset at 90 m resolution with the new CoastalDEM being better calibrated with available LiDAR using neural networks (Kulp and Strauss, 2019).

Sea level rise projections for the US were developed by NOAA (Sweet et al., 2017) adopting the risk-based approach of developing an upper bound to sea level rise (Hinkel et al., 2019). The projections of rapid ice sheet loss from Antarctica by DeConto and Pollard (2016) informed the estimation of the upper bound of sea level rise by 2100 of 2.5 m. That assessment does not take into account more recent studies that suggest the DeConto and Pollard (2016) assessments may be unrealistically high on the time frame of 2100. To date, some US jurisdictions have adopted sea level rise values for planning that are higher than the upper range of IPCC sea level rise projections at 2100 but lower than the 2.5 m upper bound provided in Sweet et al, (2017), although greater understanding of the use of sea level planning benchmarks by coastal jurisdictions globally is the subject of ongoing research (Dave Behar, Climate Program Director, San Francisco Public Utilities Commission, personal communication, 4 August 2020).

Many US coastal cities, particularly along the eastern seaboard of the country, are experiencing a rapid increase in the frequency of nuisance (or ‘sunny day’) coastal flooding due the combination of sea level rise, subsidence and astronomical tides. This flooding is affecting infrastructure such as roads, storm, waste and fresh-water systems, and private/commercial property that were not designed for repetitive salt-water exposure. Decision makers have therefore demanded more information about chronic coastal flooding in the US and NOAA has developed early warning systems for sunny day tidal flooding and impact thresholds for minor, moderate and major coastal flooding which typically begin about 0.5 m, 0.8 m and 1.2 m above a height slightly higher than the multi-year average of the daily highest water levels measured by NOAA tide gauges (Sweet et al., 2018).

Coastal services in the United Kingdom

The UK Climate Projections (UKCP) is a climate analysis tool that forms part of the Met Office Hadley Centre Climate Programme which is supported by the Department of Business, Energy and Industrial Strategy (BEIS) and the Department for Environment, Food and Rural Affairs (DEFRA).

Marine projections including sea level rise, storm surge and wind-waves have recently been updated as part of UKCP18 (Lowe et al., 2018; Palmer et al., 2018). The sea level rise projections have been developed using an analogous approach to that used by the IPCC and include a dynamic contribution from Antarctica.

The effect of future storminess changes on storm surge was assessed by running hydrodynamic models that are forced by a limited ensemble of climate models. Five Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations under two Representative Concentration Pathways; RCP 2.6 and RCP 8.5, representing a low emission and a high emission scenario respectively, were first downscaled using a regional climate model. The atmospheric conditions from the regional climate model were then used to drive a storm surge model. The five model simulations were chosen based on their ability to simulate a realistic climate over northwest Europe and also because collectively, their responses spanned a range of projected responses over the 21st century. The storm surge simulations showed that trends in extreme sea levels were small and ranged from slightly positive to slightly negative depending on the climate model being downscaled.

2.3 Regional perspective

The combination of climatological features, the varied natural coastal landscape and socio-economic considerations give rise to a varied risk profile around the nation that is discussed briefly here.

Socio-economic considerations

Australia is a coastal nation with around 85% of its population and associated industries located along its 35,000 km coastal rim (Department of Climate Change, 2009) with the majority located along the populous east coast. Department of Climate Change (2009) estimated that 157,000–247,600 of the 711,000 existing residential buildings connected by low-lying land to the coast would be vulnerable to inundation from a 1.1 m rise in sea level in combination with a locally extreme sea level and nearly 39,000 buildings would be at risk from erosion.

Tourism is Australia’s second most valuable export earner with the tourism sector employing 5% of the Australian workforce (Hughes et al., 2018). Australian beaches are among Australia’s top five tourist destinations. For example, popular beach destinations such as the Sunshine coast in Queensland and the Surf coast in Victoria earn approximately $56 million and $20 million per annum respectively while the Great Barrier reef contributes around $6 billion to the Australian economy (Hughes et al., 2018). A recent study of global erosion suggests that at least 11,426 km or 50% of sandy beach coastline in Australia could be threatened by erosion under RCP 8.5 by the end of the century (Vousdoukas et al., 2020).

The natural environment, climatology and climate change

Australia spans tropical to extratropical climate zones and experiences a range of coastal oceanic hazards including tropical cyclones in the north to frontal systems and extratropical lows in the south, which can generate storm surges and hazardous wave conditions. Four broad regional environments have been identified for the Australian coastline (Department of Climate Change, 2009):

(1) The ‘Muddy North’ region extending from Cape York Peninsula to Ningaloo, which is highly tidal, cyclone influenced and muddy.

(2) The ‘Limestone South and West’, extending from Ningaloo to Hobart, which features a lower tidal range, carbonate rocks and high wave and wind energy.

(3) The ‘Eastern Headlands and Bays’ region from Hobart to Hervey Bay, which is a region of small tides, quartz sands, moderate wave energy and many bays and estuaries.

(4) The ‘Barrier Reef’ region from Hervey Bay to Cape York Peninsula in northern Queensland, which features low-lying rocky mainland coasts, the Great Barrier Reef and islands including the Torres Strait Islands.

The key climate drivers affecting sea levels and waves have been discussed in McInnes et al. (2016) and highlight the propensity of sections of coastline to experience higher tides and storm surges due to the characteristics of the adjacent continental coast. Coastal sea levels associated with the 1-in-100 year storm tide (storm surge plus astronomical tide) for coastal Australia are shown in Figure 1a and highlight the likelihood of severe sea levels on the northwest coast due to both the large tidal range and potential for large storm surges on this shallow continental shelf region while the southwestern coastline experiences lower storm surges and tidal range. Figure 1b shows that when wave setup is also considered, 100-year sea levels increase on the southern coast due to the strong influence of Southern Ocean swells on coastal sea levels.

