White Paper: 15 priorities for Australian wind-waves research

A publication from the Australian Forum for Operational Oceanography Surface Waves Working Group*

* Lead, Writing Team and Contributors listed at end of document

November 2018

Abstract

The Australian marine research, industry and stakeholder community has undertaken an extensive collaborative process to identify the highest national priorities for wind-waves research. This was done under the auspices of the Forum for Operational Oceanography Surface Waves working group. The main steps in the process were firstly, soliciting possible research questions from the community via an online survey; secondly, reviewing the questions at a face-to-face workshop; and thirdly, online ranking of the research questions by individuals. This process resulted in 15 identified priorities, covering research activities and the development of infrastructure. The top 5 priorities are 1) Enhanced and updated nearshore and coastal bathymetry; 2) Improved understanding of extreme sea-states; 3) Maintain and enhance in situ buoy network; 4) Improved data access and sharing; and 5) Ensemble and probabilistic wave modelling and forecasting. In this paper, each of the 15 priorities is discussed in detail, providing insight into why each priority is important, and the current state-of-the-art, both nationally and internationally, where relevant.

1. Introduction

As an island nation deriving major social, economic and environmental benefits from its coasts and oceans, Australia has the potential to harness significant advantages with an enhanced focus on operational oceanography. Realising this, in 2015, a team of scientists and managers came together and established the Australian Forum for Operational Oceanography (FOO). The FOO provides a forum for discussions relating to operational oceanography, including requirements of stakeholders, industry and interested parties, and for scientific and technical discussions of common interest to practitioners working in relevant areas or users of relevant services. Very importantly, the FOO stakeholder base includes representatives from the four key 'pillars': marine industries, service providers, government agencies and research organisations.

At the first meeting of the FOO in 2015, wind-waves were identified as a priority area and a Working Group (WG), comprising members with expertise in wind-waves from all four 'pillars' of FOO, was subsequently formed. One of the activities of this WG was to define the key priorities relating to wind-waves research for Australia. Wind-waves research is typically spread over different disciplines (e.g. oceanography, meteorology, engineering, coastal science) with application across further disciplines. A concerted effort was required to bring the community together and undertake a collaborative approach to setting national research priorities. This paper describes this process and presents the outcomes.

The intention of publishing this synthesis of the WG findings is to provide guidance to the research community, and to funders of research or research infrastructure in relation to the present priorities. This process was undertaken in late 2017/early 2018 and ideally it would be regularly revisited on a 3- to 5-year cycle. While driven by Australian needs, it is likely that the results of this extensive consultation and evaluation process may also be applicable to international wind-wave research priorities.

2. Outline of process

The process to derive the research priorities loosely follows that described by Sutherland et al (2011). This is a widely used process for developing collaborative research priorities. Its key features are that it engages both researchers and stakeholders in an iterative process of priority-setting and it is highly democratic. Some examples of other priority setting activities that have followed this process can be found in global agriculture (Pretty et al., 2010), palaeoecology (Seddon et al., 2013), marine pollution (Vegter et al., 2014) and ocean research for Canada (Fissel et al., 2012).

For the present priority-setting activity, the main steps were:

1. Soliciting possible research questions via an online survey
2. Reviewing and editing the questions at a face-to-face workshop
3. Individual online ranking of the research questions

The first step was to generate a 'long list' of possible research priorities from the community. This was undertaken by inviting members of the Australian marine wave research, industry and stakeholder community to take part in an online survey. A total of 360 invitations were emailed to participants drawn from a) the FOO mailing list, b) a list of researchers who had previously attended one or more national wave research symposia and c) professional networks of the Steering Committee (a 5-member subset of the WG).

Participants were asked to enter up to 10 wind-waves related research activities that they thought the Australian community should address over the next 5-10 years. They were provided with the guidance that the level of effort for each activity should be achievable by 1 or 2 researchers within a few years. They were also asked to enter up to 5 priorities for new or enhanced infrastructure that might be needed to achieve this research.

There were 69 respondents to this survey (a 19% response rate), of which just over 50% were from research organisations, and the remainder identified as either private industry, service provider, or government. In terms of geographic distribution, the highest participation came from Western Australia (23 respondents), then Victoria (18), New South

Wales (11), and Queensland (9) with 4 participants from Tasmania, 2 from the Northern Territory, 1 from South Australia and 1 international.

In total, these 69 participants provided a total of 444 priorities, including 296 research suggestions and 148 infrastructure suggestions. Not surprisingly, there was found to be considerable overlap in the suggestions entered, so these 444 priorities were collated and merged where appropriate to provide a final long-list of 209 priorities. These were then loosely sorted into 11 themes: Climate Variability and Change; Data and IT; Interactions and Extremes; Physics and Dynamics; Renewable Energy; Strategy and Policy; Modelling and Forecasting; Nearshore and Coastal Hazards; Traditional Observation; Extended Observations and Observations Research.

A face-to-face workshop to review and refine the identified 'long list' of priorities was arranged to coincide with a national wind-waves research symposium (Lowe et al., 2018). The reviewing process was undertaken in several parallel round-table sessions where each round-table was asked to discuss the priorities in one category and edit, clarify and merge them if necessary. After this review process, 155 priorities remained. Each round-table then voted on the priorities in their category, with individuals permitted to vote to retain up to 50% of the priorities. In order to permit all symposium attendees to contribute to all categories, additional online voting was undertaken after the symposium. This online voting was also extended to those in the research community who had contributed research priorities at stage one but had not attended the symposium. A total of 58 people voted in this round.

After this predominantly researcher-based ranking, the ranked priorities were reviewed by the SC, with some minor editing and further merging as necessary. In this process, approximately one third of the remaining priorities were eliminated, comprising those that received the lowest rankings from the first round of voting. Importantly, a limited number of these lower ranked priorities were retained, as they were deemed to be potentially of interest to the wider stakeholder community. At this stage, a total number of 114 priorities remained, and they were re-sorted into the following 8 categories: Modelling; Forecasting; Observations; Community; Ocean Renewable Energy; Nearshore; Physics; and Climate. A second round of online voting was then undertaken, specifically targeting the industry and stakeholder community. A total of 22 people participated in this second online survey.

A number of options were considered for techniques to produce a final ranking. In particular, decisions needed to be made about a) whether to treat the two online surveys (researcher-based and stakeholder-based) with equal weight, or to treat all individuals with equal weight, and b) whether to use the priorities with the highest rankings overall as the 'top' priorities, or use the highest priority (or priorities) in each category.

It was ultimately decided to treat all individuals with equal weight, rather than give equal weight to the two surveys. This is partly due to the different number of participants in each survey, but also because there were a reasonable number of contributors to the researcher-based survey (due to their attendance at the symposium) who would more accurately identify as stakeholders. Overall, the ratio of the contributors to the final ranking is approximately 60:40 researcher to stakeholder.

Secondly, it was decided to use the total number of raw votes to guide the prioritisation rather than the highest number of votes within each category. The drawback of this is that priorities within the categories where fewer people provided input (voting in a category was optional) did not appear in the final rankings. However, it was seen as the best way to determine what the whole community thought was important. In addition, this reduces any impact that the selected categorisation might have had on the results (see section 4 for further discussion of this issue).

3. Research Priorities

The 15 top ranked priorities were selected and divided into two 'tiers' - a first tier with 5 priorities and a second tier with 10 priorities. The choice of this number of priorities was guided by members of the WG and a general aim to limit the number of priorities overall. These top ranked priorities are presented in Table 1 and discussed in more detail below.

Table 1 Summary of the top ranked research priorities. Priorities marked with an asterisk refer to items designated as 'Research'. See section 4 for further discussion on this.