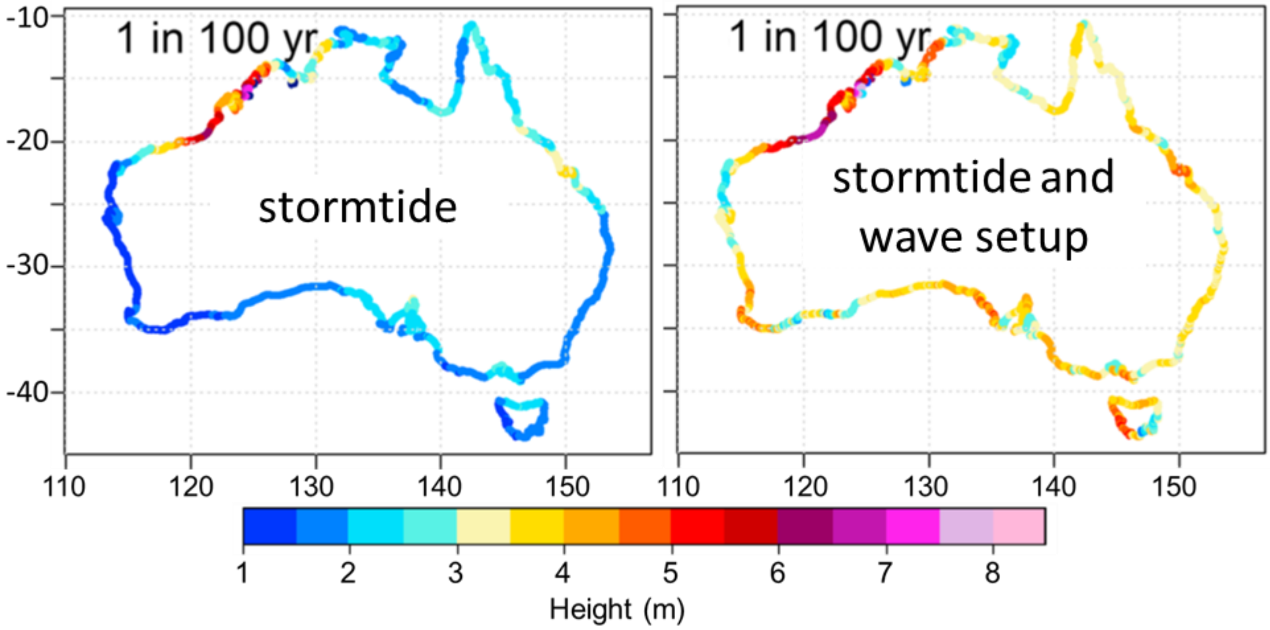

Figure 1. Sea level height associated with (left) the 1 in 100-year storm tide and (right) storm tide and wave set up (from O'Grady et al, 2019).

In terms of future changes, the tropical northern coastline will be most sensitive to changes in tropical cyclone behaviour while the mid-latitude southern and eastern coastlines are expected to be most sensitive to changes in mean sea level, wave climate, and changes in storminess (Department of Climate Change, 2009).

An assessment of how future climate change will affect sea level rise, storm surge and waves around the Australian coast is summarised in Figure 2 (Hemer et al., 2017a). This indicates that along the east coast, projections of sea level rise are higher than the global-averaged sea level rise due to the influence of the warm East Australian Current. Along the south coast, wave heights are projected to increase as a result of strengthening winds in the Southern Ocean increasing southerly wave swell and in the Gulf of Carpentaria the height of storm surges is projected to increase. Along the northwest shelf and sections of the southern coast, wave and storm surge projections indicate small decreases in the future and sea level rise is projected to be slightly lower than the global average.

While the hazards illustrated in Figure 2 have been assessed independently, there is also the possibility for non-linear interactions between the processes shown and also astronomical tides.

For example, a location of particular interest for interactions between tides and sea level rise is Port Phillip Bay which is being assessed as part of the Port Phillip Bay Coastal Hazard Assessment (McInnes et al., 2019).

Also, it should be noted that wave height is not the only attribute of the wave climate that is important for coastal hazards (Hemer et al., 2013; Morim et al., 2019). For example the east Gippsland coastline has been identified as a region where projected changes of wind and wave directions could drive large coastal impacts in the future (O'Grady et al., 2015) despite being a location where storm tides and wave heights are projected to decrease.

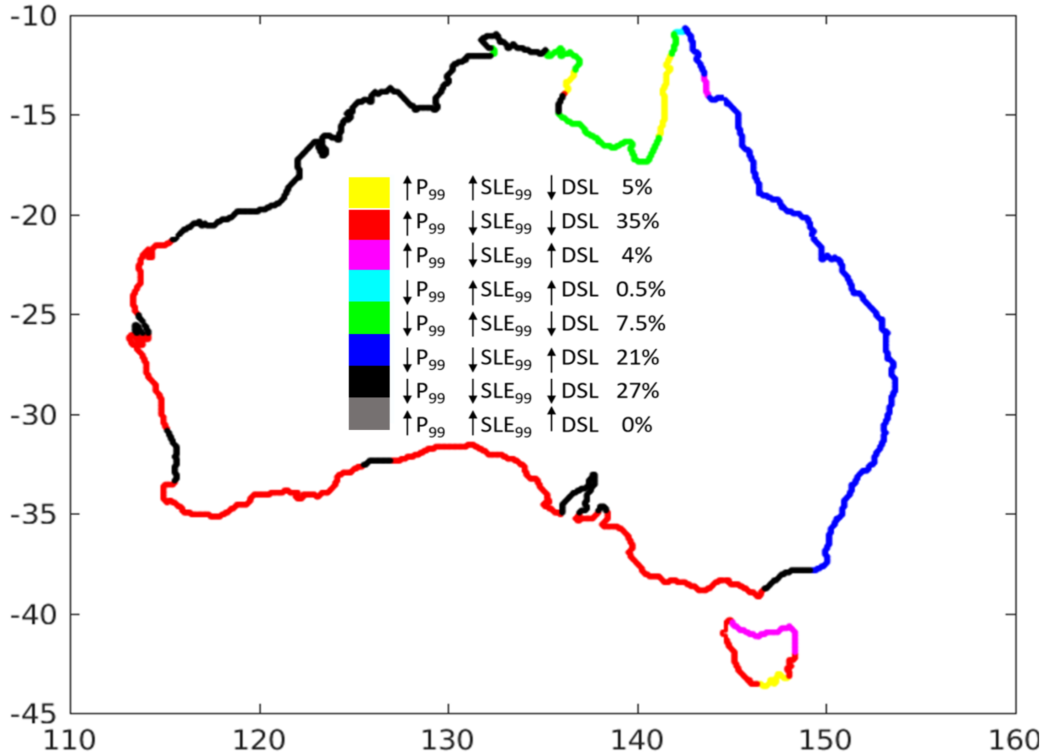

Figure 2. Regions where climate change studies indicate increase or decrease in 99th percentile wave power, sea level extremes, and locations where projected sea level rise is above or below the global average projection (source: Hemer et al, 2017).

3 Marine climate services

In this section we review the climate services under a changing climate relating to Australia’s marine regions that are available to, or desired by, relevant stakeholders. Here we focus on the marine biodiversity and resource sectors, which is primarily composed of the aquaculture, commercial fishing, recreational fishing, conservation, and tourism industries.

This is not an exhaustive list of marine stakeholders, but to some extent the review was limited by the scope within the literature. The review was undertaken by considering marine heatwaves as the main climate threat to these industries, though some of the key findings are equally applicable to other hazards associated with global warming, such as increased ocean acidity, more powerful storms, or sea level rise. The surveyed literature included peer-reviewed journal articles, as well as reports – mostly published by the National Climate Change Adaptation Research Facility (NCCARF). Following the review and identification of key needs of stakeholders, a brief review of marine climate services in Australia is provided.

3.1 Review of stakeholder needs

Researcher needs

This category outlines the identified needs of stakeholders from the academic research community. These have been separated into three sub-groups: needs from physical scientists (primarily oceanographers), needs from ecological researchers and knowledge sharing recommendations.

Physical science

Improved forecasting is essential to identify extreme heatwave events earlier (Caputi et al., 2019), identify temperature hot spots and abundance changes (Caputi et al., 2016; Hobday et al., 2017), and improve preparedness and recovery (Dunstan et al., 2018). Efforts to improve forecasting should also be coupled with the understanding of marine ecosystem responses (Babcock et al., 2019). Higher resolution modelling is also needed to make predictions on a finer spatial scale than currently available (Mapstone et al., 2010), and to provide information (including ocean modelling and fisheries modelling) at the appropriate spatial scale (NESP Earth Systems and Climate Change Hub, 2018). A general refinement on our understanding of extreme climate events, through modelling, will help to manage impacts (Babcock et al., 2019; Underwood, 1989). The relative lack of identified needs in the literature in this area may be indicative of low awareness in what the physical science community may be able to provide.

Ecological researchers

Physical science studies related to temperatures changes need to be closely aligned to ecological studies in many cases. It has already been noted that efforts to improve forecasting should be combined with efforts to understand marine ecosystem responses (Babcock et al., 2019), but the adequacy of ocean modelling and data products used in support of biological investigations needs to be established (Frusher et al., 2014; Hobday et al., 2011a). Several aspects of marine environments require extensive research, such as thresholds for vulnerable species (Holbrook et al., 2012; Holbrook and Johnson, 2012), how to establish the prioritisation of protection for biodiversity, genetic diversity, stability, resilience, or uniqueness (Johnson and Holbrook, 2014), and how to anticipate the phenology and movements of individual species in response to climate change (Johnson and Holbrook, 2014). The coupling of physical science with ecological studies will help to determine the best sites for future operations (Holbrook et al., 2012; Holbrook and Johnson, 2012).

Knowledge sharing

A number of recommendations for the communication of information between researchers and stakeholders have been identified in the literature. Information should be shared across and between multiple scales (Serrao-Neumann et al., 2016). The presentation of information should be comprehensible and transparent (Matthews and Selman, 2006; Metcalf, 2010; Metcalf et al., 2014), targeted (NESP Earth Systems and Climate Change Hub, 2018), but also appropriate for a wide range of local communities (NESP Earth Systems and Climate Change Hub, 2018). Targeted communication should be supported by research founded on knowledge of local climate change drivers for adaptation planning (Metcalf et al., 2015). Science and modelling have a role in developing methods to select the most effective suite of possible strategies (Johnson and Holbrook, 2014). Confidence levels of predictions and modelling must also be communicated to feed into risk management (Leith and Haward, 2010).

Needs from Management

Here we outline the reported needs of marine sector management. Management is a broad term, but in this context is defined as any individual or organisation that plays any role in the operation of the marine biodiversity and resource sectors. It can include local, state, or federal government. The needs from management have been divided into four sub-groups: an overview of why management intervention is needed, coordination needs, information needs from the scientific community by managers, and other information needs.

Why management intervention is needed

Effective management is crucial for protecting Australia’s marine sectors from the threat posed by extreme events under a changing climate. Management intervention is necessary for response, such as improving recovery rates from marine heatwave events (Caputi et al., 2019), but also for adaptation, such as helping fisheries remain viable under climate change (Holbrook and Johnson, 2014; Plagnyi et al., 2011).

Governance plays a role in increasing the vulnerability threshold (Serrao-Neumann et al., 2016), and strategies that build adaptive capacity and resilience are of most benefit (Leith and Haward, 2010). Management needs to integrate science that supports timely institutional responses, a broader planning perspective, and development of resilience-building strategies (Holbrook and Johnson, 2014; Miller et al., 2010). An abundance of climate information is continually generated, but it must be tailored for specific regions and sectors (NESP Earth Systems and Climate Change Hub, 2018), and needs to respect all participants, with mutual trust, and work within existing cultural protocols (NCCARF, 2010a). Some case study examples of inclusive, community-based, participatory research are given in an report by NCCARF (2010a). A process for adaptation may consist of three steps: (i) describe a structure and function of a particular stakeholder, (ii) identify aspects that can be improved, and (iii) develop plan.

Coordination needs

Coordination, integration, and knowledge sharing needs to occur not only across sectors (Johnson and Holbrook, 2014), but at, and between, multiple scales (Serrao-Neumann et al., 2016). Stakeholders should be engaged at the earliest stage, to identify priorities from the perspective of those most affected (NCCARF, 2010a). Diverse forms of knowledge help to tackle adaptation (Leith and Haward, 2010), whilst multi-stakeholder participation recognises complexity of adaptation, and creates common ground (GBRMPA and NCCARF, 2011). Local communities also have an important voice in driving adaptation approaches (GBRMPA and NCCARF, 2011; Hale et al., 2009; National Resource Management Ministerial Council, 2010). Ongoing involvement of industries in co-management and self-governance help to promote flexible management (Holbrook and Johnson, 2014). Sharing feedback on how growers are currently dealing with extreme conditions is also useful (Leith and Haward, 2010). There is a recommendation to continue the development of knowledge-action networks that include stakeholders, scientists, and government (Leith and Haward, 2010).

Information needs from scientific community

Adaptation plans should prioritise the protections of biodiversity, genetic diversity, stability, resilience, or uniqueness (Johnson and Holbrook, 2014), in which the scientific community can provide insight. Accordingly, research should be provided on anticipated phenology and movements of individual species in response to climate change (Johnson and Holbrook, 2014). The wealth of scientific information being generated can be overwhelming (NESP Earth Systems and Climate Change Hub, 2018), so risk management should take into consideration which impacts have greater or less confidence (Leith and Haward, 2010), but also the level of impact. Science can help to develop methods to select the most effective suite of possible strategies (Johnson and Holbrook, 2014). Operationalising resilience concepts in Australian marine sectors is also critical (Davidson et al., 2013).

Other information needs

Many authors stress the need for information not only from the scientific community, but from elsewhere. Details of economic and social factors that limit adaptation are essential (Holbrook and Johnson, 2012; Holbrook and Johnson, 2014), but should be focussed on addressing local pressures to marine ecosystems (Johnson and Holbrook, 2014).

More context-specific research is required to identify the limits of the adaptability envelope (Serrao-Neumann et al., 2016), but also to understand which interventions are required to avoid crossing tipping points (Serrao-Neumann et al., 2016). Economic instruments need to be designed to incentivize efficient and timely adaptation responses (NCCARF, 2010b), with a focus on helping resource-dependent communities to adjust to future socio-economic tipping points (Serrao-Neumann et al., 2016). There is some argument that management improvements do not require new science or understanding, but the development of effective, responsive institutions and tools for achieving adaptive management (Brander, 2010; Holbrook and Johnson, 2014), and an ecosystem approach to fisheries management (Hobday et al., 2011b; Holbrook and Johnson, 2014; OECD, 2011).