Tier 1	
1	Enhanced and updated nearshore and coastal bathymetry
2*	Improved understanding of extreme sea-states
3	Maintain and enhance *in situ* buoy network
4	Improved data access and sharing
5	Ensemble and probabilistic wave modelling and forecasting
Tier 2	
6*	Advancement of remote sensing capabilities to measure wave conditions in coastal environments
7*	Improved understanding of wave-induced currents and transport
8	Long-term beach / coastline monitoring
9	Nearshore modelling and forecasting
10	Development of wave data assimilation
11	Development of a standardised data and QA/QC specification for wave observations
12	Better engagement of maritime industries with research
13*	Improved understanding and prediction of coastal wave impacts
14*	Improved understanding of the effect of future climate variability and change on coastal areas
15*	Improved modelling of swell propagation

Tier 1 priorities

3.1. Enhanced and updated nearshore and coastal bathymetry

Wind-waves research has application offshore, across the shelf (e.g., supporting offshore industry, biodiversity assessments and fundamental science associated with fluxes across the air-sea interface and surface ocean), and at the coast (e.g., coastal zone – infrastructure and environmental – planning and management, coastal hazards, national security). The property of waves on the inner shelf and at the coast is heavily dependent on the characteristics of the near-shore and coastal bathymetry (and other morphological characteristics, for instance habitat/roughness, etc). However, these characteristics in the nearshore-coastal band that lies between terrestrial topography (accurately measured using aerial LiDAR techniques) and shelf waters (capable of being measured by ships using multi-beam data) are generally poorly resolved.

The coastal zone presents a challenging environment for the cost-effective measurement of bathymetry with the necessary spatial resolution and uncertainty to inform the propagation of wave energy at a scale relevant to local applications. Recent advances in mapping technology, such as aerial bathymetric light detection and ranging (LiDAR), sometimes referred as Laser Airborne Depth Sounder (LADS), allow the rapid collection of high resolution, full coverage bathymetry information over large geographic extents in nearshore waters (to depths of up to 80m in clear waters). This technology has the potential to provide detailed information on seabed bathymetry and geomorphology that would, otherwise, be difficult to collect using other approaches. Bathymetric LiDAR has been collected for wide stretches of Australia's coast; a 2011 audit identified high resolution bathymetry was available for 20% of Australia's coastal waters (with depths less than 30m) – although 60% of this was in remote or very remote regions associated with shipping lanes or exploration activities (Wilson and Tickle, 2011). Whilst such approaches have the ability to capture the spatial variability in bathymetry, the cost of acquisition often means that they remain a static dataset for large area surveys.

Furthermore, nearshore bathymetry can be highly dynamic, changing on synoptic time-scales in energetic environments. In the dynamic coastal zone, a static assumption can lead to errors in bathymetry of order of metres, which in-turn may lead to similar orders of magnitude error in predictions of wave-driven coastal sea-level and prediction of long-shore currents and thus coastal sediment budgets.

It is a substantial challenge to provide accurate, cost effective bathymetric measurements over the extent of Australia's coasts. Manual surveys of the nearshore/coastal/littoral zone bathymetry (e.g., jet-ski sounding surveys, coastal vessels) are time consuming and typically restricted to small regions of interest (Schimel et al., 2015). Autonomous vessel platforms for bathymetry acquisition show promise in coastal zone applications but are likely to be similarly impacted by local hazards (breaking waves, navigation hazards) as manned operations, thus their suitability for applications is likely to be program and location specific

(Raygoza-Barahona, 2017). Satellite remote sensing techniques (e.g., Wackerman et al., 1998; Jagalingam et al., 2015, Chybicki, 2017) to derive bathymetry provide a potential means, however they will have limited application due to spatial resolution, difficult in resolving seabed in turbid conditions, cloud-cover and reduced certainty of bathymetry soundings (Collin et al., 2018). Bathymetric inversion systems, i.e. resolving bathymetry from observed surface wave motions, are being trialed from a range of sensors (e.g., extending the cBathy research of Aarninkhof et al., 2003, Holman et al., 2013). These are being implemented using fixed platform systems (e.g., Argus; Aarnikhof, 2003), which can resolve coastal bathymetry at high temporal resolution, but are limited to specific locations. Unmanned Aerial Vehicles provide a means to apply this technology (Matsuba and Sato, 2018), capturing sub-tidal bathymetry at similar spatial resolution to that from an Argus system, but can be shifted between sites. The considerably lower costs of such a system offer greater spatial coverage than fixed infrastructure, and allow repeat surveys to capture pre- and post-storm, or seasonal, bathymetric profiles. Spatial extent covered by such a system is likely to have a small spatial footprint compared to approaches such as LiDAR.

Nationally, Australia is developing a coordinated approach to seabed bathymetry acquisition. Traditionally, the Royal Australian Navy Hydrographic Service (RAN HS) has been responsible for the wide area, bathymetric survey of Australia's coastline and littoral waters. In early 2017, Defence stood up a project called SEA2400 outlining a capability statement for the the HydroScheme Industry Partnership Program (HIPP). Planned to commence in Q4 2019, the HIPP will be a commercial hydrographic survey program delivered by Industry to support the legislated requirements of the National Survey Function. Taking into consideration the data acquisition options available, we can expect over 90% of the effort will need to be undertaken in the coastal zone in water depths less than 100 m.

Capturing an enhanced and updated Australian nearshore and coastal bathymetry is a clear priority for the wave research community, recognising the importance of this key parameter to how waves transform as they propagate towards and across the shoreface. Challenges remain in identifying and developing appropriate technologies that can provide cost-effective, accurate measurements of near-shore and coastal bathymetry. Another challenge relates to use of a common datum to enable 'stitching' of terrestrial and marine elevation databases, which has been an outstanding issue for littoral zone research. Seamless bathymetry/topography datasets are not typically compiled despite the fact that they are vital for most coastal modelling applications. See for example Wilson and Power (2018).

Meeting such challenges, and delivery of a high accuracy national coastal elevation dataset, spanning +/- 50m from sea-level, has relevance well beyond that of the waves community, significantly improving our ability to model other hazards such as tsunami and storm surge, as well as providing information to improve marine management including marine planning, monitoring, research and emergency response. The importance of improving available topographic and bathymetric elevation data to underpin adaptation planning in Australia has been recognised for some time (COAG, 2006) and its prioritisation here again recognises this. International programs such as the Nippon Foundation – GEBCO Seabed 2030 (Mayer et al., 2018) illustrate the wide spread coastal, shelf and ocean mapping applications required to support justification of this priority task at the national scale.

3.2. Extreme sea-states

An ability to accurately model and predict extreme sea states is critical for a range of coastal and offshore activities including: engineering design, beach erosion and stability, coastal and offshore shipping and nearshore flooding. Although Australia can obviously benefit from the work of the international wave research community, this is a continent with a unique and diverse wave climate. The southern coast of Australia faces the Southern Ocean, the most consistently rough ocean in the world (Young, 1999). Southern Ocean low pressure systems regularly impact our southern coast producing a wave climate with consistently high sea states. On both the north-east and north-west coasts the wave climate is totally different, with a mostly benign wave climate but punctuated by intense tropical cyclones which generate waves as large as any location on the planet (Young, 2006; Young, 2017). The central east coast is impacted by decaying tropical cyclones from the north and intense east coast lows which develop off NSW. The unique nature of this wave climate means that wave research focussed on the Australian region is critical – there is simply no other country which faces such a diverse range of wave climates.

The determination of design extreme sea states relies on statistical predictions for a given probability of occurrence (Alves and Young, 2003; Vinoth and Young, 2011). This requires long term time series of wave conditions at the required site. This can be obtained from spectral wave models e.g. Wavewatch III (Tolman and the WAVEWATCH Dev Group, 2014), in-situ observations or remote sensing/satellite measurements. Small errors in our ability to predict or measure storm waves can translate into major uncertainties in extreme value estimates. As a result, there is a continued need to: enhance wave models, extend the duration and geographic spread of in-situ observations (e.g., buoy networks), extend the duration, spatial density and accuracy of satellite data and refine extreme value statistical projections.

These are all areas where Australia has an enviable reputation. Some of the very earliest spectral wave models were developed in Australia (Sobey and Young, 1986). These models were developed specifically to predict tropical cyclone generated waves. Australian researchers also played a significant role in the development of the first third-generation wave model (WAM – WAMDI Group, 1988). Further refinements in the development of source terms for each of the physical processes in such models have had significant inputs from Australian researchers: atmospheric input (Babanin et al., 2007; Donelan et al., 2006); nonlinear interaction (Banner and Young, 1994); wave breaking (Young and Babanin, 2006) and bottom friction (Young and Gorman, 1995). Australian implementations of these international community models now run operationally at the Bureau of Meteorology, at both global and regional scales (Durrant and Greenslade, 2011) These models provide the capability to predict extreme sea states to increasing accuracy and provide the basis for the construction of long term hindcasts of wave conditions suitable for statistical extreme value analysis, e.g. Durrant et al. (2014).