Engagement needs

This category outlines the specific engagement needs of marine stakeholders identified in the literature. An extensive national survey in 2010/11 into the needs of marine biodiversity and resources stakeholders (Holbrook, 2011) found that 'communication and education' was the most highly cited need amongst all sectors. The findings of the present literature review generally support that message. The engagement needs from stakeholders have been divided into three sub-groups: the recommendation to engage in two-way communication, comments on the presentation of information to stakeholders, and the acknowledgment and communication of a broad range of information.

Two-way engagement

Engaging with the community is an essential pre-requisite for driving adaptation approaches (GBRMPA and NCCARF, 2011; Hale et al., 2009; National Resource Management Ministerial Council, 2010). Knowledge sharing must occur at multiple scales (Serrao-Neumann et al., 2016), and stakeholders should be engaged at the earliest stage, to identify priorities from the perspective of those most affected (NCCARF, 2010a). Multi-stakeholder participation recognises complexity of adaptation, and helps to create common ground (GBRMPA and NCCARF, 2011).

Clarity

Stakeholders are critical to adaptation research, and appropriate models for their participation need to be employed (Frusher et al., 2014). Some development of methods for communicating scientific results to stakeholders is needed (Frusher et al., 2014), to help better place marine industries to more effectively adapt to future climate change (Holbrook and Johnson, 2014). A 'one size fits all' approach must be avoided (Frusher et al., 2016) and researchers have due diligence to present targeted information that is appropriate for a wide range of local communities (NESP Earth Systems and Climate Change Hub, 2018). Modelling and scientific approaches need to be comprehensible and transparent, to encourage stakeholder involvement (Matthews and Selman, 2006; Metcalf, 2010; Metcalf et al., 2014).

Multiplicity

Climate and non-climate impacts or stressors are often difficult for stakeholders to distinguish (van Putten et al., 2014b). Sometimes stakeholders consider that the contribution of non-climate related factors 'swamp' climate change effects (van Putten et al., 2014a), and it is true that climate change is only one factor in driving impacts from extreme events (Kuruppu and Liverman, 2011; van Putten et al., 2014a). Nevertheless, improved access to information on climate variability and risk are critical for production and economics in a changing climate (Hobday and Poloczanska, 2010; Holbrook and Johnson, 2012). There is significant potential for aquaculture operators to access improved information on what changes are likely to occur, both direct and indirect (Mapstone et al., 2010).

3.2 Review of marine climate services

There are relatively few climate services available for operators in Australia's marine sector, but a brief snapshot is provided. Coastal services already noted previously (Section 2.2) are not covered here.

The Bureau of Meteorology provides a seasonal outlook for Australian sea surface temperature anomalies, for 5-6 months into the future, on its 'Ocean Temperature Outlooks' page (http://www.bom.gov.au/oceanography/oceantemp/sst-outlook-map.shtml). This provides a guide to likely ocean conditions, but the data are presented on a monthly basis. As such, it may be of limited use in providing information about the intensities, frequencies or durations of ocean temperature extremes, such as marine heatwaves and their likelihoods. The Bureau of Meteorology is preparing to roll-out higher resolution seasonal sea surface temperature forecasts.

Australia's Integrated Marine Observing System (IMOS) provides up-to-date (5-6 day lag) and high-resolution observations of sea surface temperature and currents (http://oceancurrent.imos.org.au), among other variables such as acidity and salinity. These data are highly valuable and might be used to determine likelihoods of emerging marine heatwaves in near real-time. But another level of analysis or interpretation is likely required before being of direct use to marine operators.

The Marine Heatwave Tracker (http://www.marineheatwaves.org/tracker.html) developed by Robert Schlegel at Dalhousie University, is a useful tool for depicting marine heatwaves and their intensities around the world. It updates at a one-week delay, is more useful for examining extreme events of the past, rather than providing predictions.

The Marine Explorer provided by the CSIRO provides a summary of CMIP5 model projections for the Australian region (https://www.climatechangeinaustralia.gov.au/en/climate-projections/coastal-marine/marine-explorer/). This is a useful tool for providing an estimate of expected mean sea temperature changes but says little about the expected change in extreme events.

The services outlined here represent the early stages of marine climate services in Australia. Hub Project 5.8 aims to add to these, but also to contribute to Australian marine climate services in a meaningful way.

3.3 Regional Perspective

Here we draw out studies that focus on particular regions around Australia's marine environment. The goal was to identify a small number of key case study regions to focus on in Hub Project 5.8. The 'significance' of regions was established using the guidance of five pre-determined criteria:

- Value of the area, be it economic, ecological, or to Traditional Owners
- Vulnerability, primarily to climate change directly, but also to other non-direct drivers
- Climate projections
- Potential for predictability of extreme events in that region
- Potential for adaptation.

A summary of the key regions identified in this section is given in Figure 3 below.

Western Australia

Much of the Western Australian coast experienced an extreme marine heatwave during the summer of 2011. Sea surface temperature was up to 5°C higher than usual, and caused significant impacts on the marine ecosystem (Benthuysen et al., 2014; Wernberg et al., 2013). Large parts of the marine ecosystem have been slow to recover (Caputi et al., 2019). Scallop fisheries around the Abrolhos Islands and Shark Bay were closed for 3-5 years, and the Shark Bay crab fishery was closed for 18 months (Caputi et al., 2019). Other marine stocks, including abalone, prawns, lobsters, and sea grass, were also significantly impacted (Caputi et al., 2019). Another marine heatwave hit in the early part of 2013, but to the north of the area most effected by the 2011 heatwave (Babcock et al., 2019). Bleaching and mortality of corals were recorded during the 2013 event (Babcock et al., 2019). Both the 2011 and 2013 marine heatwave events were linked to patterns of climate variability (La Niña for the 2013 event, but the Ningaloo Niño in both cases), and thus there is scope for prediction of such events on seasonal to annual time scales.

Southeast Australia

Unprecedented marine heatwaves have occurred in the Tasman Sea during the summers of 2015/16 (Benthuysen et al., 2018; Oliver et al., 2017) and 2017/18 (Perkins-Kirkpatrick et al., 2018), with significant ecosystem impacts (Oliver et al., 2017). But the need for adaptation to climate change from regional fisheries and marine aquaculture industries has been urged for at least a decade (Davidson et al., 2013; Leith and Haward, 2010; Metcalf et al., 2014; Ogier et al., 2012).

The Tasman Sea is a region where marine heatwave probabilistic forecasts may be possible on multi-year time scales (Li et al., 2020), with potential predictably emerging from the El Niño-Southern Oscillation, variations in the East Australian Current and propagation of anomalies from the South Pacific (Chung et al., 2017; Cougnon et al., 2020; Li et al., 2020; Oliver et al., 2017; Oliver et al., 2018).