The establishment and maintenance of a coastal buoy network for a country with such a long coastline is discussed further in section 3.3. In relation to extreme sea states, there are doubts about the ability of floating buoys to accurately measure wind speed and wave height under extreme conditions (Bender et al., 2010) however, they still represent the best (only) ground truth available.

Satellite networks provide the potential for truly global wave measurement. For a continent with a coastline as long as Australia, the potential advantages are huge. Again, Australia has played a significant role in the development of such systems (Zieger et al., 2009; Young et al., 2017) and particularly the use of these systems in determining extreme value estimates (Alves et al., 2003; Vinoth and Young, 2011). For use in determining extreme wave conditions, it is necessary to compile long term multi-platform satellite databases. This means that the various platforms need to be carefully calibrated and validated to ensure a consistent dataset. Such systems are now becoming available. Although, exactly how one can optimally use satellite data for extreme value prediction is still an active research area, the potential is clear. This will have significant advantages for the Australian continent.

Developments in each of these areas: numerical modelling, buoy networks, satellite datasets and statistical analysis will enhance the ability to predict extreme wave conditions around Australia.

3.3. Wave buoy network

As noted in the previous section, in situ wave observations are a critical component of Australia's marine observing system, providing important verification data for national and regional scale models, calibration and validation data for satellite sensors, and data to support offshore and coastal industry and recreational pursuits. The publicly available national wave data network for Australia currently consists of approximately 35 wave platforms distributed around the Australian coastline (Greenslade et al., 2018), operated by 7 different agencies, predominantly State Governments (Qld, NSW, and WA), Bureau of Meteorology, and Industry contributed data (Pilbara Ports, Woodside and ESSO). The depth of deployment for these buoys ranges from 10 m at the shallowest site (Albatross Bay, Qld) to 125 m at the deepest site (North Rankin, WA). This is a disconnected network, in that each custodian operates their set of buoys independently, with little coordination between agencies. As a consequence, we see differences between agencies in the sampling characteristics and variables archived. These differences are introduced, as different buoys have been targeted to meet the needs of different applications or industries, which in many instances have been significant contributors to operational costs. Standardisation of these processes would add value to the network and is discussed further in section 3.11.

Strengths of the current network are the relatively broad coverage of data available, and in some instances long temporal records are available. A consistent platform (Datawell waveriders) across most sites may also be a potential strength, given current studies demonstrating variability in wave measurements from different sensors (Jensen et al., 2015). In addition, recent research investigating long-term changes in buoy derived records in the US NDBC wave records have identified significant homogeneity issues that come about due to poorly documented transitions between buoy platforms (Gemmrich et al., 2011). Transition between platforms/models from a consistent manufacturer (i.e., Mark I, II, ..V) may be easier to resolve in any rigorous assessment of the available long-term records from Australian buoys.

Whilst the network has a relatively broad coverage, some notable gaps are present. Greenslade et al. (2018) analyse the CAWCR wind-wave hindcast to determine the extent to which Australia's waters are represented by the current distribution of wave-rider buoys. They show the network represents most features of the wave climate relatively well, aside from gaps in eastern Tasmania/Bass Strait, and across the Northern Territory. They assess variability in the monthly mean record – capturing seasonal and longer term variability, but are unable to resolve to what extent synoptic scale features are represented. Directional measurements have been completely absent along the southern margin of the continent between Esperance, WA and Eden, NSW, however the current transition of Bureau of Meteorology buoys to directional buoys at Cape de Couedic, SA and Cape Sorell, W. Tas, will in part overcome this limitation. Significant wave data holdings exist in private industry around Australia, particularly by industry supporting the oil & gas industry on Australia's north-west shelf. Establishing shared data arrangements across research, government and industry to address national challenges would ensure optimal benefit is gained from public and private infrastructure investment.

Recent developments have seen the emergence of smaller and lower cost wave buoy instruments (e.g., Datawell 'mini' wave rider and Spoondrift Spotter, Smit et al., 2017). Several Australian research groups and State agencies have purchased these devices to support process studies, event monitoring and to assess performance, but longevity has not yet been demonstrated for a sustained observation system.

In relation to satellite calibration, a limitation of the current distribution of operational buoys is the proximity that all have to the coast. Wave information is being increasingly retrieved from satellite remote sensing platforms (altimeter and SAR). The presence of land within the satellite footprint degrades the wind-wave signal, and is therefore a critical limitation for calibration and validation applications. With the Australian buoys being the most significant network of in-situ wave observations in the southern hemisphere, off-shore buoys for calibration/validation of the existing (altimeter, SAR) and future (e.g., CFOSAT-SWIM, ESA proposed SKIM) wave measuring satellite remote sensing platforms would be an invaluable addition to the network. On the other hand, in relation to wave model verification, models are being developed and implemented at higher and higher spatial resolution due to the increased availability of computational resources. This brings wave model data closer to the coast, in shallower water, and thus there is an increasing need for sources of verification data closer to the coast.

3.4. Data access and sharing

In order to undertake analyses of sea-state on a national, regional scale or local scale there is a need for access to data with a broad spatial distribution. Depending on the application, potential data sources may include in situ buoy observations, remotely-sensed data, modelled wave data and bathymetry or coastline information.

The publicly available Australian wave buoy network does span a broad domain (notwithstanding the issues highlighted in Section 3.3), however, as noted previously, the infrastructure is operated by number of different agencies, some state-based, some federal and some provided by private industry. Presently, only the Bureau of Meteorology obtains a direct feed of buoy data from all agencies (Moltmann and Proctor, 2018) so it can be a cumbersome and time-consuming process to acquire a set of wave observations for any national- or regional-scale study. Furthermore, there is currently little consistency between agencies in relation to metadata, specific parameters archived, data processing techniques (see Section 3.11) etc. There is clearly a need for national integration of, and easy access to existing historical wind and wave observations.

The pursuit of this is an ongoing process, with numerous technical and political challenges. Recent positive steps have been undertaken by the Integrated Marine Observing System (IMOS) Australian Ocean Data Network[1] , which has commenced the process of seeing the public buoy data – both historical and near real-time – being made more accessible to the Australian marine data user community. This challenge also exists with modelled wave data. The CAWCR hindcast (Durrant et al, 2014) is a national wave climate dataset that is publicly available, however it does not meet requirements of all users and is updated only on an ad-hoc basis. Similar difficulties emerging from limited data management and delivery resources have been encountered at a regional scale in delivering modelled wave hindcast data for NSW to end users (Kinsela et al., 2014).

The international wave satellite remote sensing (SRS) community has exerted considerable effort, particularly via the GlobWave program which ended in 2014, in providing calibrated and validated SRS wave data streams to increase uptake of satellite derived surface wind-wave and swell data by the scientific, operational and commercial user community. Continued effort however is required to collect, calibrate and validate, and distribute ocean surface wave data for uptake by the Australian community, and more broadly. The IMOS SRS Surface Waves sub-facility is addressing this challenge, to strengthen Australian capability in wave remote sensing (currently focussed on altimeter and SAR data streams), support calibration/validation efforts in the Australian/Southern Hemisphere region, and facilitate uptake of data amongst local users.

Accessibility and sharing of bathymetry data is also an issue. This been challenging in the past due to the absence of a nationally coordinated program. AusSeabed[2] is a national initiative established to facilitate the collaborative collection and update of seabed mapping data within Australia's maritime jurisdiction. The initiative is a collaboration of Commonwealth, State and Territory entities, as well as partners from universities and industry, led by Geoscience Australia. This initiative has a strong emphasis on coordination

[1] portal.aodn.org.au
[2] ausseabed.gov.au

of shelf collected multibeam derived bathymetry, with the coastal zone remaining a critical gap. However, it does provide a framework to focus efforts for collection and coordination of data gathered in the near coastal zone.