The southeast Australian coastline is also of interest in terms of future changes to storm tracks and extreme waves related to severe weather events such as cold fronts and east coast lows (O'Grady et al., 2019). Port Phillip Bay in southeast Australia is also the subject of a detailed coastal hazard assessment, that is considering the impact of sea level rise on tides, storm surges and waves within the bay and in turn the combined effects on coastal inundation, erosion and groundwater (McInnes et al., 2019). The southeast of Australia is also a region with large potential sources of wave and tide energy resource (Hemer et al., 2018).

Great Barrier Reef

The Great Barrier Reef is clearly of significant ecological, cultural, social, and economic value to Australia. It has experienced several coral bleaching events in recent years, related to both temperature and acidity changes, and its long-term health and ecological viability is under threat (Babcock et al., 2019). El Niño conditions typically push warm water towards the western Pacific and the Coral Sea, and extreme El Niño events are projected to increase in frequency under global warming (Cai et al., 2014).

Torres Strait

In December 2017, the Earth Systems and Climate Change (ESCC) Hub and the Torres Strait Regional Authority (TSRA) jointly convened a workshop to bring together researchers and managers to review the current state of knowledge on the impacts of climate change in the region.

The workshop focussed in particular on the impacts on fisheries and marine ecosystems. It is clear that the climate is changing, with expected further declines in reef health and diversity, increased sea temperatures and sea levels, and reduction in water quality (NESP Earth Systems and Climate Change Hub, 2018). The Traditional Custodians are island-based, and as a result are heavily dependent on their marine resources.

Consultation and engagement with Traditional Owners and fishers is paramount to appropriately target actions for key fisheries and vulnerabilities. Low lying islands within Torres Strait are also particularly vulnerable to sea level rise and extreme sea level events. Strong tidal currents within this region mean that tidal energy provides an opportunity for this region (Hemer et al., 2018).

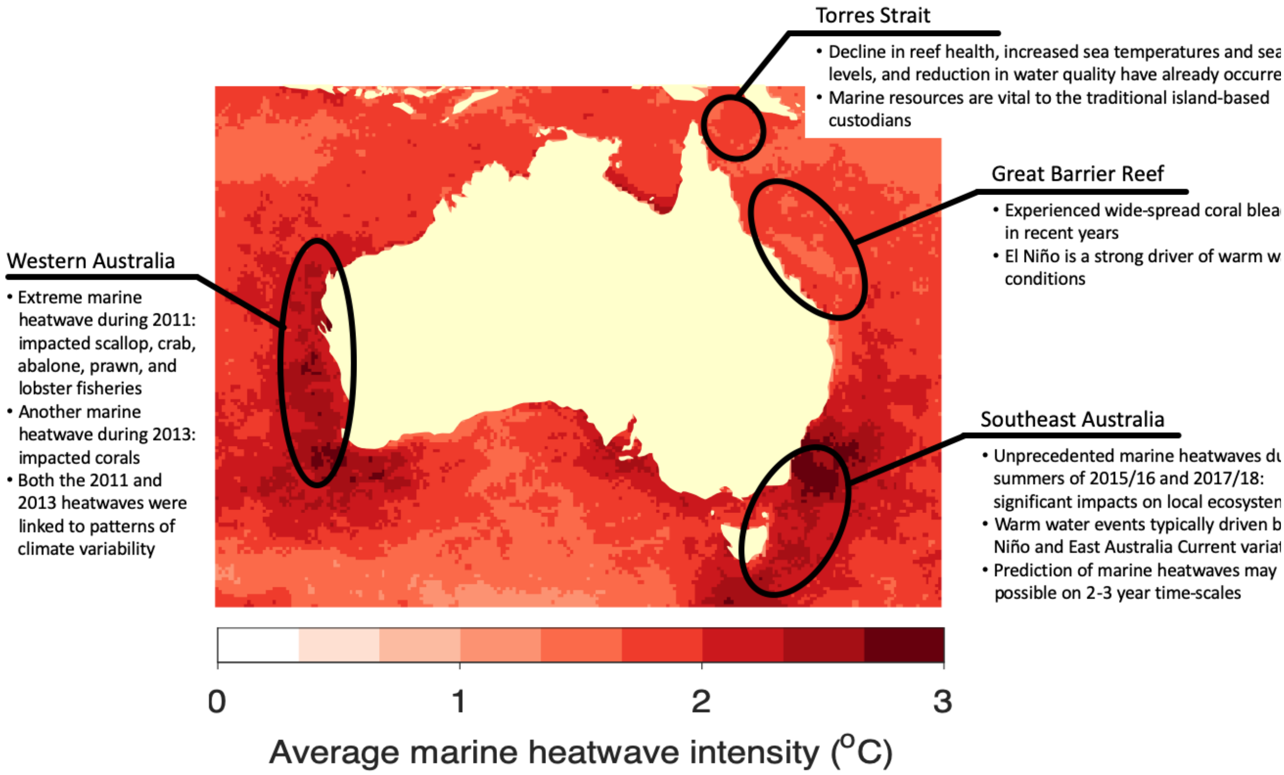

Figure 3. The four identified significant marine regions around Australia, as determined by five criteria (see Section 5.3). The shading denotes the average intensity of marine heatwaves over the period 1982-2014, which is measured in °C above the local mean sea surface temperature.

4 Marine services for offshore industries

This section reviews the climate information needs of offshore industries such as energy and shipping. The information needs of these sectors include met-ocean variables such as winds, waves and severe weather conditions as well as variables relating to ocean chemistry (e.g. acidification) because of implications for infrastructure.

4.1 Review of stakeholder needs

Researcher needs

Australian perspective

The Australian Forum for Operational Oceanography (FOO) brings together representatives from marine industries, R&D providers, service providers, and government agencies to explore opportunities and risks in Australian marine industries with the aid of operational oceanography. The third meeting of FOO was held in Melbourne in October 2019, and it highlighted a number of stakeholder needs, but particularly many needs from researchers (FOO, 2019):

- standardisation of Australian wave data archive practices
- increasing the push, and improving the strategy, for data sharing
- driving innovation in the development of new ocean resource industries such as offshore aquaculture and tidal energy, in the context of the new Blue Economy CRC
- designing models for tropical cyclone wind and waves for northwest Australia
- integrating Bayesian statistical methods with physical models to predict solitons to provide industrial tools for decision-making under uncertainty
- improving short-term wave forecasting algorithms
- using ocean models for safety and mission success from a Naval perspective
- using of predictive tools to locate containers lost at sea and which pose dangers to maritime traffic
- seasonal forecasting to manage the impacts of extreme ocean temperatures on Australian marine industries
- product development to support the future management of the Great Barrier Reef, including safety for shipping within the Park
- products to verify sea states for the efficiency and safety of port operations.

Industry needs

Australian perspective

Industry can play a significant role in data sharing capabilities. The Australian Forum for Operational Oceanography (FOO) recommends that industry members establish the business case for enhanced data sharing in the Australian region, particularly the North West Shelf (FOO, 2019). The met-ocean committee of the International Association of Oil and Gas Producers (IOGP) provides a mechanism to explore this further (FOO, 2019).