3.5. Ensemble and probabilistic wave modelling and forecasting

Ensemble systems aim to provide not only a forecast of future conditions, but also the uncertainty relating to that forecast. Ensemble modelling in Numerical Weather Prediction (NWP) is based on the principle that in non-linear systems, large forecast errors can arise from small errors in initial conditions (or elsewhere in a model system). Traditionally, an ensemble forecast is created through perturbing initial conditions and evolving a number of dynamic models in time from those initial conditions.

One the main sources of error in wave forecasts is errors in the wind forcing (Cavaleri, 2009; Cardone et al., 1996; Durrant et al., 2013) although it may be noted that as atmospheric models improve, this is becoming a less dominant factor. Nevertheless, it is possible to capture the uncertainty in a wave forecast that is due to wind errors, by forcing a wave model with an ensemble of NWP forecasts. Another way to generate a wave ensemble could be to acknowledge that the wave model physics is not perfectly known, and perturbations could be incorporated in the wave model source terms.

Assuming the ensemble members are randomly drawn from the underlying probabilistic distribution, it is possible to provide probabilistic forecasts. These can be provided in several forms, e.g. *there is a 40% probability that SWH will exceed 5m*, or, *the SWH that has a 5% probability of being exceeded is 7.4 m*. These sorts of probabilistic forecasts can be very useful for decision-making.

Ensemble systems require very large computational resources and so are mostly run by centres with access to high performance computing systems. Internationally, ensemble wave forecasts are produced at ECMWF (Saetra and Bidlot, 2004), NCEP (Cao et al, 2009) and the UK Met Office (Bunney and Saulter, 2015). Within Australia, the Bureau of Meteorology has recently implemented an operational wave ensemble forecast system specifically for Tropical Cyclones (TCs) on the northwest shelf of Australia (Zieger et al, 2018). This system uses the 50-member ECMWF global atmospheric ensemble, bias-corrects the ensemble members for TC intensity and size (Aijaz et al, submitted), and runs 50 identical versions of Wavewatch3 (Tolman and the WAVEWATCH Dev Group, 2014) under the resulting bias-corrected winds from each ensemble member. In the near-term, it is likely that the Bureau will implement operational NWP ensembles on global, regional and smaller scales, which will provide the opportunity for a wider range of ensemble and probabilistic wave forecasts.

Tier 2 priorities

3.6. Advancement of remote sensing capabilities to measure wave conditions in coastal environments

Satellite remote sensing (SRS), using altimeter (Geosat, Geosat Follow-On (GFO), ERS-1, ERS-2, Envisat, Topex-POSEIDON, Jason-1-3, Sentinel-3A/B, Cryosat-2, SARAL/Altika, HY-2, Sentinel-6A/JasonCS), synthetic aperture radar (SAR; Sentinel-1A/B, and CNSA GF-3), and multi-spectral imager (Sentinel-2A/B) sensors, provides global wave parameters such as significant wave height, period, as well as directional ocean swell spectra.

SRS wave observations provide a measure of the spatial variability of wave climate, poorly captured by in-situ measurements. They are also the dataset most suited to resolving historical variability and change in wave climate on global scales (e.g., Young & Donelan, 2018). This strength has been recognised, with the newly established ESA Seastate Climate Change Initiative (CCI), which seeks to establish a coherent historical SRS derived wave record across sensors, ensuring consistent derived fields between missions.

SRS can generally provide good quality open ocean observations (noting that new sensors require validation and calibration) but as noted previously, the presence of land within the satellite footprint degrades the wind-wave signal, so SRS applications are limited to regions away from the coast. Recent satellite launches are attempting to address this, e.g. the SARAL/ALTIKA satellite incorporates a relatively small antenna beam-width which reduces the size of the altimeter's footprint, allowing wave estimates closer to the coast.

In addition to Satellites, waves are retrieved from other remote sensing platforms (i.e., shore mounted platforms, Unmanned Aerial Vehicles, and aerial surveys). Growth is seen particularly in coastal applications (from shore mounted systems, and increasingly UAV) to complement in-situ field measuring programs/process studies by providing a spatial distribution of wave properties on beach wide scales.

Approximately five shore mounted video systems (ARGUS or similar) are deployed in Australia, but distribution is very sparse focussed on the Sydney and Gold Coast beaches, with a system to be installed on the WA coast in 2018. This system has many applications predominantly focussed on morphological change in the littoral zone - quantifying storm driven shoreline change, and measurement of surf zone bathymetry, amongst others. To achieve these objectives, characteristics of the wave field are used to derive these features, but the wave information itself is of lower interest. Wave characteristics are of higher interest in emerging UAV systems, with trials to retrieve wave fields using passive optics, GPS reflectometry, and LiDAR systems underway. These systems are in early development, but emerging as potentially useful systems for varied applications in the near-shore zone, further increasing value from the growing number of UAV systems measuring terrestrial side morphological change. Airborne mounted wind-wave retrieval systems (e.g., Modular Aerial Sensing System, Melville et al., 2015) provide a valuable supplement to satellite remote sensed data, with high resolution, and sampling unconstrained by orbit characteristics. Application of aerial sensor wave retrieval has not been taken up in Australia for several years, despite potential application for process studies.

3.7. Improved understanding of wave-induced currents and transport

Knowledge of ocean surface currents is essential for navigation, search and rescue, environmental monitoring, ecosystem management, sediment transport and fisheries, not to mention understanding the global climate while knowledge of interaction with the seabed is critical to sediment transport and understanding beach response to storms and even sea level rise. The role of wave-induced currents in the global context of ocean circulation close to the surface is not well understood and as a result is not accounted for in most ocean models. It is often accepted that the wind-stress, parameterised in some way, can account for surface currents resulting from the wind forcing. Wind tangential stress does indeed generate surface currents directly, but at wind speeds greater than 7.5 m/s (which is approximately the global mean wind speed, Zieger et al., 2014) most of the wind stress is supported by waves (e.g. Kudryavtsev and Makin, 2002). Under these conditions, a significant component of the surface current is not directly related to the local wind either in its speed or direction (because waves integrate the wind forcing over large area) or is completely unrelated to the local wind (because it is swell) – see Babanin et al. (2017) for a recent review of the wave-current interaction problem.

Wind-generated waves can facilitate or moderate the ocean surface currents in three major ways. The first is via the Stokes drift due to the nonlinear nature of surface waves. This role of the ocean waves is known in principle, but is not always appreciated and accounted for. Reliable parameterisations of the Stokes drift for wind waves incorporating the full wave spectrum are still missing.

The second essential contribution, which is perhaps larger than the Stokes drift is usually not even well perceived. All third-generation wave forecast models incorporate a dissipation source function which describes the loss of energy due to wave breaking and other processes in the ocean-interface system. The dissipation integral describes the total flux of energy out of the wave field. The energy passed to the ocean is largely spent on generating turbulence near the surface and on work against buoyancy forces acting on bubbles injected in the course of the wave breaking. The momentum-loss integral of the dissipation function gives the so-called radiation stress which is presumed to be going to the currents (although some of it may in fact be going back to the wind, or to the bottom in shallow areas). It should be pointed out that in present wave models, radiation stress is parameterised in terms of wave-height differences along the propagation direction. Obviously, such a parameterisation does describe the energy dissipation, and can then be used to estimate the momentum loss, but only in the areas where dissipation is much larger than the energy input, i.e. usually in shallow waters. In deep water, the mean wave height is not a good proxy for the energy loss. It may in fact grow under wind action, or not change if this action is balanced by the white-capping dissipation, but the integral, and hence the radiation stress is not zero.

The third, and even less well understood process, is due to the scattering or dispersive nature of wave-induced currents. Wave breaking demonstrates features of a random process on the two-dimensional ocean surface. This is due to directional spreading of the wave spectrum, the three-dimensional structure of wave crests and random phases of ocean waves and their groups. Surface currents induced this way, therefore, will have features of two-dimensional turbulence behaviour, which in some applications – such as search and rescue, drift of debris and pollution – may have significant impact on the quality of relevant predictions based on assumed surface currents (e.g. Soomere et al., 2015).