Fast flowing offshore currents that are generated during both positive (high coastal water levels) and negative (lowered coastal water levels) storm surge events can have a significant impact on offshore structures (Side et al., 2013). Also of interest to offshore industries are "weather windows", which allow for the deployment, operation and maintenance at offshore structures to be conducted safely (Side et al., 2013). Overall, marine managers are increasingly aware of the relevance of the disclosure of climate change related risk over the 30+ year planning horizon need to address risks to the blue economy (FOO, 2019).

From 2011 to 2013, the National Climate Change Adaptation Research Facility (NCCARF) commissioned a research project into 'Enhancing the Resilience of Seaports to a Changing Climate'. The study addressed three key work packages: 1) understanding future risks; 2) functional resilience of the port environs; 3) structural resilience of core port infrastructure (McEvoy and Mullett, 2013). The sourcing and interpretation of future climate information for that work proved to be a considerable challenge. The data required to deliver to each of the work packages were not available from the state-of-the-art climate services (CSIRO's Climate Futures). In particular, they noted the concerns of the port authorities were predominantly on the seaward-side (moving and mooring, loading and unloading ships), which are most affected by current climate variability. They found that future risk information on the climate-related variables (wind, wave, currents) were not available from the available services (McEvoy and Mullett, 2013).

International perspective

The ECLISEA project reviewed the data and information needs of several offshore sectors including offshore energy and shipping in Germany, Spain, France and Greece (ECLISEA, 2019). The offshore energy sectors were mainly renewable energy sectors such as offshore wind, waves and tides. Information needs were mainly about present climate information such as wind speed and extremes, storm surges, waves, currents, thermodynamic data and precipitation as well as forecasts for extreme events.

However, climate change information about future storm intensities and technical and economic data on future wind energy potentials was deemed important. Obstacles for the uptake of climate data were also identified and included perceived unreliability of climate change scenarios together with large uncertainties. The industry appeared to not understand how to work with climate change data, citing their data needs as being 24/7.

For the shipping sector, weather and climate data was important for day to day operation and navigation including early warning of extreme weather events. Climate information was seen as important for climate adapted port management, port planning, and construction projects. Again, obstacles included large uncertainties in climate change data, a mismatch in the temporal scales of present weather forecasts and projections for many decades ahead and insufficient staff to implement climate adaptation measures.

Climate change has been recognised as causing hazards for the offshore oil and gas industry from both slowly evolving changes as well as acute changes with the level of vulnerability being specific to the type of asset (Brown et al., 2019). Interaction of different changes in climate can create risks including impacts on primary energy production, energy transformation, energy demand as well as energy transportation, storage and distribution. Changes in wind and wave speed and direction as well as variability can impact offshore wind generation and may also have a significant impact on wind design loading of offshore structures (Bisoi and Haldar, 2017; Brown et al., 2019). Sea level rise and increases in storm severity, including changes in wave height and storm surge may increase loading on offshore platforms, especially if the air gap (the distance between the water level and the bottom of the deck) is significantly reduced (Brown et al., 2019). Wave climate change has also been shown to impact the design of ships (Bitner-Gregersen et al., 2013). In order to prevent hull girder failure, steel weight of the deck in the midship region should be increased by 5–8 % if the extreme significant wave height increases by 1 m (Bitner-Gregersen et al., 2013). However, the ability to avoid of adverse extreme wave conditions in the future in view of more accurate weather forecasts could also see design criteria relaxed in the future.

Engagement needs

Australian perspective

A subgroup of the FOO, the Surface Waves Working Group, has representatives from all pillars of the forum. It notes that more engagement between industry, service providers and Defence would be beneficial for Australian offshore industries (FOO, 2019). To this end, providers should engage end-users in any product development (FOO, 2019).

4.2 Review of services for offshore industries

Australian perspective

For the seaports sector, following the NCCARF seaports climate resilience study, the Climate Smart Seaports tool (McEvoy and Mullett, 2013) was developed (https://code.google.com/archive/p/climate-smart-seaports/). This enables interested users to begin the process of a climate risk assessment to Australian ports, designed for use primarily by Ports personnel who make decisions around long-term port planning for infrastructure, assets and management systems. Climatological data is taken from CSIRO and the Bureau of Meteorology public archives. It makes use of the CSIRO Climate Futures tool, for different NRM regions, for three different time frames, and is constrained to exploring climate variables (temperature, rainfall, wind speed, relative humidity, and sea-level rise) which limits applicability for seaward-side port operations.

These climatological data are combined with trade, population and port specific data to round out their analysis. The application creates a ‘workboard’ to gather this data, and then create reports and publish them, making them accessible and searchable on the ‘Research Data Australia’ (http://researchdata.ands.org.au), Australian National Data Service (http://www.ands.org.au).

For the marine renewable energy sector, the Australian Wave Energy Atlas provides Australian wave energy resource data developed by Hemer et al. (2017b). It highlights that Australia has arguably the largest wave resource of any country in the world. However, owing to the distribution of the Australian electricity grid, only a fraction of the resource is accessible (within 50km of Australian grid). The Atlas is easy to use, has processing capability and many other features to support future developments in Australia (Hemer et al., 2018).

The Australian Wave Energy Atlas is hosted by the Australian Renewable Energy Mapping Infrastructure (AREMI) and is openly available to all users via (http://nationalmap.gov.au/renewables/#share=s-gGd5ztFcxe2ysy9f).

Features of the Atlas:

- easily accessible – integrated within the publicly available web-based Australian Renewable Energy Mapping Infrastructure (AREMI) tool
- easy-to-use format
- dynamic processing capability enabling users to undertake analysis and processing of the data in different ways according to the information they require
- fast processing times
- compatibility with other datasets and portals by strict adherence to Open Geospatial Consortium (OGC) standards
- delivers resource information (e.g., Figure 4) alongside complementary spatial information, including marine spatial constraints (e.g., complementing and competing marine uses), supporting marine infrastructure (e.g., ports and facilities) and supporting electricity infrastructure (e.g., electricity network)
- novel portal design that addresses the challenge of managing data from multiple sources, and ensures the Atlas is presenting data that is the most up-to-date, and
- a detailed technical report about the resource assessment process underpinning the information provided by the Atlas.

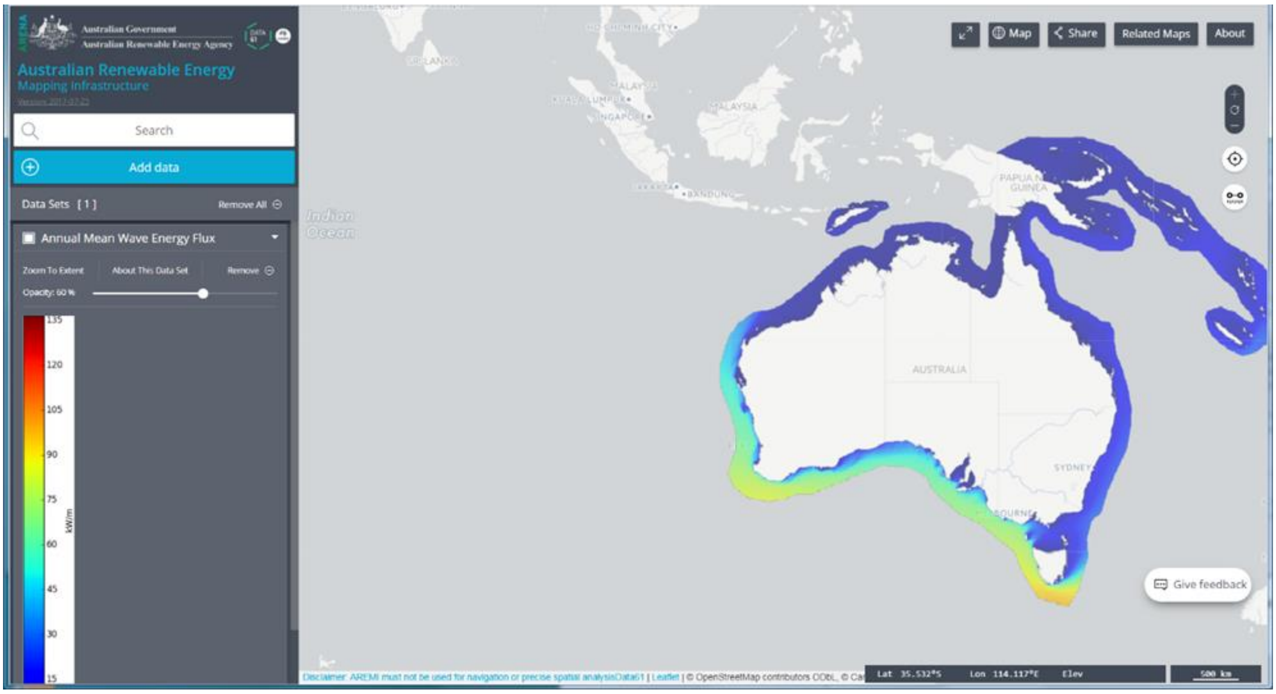

Figure 4. A screenshot of the Australian Wave Energy Atlas (AWavEA), displaying the Annual Mean Wave Energy Flux (in kW/m) and key, as incorporated into the Australian Renewable Energy Mapping Infrastructure (AREMI).

International perspective

The data portal of the Coastal Observing System for Northern and Arctic Seas (COSYNA) provides meta data, observed data and model data about currents, waves, sea surface temperature, salinity and chlorophyll (ECLISEA, 2019). The portal does not provide future climate projections data (https://www.hzg.de/institutes_platforms/cosyna/data_management/index.php.de).

4.3 Regional perspective

The offshore industries of key focus in this section relate to energy extraction and includes established oil and gas industries as well as emergent offshore wind projects, and precommercial trials of marine renewable energy particularly for wave and tidal energy. Oil and gas industries in Australia are located primarily in Bass Strait, offshore Western Australia and the Timor Sea.

Tide and wave energy resources in Australia together with examples of technology trials are shown in Figure 5 and indicates that Australia’s rich wave energy resource extends from the southwest to the southeast coast. The tide energy resource is focused along the coastline of the northern half of the continent including Torres Strait as well as in the strong tidal current regions adjacent to Flinders and King Islands in Bass Strait.

A number of tidal and wave energy trials have taken place around the coastline as indicated in Figure 5 with the southwest WA coast, Bass Strait and the coast to the west and the NSW to southeast Queensland coasts being the main areas of wave energy trials while Torres Strait the NSW, Bass Strait and locations on the northwest coast and Darwin being the main areas of tidal energy trials.

Australia's first offshore wind farm, the *Star of the South Project*, has been proposed for a location offshore of Port Albert and McLoughlins Beach in Victoria's southeast and is currently in its feasibility phase. The proposed $8B AUD, 250 turbine wind farm with 2 GW capacity has the potential to provide nearly 20% of Victoria's current power supply and will connect via approximately 25 km of submarine and 70km of underground cables to existing electricity networks in the Latrobe Valley.