3.8. Long-term beach / coastline monitoring

The ability to quantify and model contemporary and future coastline variability and change, at a range of timescales spanning now-casting (coastal hazard Early Warning Systems), extreme storm erosion (coastal erosion risk assessment) and decadal-scale shoreline evolution (projecting future coastline impacts of climate change), offers the very real potential to inform and guide future development and economic growth around Australia's open coastlines. Coastal planning, coastal management and emergency preparedness are responsibilities that cross-cut all three tiers of Australian government. For Australia to develop, calibrate and validate improved quantitative predictions of coastal hazards and accurate projections of future coastline changes, a nationally-coordinated program of sustained, long-term coastline observations is required.

Coastal erosion is a first-order challenge to society and the natural environment in Australia, as it is internationally (Mossinger et al, 2013). A recent review of coastal erosion risk assessment practices in NSW identified a lack of observational data to be a particular impediment to improved understanding of coastal change and risk assessment practice and application (Kinsela and Hanslow, 2013). In this context, coastline modelling underpinned by sustained and nationally-coordinated coastline observation is needed to:

- provide reliable and risk-based predictions of the erosion and recovery of beaches during and after a single or cluster of storms and to quantify the present and future impacts of sea-level rise;
- inform coastal policy, planning and management at all three levels of local, state and federal government; and

- provide the basis for present and future risk assessment and real-time geohazard forecasting.

Presently in Australia there is a substantial gap in rigorous observations and resulting data-streams of shoreline conditions, coastal erosion, variability and trends around the continent. With a few notable exceptions (e.g. McLean et al., 2010; Turner et al, 2016) the existing observations around the Australian coastline are characteristically sparse, ad-hoc, largely uncoordinated and too often dependent upon the motivation of individuals (and often volunteers). As a result, the coverage and sustainability of these observations is unsecured, incomplete and inadequate; and the limited data that does exist, largely inaccessible. The IMOS and Terrestrial Environment Research Network (TERN) observing networks are providing invaluable and unprecedented data-streams of real significance and application to the wider coastal zone and deeper ocean; IMOS principally seaward of the 50 m depth contour, and TERN's primarily inland of the open coastline. A critical missing gap that falls between these two existing observation programs is rigorous and sustained observations of the littoral zone specifically encompassing the land-ocean boundary, which also represents the region of the ocean with which the great majority of society directly interacts. Nominally spanning water depths of 50 – 0 m along open coastlines and extending landward to include frontal dunes, this critical region where the land meets the ocean currently falls outside any nationally-coordinated monitoring effort. The establishment of a coordinated National Coastline Observatory would have a very unique focus on local– to national-scale geoscience assessment of geohazards in the coastal zone.

Fundamentally, and irrespective of the coastline modelling approaches used, sustained and nationally-coordinated observations of present-day sandy coastline variability and trends at regionally-representative coastal settings around the entire Australian continent are a necessary prerequisite to further improve the practical tools that will be relied upon to predict and forecast coastline hazards into the future (shoreline erosion, shoreline retreat, coastal inundation and flooding, coastal hazard lines, coastal infrastructure at risk, etc.). The Federal Government's recent Coastal Compartments Project (DEE, 2018) has now established the geographical framework to inform and guide the practical design of a National Coastline Observatory.

3.9. Nearshore modelling and forecasting

The nearshore zone defines the critical interface between the land and ocean, containing a large diversity of coastal environments (e.g. sandy beaches, coral and temperate reefs, wetlands, mangroves, rocky shorelines, etc.). Australia's infrastructure and ecosystems located within the nearshore zone are vital to its economy, livelihood, commerce activities and security. However, the nearshore zone is a constantly changing region of the ocean that is also continuously threatened by extreme storms, sea level rise, and anthropogenic impacts. To effectively manage coastal regions requires a detailed understanding of nearshore processes, and in particular an ability to predict changes that are occurring now and into the future.

Predicting nearshore processes (including hydrodynamics, sediment transport and morphological changes) remains a great challenge in physical oceanography and coastal engineering given, for example: 1) the highly nonlinear nature of the processes, including complex feedbacks that operate; 2) the wide range of spatial and temporal scales that usually must be considered, and 3) the complexity of nearshore bathymetry that can also rapidly evolve. For most of Australia's coastline (by some estimates up to [??%], Short and Woodroffe 2009), wind generated swell waves provide the dominant source of energy that drives nearshore hydrodynamic processes. As swell waves approach a coastline and transition into intermediate and then shallow water, they undergo a number of key transformations (e.g. due to refraction, frictional dissipation, nonlinear changes in wave shape, etc.). In sufficiently shallow water, groups of incident swell waves break in the surf zone, and through nonlinear transfers of the swell energy, a range of other flows are generated including: mean wave-driven currents, low frequency (infragravity, IG) waves with periods 25-250 s, and very low frequency motions with periods >250 s. All of these hydrodynamic processes can be significant in the nearshore zone, and hence ultimately drive coastal sediment dynamics, morphological and biogeochemical changes - the accurate characterisation and prediction of these processes represents arguably the greatest challenge in nearshore hydrodynamic modelling and an area where significant research is still needed.

Broadly speaking, there are three classes of wave models used for nearshore hydrodynamic predictions, each with advantages and disadvantages: 1) phase-averaged (spectral) models, e.g. SWAN and WW3, 2) surf beat (infragravity) resolving models, and 3) fully phase-resolving models. Each class of model will continue to have key roles in different nearshore modelling applications; compromises will always need to be made between the scales of motion that must be directly resolved, the size of the overall model domain and the computational resources available. Given that each class of nearshore model relies on parameterising the wave-driven processes that cannot be directly resolved, a major focus of nearshore research has been on improving empirical parameterisations within models, and thus often guides experimental research programs. As a consequence, the research needed to improve nearshore model predictions can vary to some degree between the class of model considered.

Through improvements in nearshore observations (including bathymetry), advances in national computational infrastructure, and new developments in a range of numerical wave models, nearshore predictions are on the path to significantly advance over the next decade. While historically all of the main classes of nearshore models have been developed, tested and calibrated for a narrow range of coastal environments and wave climates (particularly for sandy coasts along North America and Europe), new applications of nearshore models to Australia's diverse coastline are helping to identify gaps in process-knowledge within existing models and approaches to improve them; ultimately this will enable nearshore models to be confidently applied to a much broader range of coastal systems. In NSW for example, the recent development of a nearshore wave model covering 2,000 km of Australia's coastline, and an associated suite of wave transformation functions at 14,000 nearshore locations, has demonstrated reliable and efficient means of generating shallow-water wave data at large spatial scales (Taylor et al., 2015; Baird Australia, 2017).

The exponential growth in computing capabilities (including boosts to national supercomputing infrastructure in Australia) are gradually shifting the focus of nearshore modelling applications to the use of phase-resolving wave models that had previously been computationally prohibitive. This is helping to provide new insight into a range of nearshore hydrodynamic processes, including the full spectrum of wave motions that drive hazards and change in the nearshore zone. Nevertheless, there are still major opportunities to further improve phase-resolving wave models, in particular how to best incorporate sub-grid-scale processes; for example, new approaches to incorporate wind wave growth, improved descriptions in wave breaking, and dissipation by the complex bottom roughness characteristic of coastal ecosystems. With parallel improvements in regional wave predictions around Australia, this is also providing new opportunities to improve nearshore predictions through the downscaling of waves from shelf to shoreline (including wave transformations in intermediate water depths that are not well accounted for in wave forecasts). Over time these continuous improvements in nearshore model predictions and capabilities within Australia should lead to the development of increasingly operational predictions of nearshore waves along the coastline of Australia; likely starting with phase-averaged models regularly updated with nearshore bathymetry, followed by increasing use of phase-resolving models in nearshore forecasts.

3.10. Development of wave data assimilation

Data assimilation (DA) describes the process of combining observations and numerical models to provide an analysis, which is as close as possible to the true state. It is used in hindcasting studies to produce optimal estimates of historical wave fields for climate studies, engineering applications, event analysis etc. and in forecasting, to provide an analysis that can be used as the initial conditions for a forecast model. One of the main challenges in DA is related to the fact that observations are limited in time and space and so do not provide full information on the state of the environment. This is particularly relevant for marine systems such as wind-waves. On the other hand, numerical model data may be available everywhere (notwithstanding the requirement for discretization in space and time) but there may be limited understanding of the nature of the errors in the model system (i.e. size, distribution, rate of growth etc.), which is necessary for data assimilation.