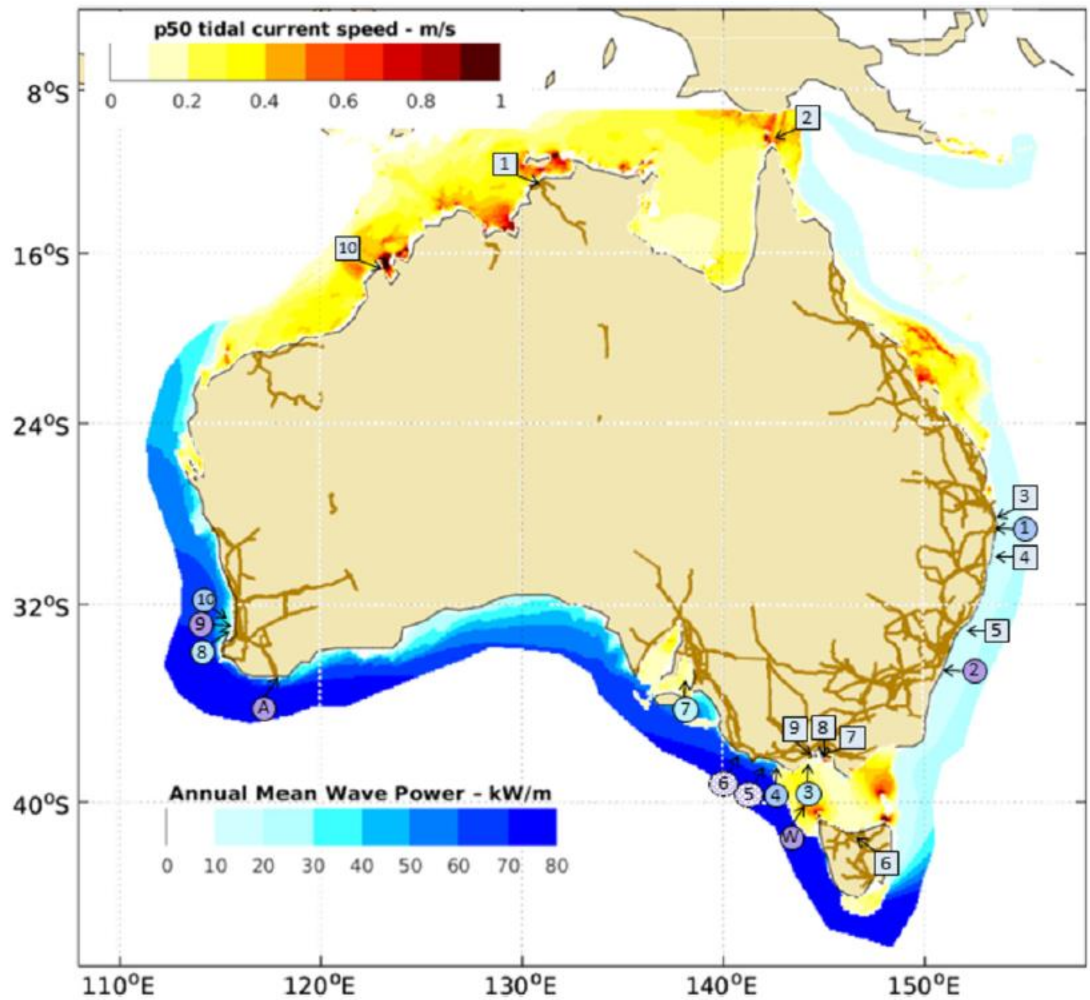

Figure 5. Map displaying the distribution of Australia's resources for wave energy (blue colours) and tide energy (yellow to red colours) (source: Hemer et al, 2018) based on assessments of wave energy (Hemer et al. 2017) and tidal energy (Behrens et al. 2012). The tidal resource is derived from a coarse resolution model, and underestimates available resource, but demonstrated distribution of the most energetic regions. Wave and tidal resource areas are almost mutually exclusive. Circles (squares) represent locations of wave (tidal) energy developments. Numbers correspond to projects listed by Manasseh et al. (2016) with two additional projects being (A) Carnegie Clean Energy Ltd's CETO6 Albany Wave Project, and (W) Wave Swell Energy Ltd's bed mounted Oscillating Water Column (OWC) project planned for King Island. Distribution of Australia's transmission lines are displayed.

5 Conclusions

5.1 Summary

Our review of stakeholder needs for the three sectors considered the researcher, management and engagement needs. For the coastal climate services, researcher needs included better understanding of the interaction of coastal physical processes particularly in the context of their interaction with coastal geomorphology. There was also a need to understand these processes at higher spatial resolution, although advancements in these areas can be challenged by lack of underlying datasets and observations. For the marine sector, a high priority was for better understanding of physical ocean processes at higher spatial resolution while for ecological applications, more research on impact thresholds was deemed necessary. The offshore sector identified as high priorities more research on met-ocean extreme conditions and forecasting of variables such as tropical cyclones and waves.

Sea-level rise projections were the most established and wide-spread of the climate change information used for coastal land-use and adaptation planning. Additional information required to develop actionable information from sea-level rise projections included extreme sea level and land-elevation data, but their availability and accuracy depended on location. Projected changes to extreme sea levels caused by storm surges and waves were not as widely available in Australia as they are elsewhere. While projections of storm surge and waves exist, uncertainties have not been fully evaluated and the processing required to deliver projections to stakeholders had not been undertaken. For the marine and offshore sectors, information and activities related to climate change adaptation were not well established.

The role of management was recognised as necessary to reduce impacts and enable adaptation planning. Coordination across multiple sectors and industries and stakeholder consultation to clarify information needs was deemed necessary to ensure that decisions and tools to support management decision-making were fit for purpose.

Tools and services supporting coastal management and planning are well established in Australia at the national scale. Information relating to extreme sea levels and associated coastal impacts are available in specific locations where targeted studies have been undertaken.

Providing information at the national scale presents an opportunity for Project 5.8. Services for marine and offshore industries were more limited and tended to focus on providing data over short outlook periods. Information on longer (decadal to multi-decadal) timescales was limited and further work is required to establish whether and how these sectors would utilise such data if it was made available.

The regional perspective sections in each section have provided information about the Australian coastal, marine and offshore regions to help prioritise locations where further focused study could be of benefit. Considering socioeconomic, physical and climatological factors, coastal regions of particular relevance include the eastern coastline (including the Great Barrier Reef) because of its beach attractions together with potential for higher sea level rise in the future which will exacerbate coastal hazards. Locations along the southeast coastline are also of interest because of the potential for wave climate change together with non-linear interactions between multiple climate drivers to influence coastal hazards.

From the marine sector, the regions that have been identified, with guidance from the literature, are quite large in areal extent, and in total, cover a big proportion of Australia's marine environment. However, several additional studies have focussed on more local areas and communities. Case studies of coastal communities have been conducted in three of the regions we have identified (van Putten et al., 2014b): Geraldton (Western Australia), St Helens (Southeast Australia) and Bowen (Great Barrier Reef). The study finds that the structure and functions of these coastal communities are transforming, partly due to shrinking fishing industries, on which global warming has had an impact.

The vulnerability to climate change of the marine ecosystems linked with these communities has also been assessed (Metcalf et al., 2015). Communities of greater population tend to have higher adaptive capacity, whereas there is greater marine resource dependence in smaller communities (Metcalf et al., 2015). Governance interventions in responding to extreme events have been largely reactive to date, but planning for increasing marine vulnerability will provide stronger buffers against crossing ecological and social tipping points (Serrao-Neumann et al., 2016).

In terms of offshore industries, oil and gas industries in Australia are located primarily in Bass Strait, offshore Western Australia and the Timor Sea. Marine renewable energy is at an early stage of technical development, but numerous tidal and wave energy trials have taken place around the coastline. For wave energy the southwest WA coast, Bass Strait and the coast to the west and the NSW to southeast QLD coasts have been the main areas of trials whereas for tides, Torres Strait, Bass Strait, locations on the northwest coast and Darwin have been the main areas of trials.

5.2 Next steps

The aim of this review has been to identify the information needs of stakeholders as well as the tools that have been developed to disseminate information for users. Whilst it is not feasible that Hub Project 5.8 addressed or adhered to each of the identified stakeholder needs, we have nevertheless aligned with many of them. The next steps will involve using this information in the development of case studies that package and showcase the newly developed information. This will be undertaken for selected locations around Australia with the aim to provide the most compelling impact stories based on the regional review undertaken in the previous section.

For the coastal sector, priorities will include the development of sea level rise projections that include available updated components (e.g. a potentially larger contribution to sea level rise from Antarctica due to dynamical ice sheet losses) as well as developing projections of wave climate change from available global datasets. These can be applied to modified extreme sea level baselines that have recently been updated to include wave setup at the national scale.

Part of Project 5.8 analyses the representation of marine heatwaves around Australia in the next generation of global climate simulations: the Coupled Model Intercomparison Project, phase 6 (CMIP6). The CMIP6 models generally have higher spatial resolution than the previous generation (CMIP5), which is useful for smaller scale regional analysis. There are early indications that the intensities and durations of marine heatwaves are improved in CMIP6 with respect to CMIP5 (Grose et al., 2020). Project 5.8 will deliver a first look at projections of marine heatwaves in the Australian region from CMIP6.

Increasingly, the offshore industrial sector is aware of the need for climate services to assess resilience to known climate risks. Awareness raising of the potential risks and opportunities for this sector can be achieved by providing regional coastal outlooks of potential changes to met-ocean conditions that will arise from changes in atmospheric circulation patterns due to climate change. Expansion of scope of application of met-ocean climate variable projections to other maritime and offshore industry sectors can be efficiently achieved through tailoring of the variables being compiled for the coastal climate applications.

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