There has been considerable development in wave DA internationally over past decades and a number of different techniques, with varying levels of complexity are available, e.g. Optimal Interpolation (Lionello et al., 1992), extended Kalman Filter (Voorrips et al., 1999), ensemble Kalman Filter (Almeida et al., 2016) and 4D variational assimilation (Orzech et al., 2013). Increased computational capacity is allowing more sophisticated DA techniques such as those which are based on ensembles. Wave DA is an area in which advances in machine-learning and Artificial Neural Networks could be of benefit (e.g. Wahle et al., 2015).

A range of different observational types can be used for assimilation studies, depending on the application. In situ buoys and coastal radars are useful for hindcast studies and can provide full directional wave spectra, as well as integrated parameters (e.g. Hs, Tp). However, their spatial coverage is limited and since they are typically located in coastal regions, and they are not well suited for global or regional scale forecasting applications. Satellites provide global coverage (although sparse in both space and time) and can provide Hs (altimeters) or wave spectra over the low frequency portion of the spectrum (Synthetic Aperture Radar).

Within Australia, the Bureau of Meteorology at one stage had an operational system to assimilate satellite altimeter data within the AUSWAM forecast system (Greenslade, 2001; Greenslade and Young, 2005). However, the DA was not implemented when the operational wave modelling framework was transitioned from WAM to Wavewatch III. Part of the reason for this was that as NWP and wave models improve in accuracy (due to higher resolution, improvements to physical parametrisations etc.) the incorporation of wave data assimilation becomes a lower priority compared to other possible wave model developments such as ensemble systems, or coastal modelling. Indeed, the results of the present priority ranking have supported this.

3.11. Development of a standardised data and QA/QC specification for wave observations

Observations of the sea surface wave state can be presented in several forms, such as directional energy spectra or non-directional wave parameters, depending on the level of processing of the “raw” sensor observations performed before the data are transmitted or collected for use. This allows for many levels of variability in the type, quality and reliability of the observations that are available for analysis and/or operational use. The uncertainty implied by the processing is further compounded by the range of measurement techniques and the eccentricities of specific measurement devices.

The costs associated with providing the physical and communications infrastructure, deploying and maintaining wave observation devices are expensive. At present, within Australia one will encounter wave observations in many ad-hoc legacy standards, data formats and limited metadata from a variety of sources and providers across the maritime community. This variability in the reliability, provenance and quality standards of the data reduces the interoperability and usefulness of data as a body, and the credibility for specific mission-critical applications such as decision support systems. Standardisation of the data and metadata will enable the necessary transparency and interoperability for the community to fully realise the value for these considerable and often ongoing investments.

Such standardisation will not be without its challenges. In the field there is a variety of sensors based on different technologies, from different eras of microprocessor, storage and communications capabilities, with differing end-goals and processing strategies in use. These challenges also present opportunities, as understanding the eccentricities of individual sensors and their configuration and maintenance histories (QA, quality assurance) as well as the data testing and verification that has been performed (QC, quality control) can enable other uses for the observations, particularly when "raw" (unprocessed) data is available for reprocessing. Advances in data transfer and storage technology can make the provision of raw data more viable, enabling re-processing of QA processes optimised for the intended use.

The process of maintaining data quality from a metocean device network relies on both QA and QC. The QC processing of wave observations will differ according to the intended use of the data, e.g. provision of real-time swell spectra versus long-term climatological studies. Understanding the limitations of wave data through provision of metadata can be essential to ensure that data is used to its fullest potential and not used erroneously. As such, a QA/QC framework is complementary to metadata conventions that can jointly enable flexibility in the usefulness of wave observation data sets.

An established standard for a QA/QC framework is QARTOD, developed by IOOS and NOAA, with support from IMOS. QARTOD is a real-time QC focused framework, which makes it an ideal candidate for use with industry applications such as OMC International's real-time under keel clearance (DUKC®) decision support technology. QARTOD-based wave QC is presently being rolled-out to port operations nationwide (and beyond).

As a QC framework it allows flexibility and has provided a useful framework for managing a suite of tests and also standardised definitions that are applicable across a wide range of devices.

3.12. Better engagement of maritime industries with research

Historically, there has been a deliberate intent to separate science from society, with the aim of maintaining scientific independence and objectivity. Over recent decades, this approach has fallen out of favour, with the sense that this separation does not necessarily lead to improved uptake of research or enhanced decision making. Close engagement between industry and research is now acknowledged as important in many fields, and tangible actions are being taken to ensure that it occurs on a broad scale. In general, improved engagement will benefit all groups - the benefits to industry are that research can be more aligned to their needs, and benefits to research are that industry can provide a potential source of funding, outside the public sector and a direct pathway to application. For specific projects, there will be increased uptake of research outputs if users are involved in the design of research activities right from the start. This is the principle of 'co-design', in which collaboration and interaction between producers and users of knowledge starts at the onset of a project and continues throughout the entire project. With deep engagement at the onset, industry and other users of research can provide a clear description of their needs, and researchers can provide the best assessment of what is feasible, and the level of effort required.

On an international level, several global organisations are re-framing their strategies in order to better embrace engagement. As an example, Future Earth, a program coordinating research for global sustainability, evolved from a number of other global programs and has as one of its goals, the enhancement of engagement across science, technology, business, government, and civil society. Within Australia, a significant amount of research is supported and funded by industry, for example the offshore oil and gas industry has supported a number of research projects relating to the impacts of Tropical Cyclones on offshore structures. These industry funded projects, while specifically targeting industry needs, can also provide benefits that flow on to other users, for example, improved Tropical Cyclone forecasts for the public.

The recent establishment of the FOO as discussed in the Introduction is a positive step forward to encourage greater engagement between research, industry and other stakeholders. The present process, which engages both the industry and research communities in the development of wave research priorities was initiated under the auspices of FOO and is a key example of enhanced engagement.

3.13. Coastal wave impacts

The East Coast Low storm event that severely impacted the Queensland, NSW, Victorian and Tasmanian coastlines in June 2016 (Harley et al., 2017) was a reminder of the extent to which damage from storm waves can and will threaten the safety of Australia’s coastal communities and cause tremendous damage to its coastal infrastructure. This experience highlighted the need to better understand, model and predict the impacts of extreme waves on Australia's coasts, including coastal erosion, and inundation.

Along much of Australia’s most highly-developed coastlines, coastal impacts due to wind-waves occur due to wave runup colliding with and/or over-topping dune and shorefront infrastructure, and chronic erosion attributed to changes in the wave driven sediment budget.

Wave runup represents the landward limit of wave action on a coastline and is the super elevation of the shoreline above the still water level (SWL) or mean offshore ocean water level due to two wave driven processes: swash and wave generated setup. Predicting wave runup levels is critical for coastal management and engineering applications, from obtaining wave overtopping volumes to coastal engineering structure design. Further, the maximum wave runup limit controls the landward limit of coastal erosion during storm events.

The majority of research into methods for estimating wave runup has focussed on sandy beaches and hard structures, such as seawalls (e.g., EurOtop, 2016). Typically, wave runup is estimated using empirical formulae to predict the vertical level of a wave runup exceedance level (e.g., the 2% runup exceedance level, R2%) relative to the SWL using easily obtained parameters such as offshore wave conditions and local beach slope (Wassing 1957, Hunt 1958). While much research has been conducted to improve predictive capacity, recent work by Blenkinsopp et al. (2016) and Atkinson et al. (2017) assessed several of the most widely used empirical formulae for wave runup on beaches and found them to be subject to significant errors if used without suitable adjustment and optimisation of the empirical constants. This suggests that additional work is needed to identify additional factors not typically considered in runup prediction that may have some influence on wave runup such as beach type, surf zone width and type, tidal phase, and nearshore bathymetric profiles.

More computationally expensive methods, such as wave-resolving models (e.g., IHFOAM; Higuera et al., 2013), may be able to provide improved wave runup predictions, with Martins et al. (2017), for example, reporting very good agreement between measured and modelled shoreline elevations. The calibration of models such as these, however, typically requires significant site-specific data, which is often not readily available (see section 3.8), in addition to significant computing power.

In some circumstances, wave runup can generate wave overtopping of a coastal barrier, rock platform, or engineered structure which occurs when the runup elevation exceeds the elevation of the coastal barrier. This is reasonable rare on sandy coasts in Australia due to the well-developed coastal barrier systems, however, it is highly relevant in regions where rocky shore platforms are present. In these settings, the most widely used empirical formulae for predicting wave overtopping and associated parameters are those presented in EurOtop (2016). Like the prediction of wave runup at beaches, empirical overtopping formulae are derived from fitting to experimental data, and, there remains significant error associated with the use of these empirical formulae. To that end, emerging research in Australia on wind-wave hazards at rock platforms (e.g. to rock fishers) has taken other approaches such as using morphological exposure measures (e.g., Kennedy et al., 2016) or using a data driven approach to develop site-specific predictive tools (e.g., Kinsela et al., 2017; Power et al., 2018).

Open coast inundation by extreme wind-waves along the Australian coastline (due to combined storm surge, wave setup and catchment processes) is rare, but can occur during severe Tropical Cyclones. For example TC Yasi, which made landfall on the Queensland coast in 2011, resulted in a disaster situation being declared for a number of coastal areas from Cairns to Mackay. Significant inundation was reported along with high erosion damage (Qld DERM, 2011). Despite the low frequency with which open coast inundation occurs, one compounding factor is that inundation can be triggered following coastal erosion, with significant erosion potentially compromising the coastal barrier and thus providing pathways along which inundation can occur. Additionally, if stormwater drainage infrastructure is open to the coast, inundation can also occur through seawater being driven back through storm drains thus inundating low-lying land without actually overtopping dunes or structures. It is worth noting that the magnitude of extreme storm surge levels and offshore wave heights varies nationally by factors of at least 6 and 5 respectively (Mariani et al. 2012), thus highlighting the need for site specific investigations.

Chronic erosion is observed along much of Australia's coastline. This occurs in regions where the local sediment budget is disrupted. This budget is predominantly driven by the local wave climate, with longshore and cross-shore contributions. Anthropogenic interference of this budget (e.g. via structures which alter sediment supply) will alter shoreline position and is often manifested as observed erosion. Similarly, changes in local wave climate (e.g., climatological – see section 3.14) may have similar influences and create chronic erosion issues.

3.14. Improved understanding of the effect of future climate variability and change on coastal areas

Future climate variability and change will impact the wave climate, and hence coastal areas, via two mechanisms. First, through variability and change in the characteristics of the atmospheric circulation, via changes in intensity, frequency and paths of the wave generating storms. Second, through morphological change in nearshore areas (i.e., less than 50 m depth). Morphological change will result from either changes in sea-level, altering water depth, changes in the sediment budget altering morphology, or potential changes in reef morphology, such as might occur during decalcification of carbonate reefs. Both mechanisms will lead to changes in not only wave heights at the coast, but also changes in wavelength and direction characteristics that are equally critical to coastal and shoreline stability.

Study of changes in wave climate – both historical and future – is a relatively new field. The historical observational record is sparse, with only a limited (~30 year) record to resolve climatological variability or change. Future changes have received even less attention; the first time waves were included with any rigour within an Intergovernmental Panel for Climate Change was in the 2013 fifth assessment report (Church et al., 2013), and it is only in 2017 that the contribution of waves to coastal sea-level was listed as a critical consideration alongside sea-level rise following the World Climate Research Program sea-level conference (Stammer et al., 2017). To date, the wave climate community has largely focussed on the effects of climate driven changes in atmospheric circulation on wave climate. While some robust features of change are apparent – for instance, the projected future trend towards increased wave heights in the Southern Ocean, of relevance to activities along Australia's southern and western coasts (and consistent with reported historical trends, Young et al., 2011), considerable uncertainties exist with the future wave climate projections (Hemer et al., 2013; Morim et al., 2018). The projections of wave climate are heavily dependent on the skill of general circulation models to provide reliable marine surface wind fields. Marine surface winds have received little attention from the climate modelling community; the interest in waves (and storm surges) requires increased collaboration between the wave and climate science communities to improve understanding of the effects of future variability and change on coastal areas.

Recent studies focussed on the Perth, WA coast suggest high future sea-level scenarios will have a greater influence on wave climate at the coast than future changes in atmospheric conditions (Wandres et al., 2017). Few studies have investigated the complex integrated relationship between sea-level rise, and other co-incident coastal hazards (storm-surges, coastal precipitation, waves) in how coasts will respond under future conditions. Further complexities involve interactions between waves and the long-term evolution of coastal morphology; both along sandy coasts where available sediment budgets can modify how the coast responds to incident waves, and potentially on reef-lined coasts, should reef morphology be destabilised. These scenarios have received little attention, with further studies required to resolve importance of integrated or coupled system modelling to resolve future coastal wave climate change and consequent coastal response.

3.15. Improved modelling of swell propagation

Swell refers to wind-generated waves which have propagated away from the storm that produced them. Swell waves are present over more than 80% of the ocean surface and can cause significant adverse impacts on maritime operations. The existence of low frequency swell can influence port operations, recreational activities, and can also have a major impact on offshore platforms and operations. While integrated parameters such as Significant Wave Height are generally well forecast by third-generation wave models such as WW3, the energy distribution across the wave spectrum is often poorly described. In particular the low frequency swell component can be poorly predicted, both in terms of wave amplitude and arrival time. Jiang et al. (2016) showed through joint analysis of buoy observations and model reanalysis that model predictions of swell can be tens of hours early or late compared to observations.

Swell attenuation is driven by a number of dissipative and non-dissipative processes. The dissipative phenomena include interaction with turbulence on the water (Babanin, 2006, 2012) and air sides (Ardhuin et al., 2009), with adverse winds (Donelan, 1999) or currents (Babanin et al., 2017). Non-dissipative contributions to the gradual decline of wave amplitude come from frequency dispersion, directional spreading, refraction by currents, and lateral diffraction of wave energy (Babanin and Waseda, 2015, Jiang et al., 2017). The interactions with local winds/waves can, on the contrary, cause swell growth (e.g. Young, 2006, Ardhuin et al., 2009).

In order to better understand the modelling problem, the evolution of swell should be measured along its propagation path which can be thousands of kilometres long. In situ measurements along these great circle paths are not impossible, but are extremely challenging (Snodgrass et al., 1966). Satellites show promise in this area (Ardhuin et al., 2009), but to date, there have been limitations to their capability (Jiang et al., 2017). With the practical significance of swell impacts across a very broad range of maritime operations and recreational activities, and with the analytical and experimental research difficulties involved, understanding swell dynamics and improving swell prediction presents a challenge to the wave observing and modelling community.

4. Discussion

A possible issue that arises when attempting to prioritise research activities is the need for a certain level of categorisation of the activities, and the possibility that different categorisations might produce different results. An example in the present case is 3.14: *Improved understanding of the effect of future climate variability and change on coastal areas*. Under the final categorisation considered in this process, this item came under 'Climate' but it could arguably also be placed in the 'Nearshore' category. Indeed, during this process, this particular priority appeared in both those categories at different times. This is relevant because a particular priority may have a different ranking depending on which category it appears in. For example, it may be seen as a high priority compared to other climate priorities, but a low priority compared to other nearshore priorities (or vice versa). In the present process, participants were permitted to vote to retain up to 50% of the priorities in each category. Given this large number of possible 'yes' votes, if an issue is thought to be important, it will likely get a 'yes' vote whichever category it appears in. This will therefore reduce any impact of the selected categorisation.

A common thread running through many of these priorities is the nearshore - 6 out of the top 15 priorities refer directly to the coast. This is perhaps not surprising as Australia is a distinctly coastal-focused nation. Half of Australia's coastline comprises sandy beaches with over 85% of Australians living within a narrow coastal strip, which will only increase (ABS, 2002). Population growth and the need for expansion in infrastructure and services go hand-in-hand, placing immense pressure on the coastal zone. Recent attempts to assess our national assets currently at risk to coastal hazards include: roads ($46-60 billion); commercial buildings ($58-81 billion); residential property ($41-63 billion) (DCCEE, 2011). No less significantly, the cultural and economic value of beaches is also well recognised and helps define the Australian way of life. For example, the NSW government has ranked beaches in its top 4 most valuable natural resources (NSW Government, 2006).

In the initial solicitation of research questions, participants were asked separately about research and about research infrastructure. There was considerable overlap between the two sets of responses, and they were merged for subsequent analysis and ranking. It can be seen that in the list of highest priorities, there is a mix of: a) research activities to increase our understanding (e.g. extreme sea-states); b) tasks or community-based activities (e.g. data sharing); and c) efforts to build supporting infrastructure (e.g. wave buoy network). This mix of developing infrastructure, tasks, and increased understanding is not considered to be a major issue in this context because the target audience for this process includes funders of research and research infrastructure, and the research community. Indeed, all of the infrastructure-related priorities need to have participation from the research community and all of the more fundamental research priorities are dependent to a certain extent on enhanced infrastructure.

In addition to different categories of activities in the list of final priorities, it is worth also highlighting the issue of the scope and size of individual priorities. As noted by Sutherland (2011), it is natural that broader questions will attract more support than more specific questions and this can affect the ranking. In the present process, the initial solicitation of research questions provided the guidance that they should be 'achievable by 1 or 2 researchers within a few years'. Despite this, a broad spectrum of effort level was seen in the initial priorities, and despite (or perhaps because of) several rounds of editing and merging, it can be seen that the resulting priorities in Section 3 have varying levels of effort required and some are more specific than others.

Rather than a detraction, the range of different activities and varying levels of scope can be seen as a benefit in the present process, as it can provide an indication of the feasibility (assumed here to be a combination of cost and difficulty) of each priority – in addition to the importance of each priority determined by the community, cost and difficulty are relevant factors in determining priorities for funding. While the assessment of the cost and difficulty of the research-focussed priorities is an almost impossible task (as research is an open-ended activity) it is possible to estimate the cost and difficulty of the other priorities. In this context, the priorities that were identified as 'research' are Numbers 2, 6, 7, 13, 14 and 15 (see Table 1) and are not included in this assessment.

The results of the assessment of the remaining research-enabling priorities are shown in Figure 1. In this figure, the vertical axis represents an assessment of the relative difficulty (i.e. do we know how to do it?), the horizontal axis represents an assessment of the cost and the size of each circle represents the priority ranking, although it should be emphasized that all of these tier 1 and tier 2 priorities have been assessed to be the highest priorities out of the initial long-list of 209 items.

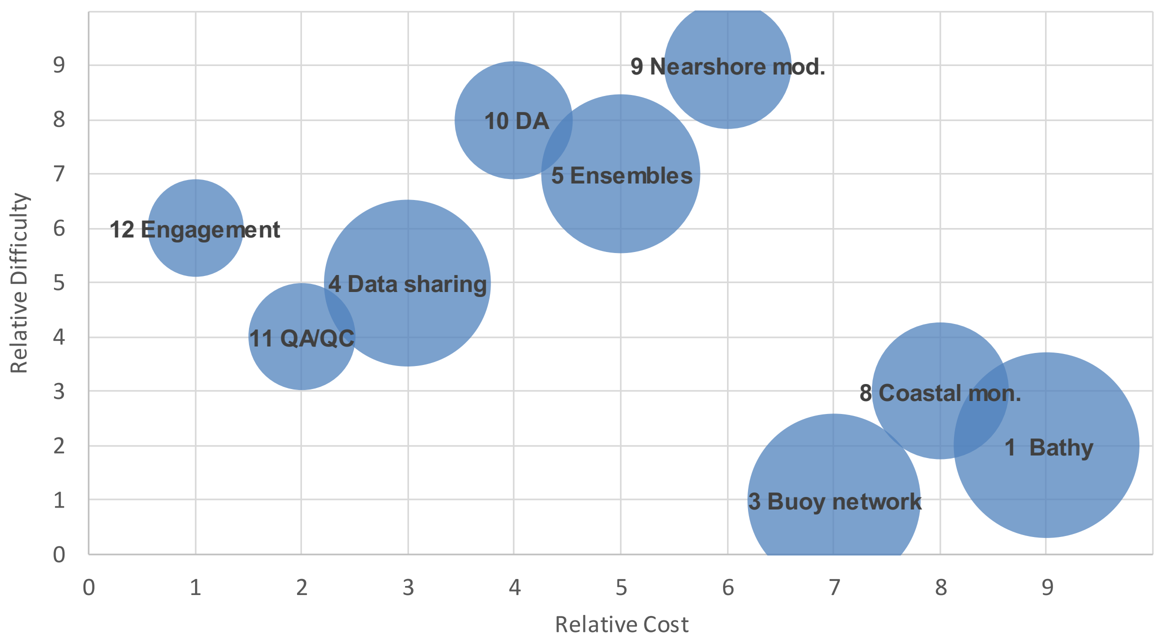

Figure 1 An assessment of the 'feasibility' of each priority. The size of the circles and the numbers within the circles represent the priority rank as listed in Table 1.

Interestingly, it can be seen that the priorities fall into three clusters. The first cluster includes the major infrastructure activities (bathymetry, wave buoy network and long-term coastal monitoring). These are the most expensive items, but also the most straightforward, and they appear in the lower right corner of the figure. These would have a large initial cost, but then a smaller ongoing cost to maintain them. They can be described as research-enablers – they are essential for supporting the more research-focussed activities. A second cluster includes research-enabling activities that don't require large infrastructure projects (engagement, data sharing and QA/QC). These are less expensive, but less straightforward and focus more on community activity. These appear near the left-hand side of the figure. The third cluster includes the task-related activities (data assimilation, ensemble modelling and nearshore modelling). These are of intermediate cost, but they involve some level of difficulty, perhaps incorporating some research. These appear in the upper middle portion of the plot.

Importantly, this figure can give an indication of the 'low-hanging-fruit', i.e. high priority, low cost and easy to do. Depending on where one draws the line, the second cluster including the community-based research enablers falls into this category. No 4: *Improved data access and sharing* is the highest priority (largest circle) in this category and, indeed, much progress is already being made toward this with the continued development of the Australian Ocean Data Network, as has been discussed in Section 3.4.

5. Closing remarks

This work has presented a number of priorities relating to wind-waves research and infrastructure that have been identified as important by the Australian wind-waves research, industry and stakeholder community. This can guide funders and other organisations as to how they might prioritise their activities in the medium term. Progress is already being made on many of these activities. The challenge will be to ensure that these priorities are supported and regularly reviewed as regards their progress and continuing validity.

6. Acknowledgements

The IMOS office is thanked for providing access to their *surveymonkey* registration. We also acknowledge Chris Yetsko, for contributions to the prioritisation process.

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Author List

First name	Surname	Organisation	Role
Diana	Greenslade	Bureau of Meteorology	Lead
Mark	Hemer	CSIRO	Steering Committee/Writing team
Alex	Babanin	University of Melbourne	Steering Committee/Writing team
Ryan	Lowe	UWA	Steering Committee/Writing team
Ian	Turner	UNSW	Writing Team
Hannah	Power	University of Newcastle	Writing Team
Ian	Young	University of Melbourne	Writing Team
Daniel	Ierodiaconou	Deakin University	Writing Team
Greg	Hibbert	OMC	Writing Team
Greg	Williams	RPSMetocean	Steering Committee
Saima	Aijaz	Bureau of Meteorology	Contributor
João	Albuquerque	University of Auckland	Contributor
Stewart	Allen	Bureau of Meteorology	Contributor
Stuart	Anstee	Defence	Contributor
Michael	Banner	UNSW	Contributor
Paul	Branson	CSIRO	Contributor
Steve	Buchan	RPSMetocean	Contributor
Andrew	Burton	Bureau of Meteorology	Contributor
John	Bye	University of Melbourne	Contributor
Nick	Cartwright	Griffith University	Contributor
Amin	Chabchoub	University of Sydney	Contributor
Frank	Colberg	Bureau of Meteorology	Contributor
Stephanie	Contardo	CSIRO	Contributor
Francois	Dufois	UWA	Contributor
Craig	Earl-Spurr	Bureau of Meteorology	Contributor
Grant	Elliott	Woodside	Contributor
David	Farr	Bureau of Meteorology	Contributor
Jan	Flynn	Woodside	Contributor
Ian	Goodwin	Macquarie University	Contributor
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