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15 Priorities for Wind-Waves Research

An Australian Perspective

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ABSTRACT: The Australian marine research, industry, and stakeholder community has recently undertaken an extensive collaborative process to identify the highest national priorities for wind-waves research. This was undertaken under the auspices of the Forum for Operational Oceanography Surface Waves Working Group. The main steps in the process were first, soliciting possible research questions from the community via an online survey; second, reviewing the questions at a face-to-face workshop; and third, 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 five priorities are 1) enhanced and updated nearshore and coastal bathymetry; 2) improved understanding of extreme sea states; 3) maintain and enhance the in situ buoy network; 4) improved data access and sharing; and 5) ensemble and probabilistic wave modeling 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. While this process has been driven by Australian needs, it is likely that the results will be relevant to other marine-focused nations.

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As a nation deriving major social, economic, and environmental benefits from its coasts and oceans, Australia is well positioned to advance its prosperity, security, and quality of life with an enhanced focus on operational oceanography. Realizing 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. Most importantly, the FOO stakeholder base includes representatives from four key "pillars" within FOO (marine industries, government agencies, research organizations, and providers of operational oceanographic services), so that research priorities are identified and delivered to support end user (stakeholder) needs.

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.

The goal of wind-waves research is to deliver wave knowledge and information to meet societal needs. These needs span oceanographic services across time (hindcasts, near-real-time, synoptic forecasts, seasonal and long-range climate projections) and spatial scales (global, regional, beach-scale down to individual waves), requiring improved knowledge of wave properties and their impacts. Ultimately, these requirements cover improved wave observations and monitoring, wave physics and parameterizations, modeling frameworks, boundary conditions (bathymetry and surface forcing), and response models (e.g., morphology, energy, socioeconomics). Multidisciplinary collaboration across the community in areas such as data access and policy development will further enhance the benefits society gains from wind-waves research.

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 will be regularly revisited on a 3–5-yr cycle.

This process has been driven by Australian needs, however, Australia is one part of the larger international waves community. It is likely that the results of this extensive consultation and evaluation process are relevant to the international community and, in particular, other marine-focused nations.

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 that it is highly democratic. Some examples of other priority setting activities that have followed this process can be found in paleoecology (Seddon et al. 2014), 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, and
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 research, industry, and stakeholder community to take part in an online survey. A total of 360 invitations were emailed to participants drawn from 1) the FOO mailing list, 2) a list of researchers who had previously attended one or more national wave research symposia, and 3) professional networks of the Steering Committee (SC: a five-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 one or two researchers within a few years. They were also asked to enter up to five 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 organizations (i.e., universities or government research agencies), and the remainder identified as private industry, service provider, or government (non-researchers). In terms of geographic distribution, the highest participation came from Western Australia (23 respondents), then Victoria (18), New South Wales (NSW, 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 444 suggested priorities, including 296 research suggestions and 148 infrastructure suggestions. Not surprisingly, there was considerable overlap in the suggestions entered, so these 444 priorities were collated and merged where appropriate to provide a long list of 209 suggested 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; Modeling and Forecasting; Nearshore and Coastal Hazards; Traditional Observations; Extended Observations; and Observations Research.

A face-to-face workshop to review and refine the long list of priorities was arranged to coincide with a national wind-waves research symposium with around 60 participants (Lowe et al. 2017). 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 items remained. Each round-table then voted on the suggested priorities in their category, with individuals permitted to vote to retain up to 50% of the priorities. 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 eight categories: Modeling; 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 1) whether to treat the two online surveys (researcher-based and stakeholder-based) with equal weight or to treat individuals with equal weight, and 2) whether to use the priorities with the highest rankings overall as the "top" priorities or to 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 around 20% of the contributors to the researcher-based survey (through their attendance at the symposium) would more accurately identify as stakeholders. Overall, the ratio of the contributors to the final ranking is approximately 60:40 researcher to stakeholder.

Second, it was decided to use the total number of raw votes to guide the prioritization 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 categorization might have had on the results (see "Discussion" section for further discussion of this issue).

Research priorities

The original intention of this process was to identify a limited number of priorities, so that any future efforts could be clearly focused. To this end, the top five priorities were identified and are referred to here as "tier 1" priorities. However, the SC noted that there were a number of priorities that did not rank highly enough to get into the top five, but that would be worth identifying and discussing. Ultimately, a further 10 priorities were identified, and referred to here as "tier 2," providing a total of 15 top-ranked priorities. These top-ranked priorities are presented in Table 1 and briefly discussed below. Further discussion of these priorities, including the current state of the art and relevant activities within Australia, can be found in a related white paper at www.foo.org.au/priorities/surfacewaves/.

Tier 1 priorities

1) Enhanced and updated nearshore and coastal bathymetry. Capturing an enhanced and updated Australian nearshore and coastal bathymetry is a clear priority for the wave research community, recognizing the importance of this key parameter to how waves transform as they propagate toward and across the shoreface. Challenges remain in identifying and developing appropriate technologies that can provide cost-effective, accurate measurements of nearshore and coastal bathymetry. This is particularly the case in shallower areas where the bathymetry needs be surveyed on a regular basis, as it can undergo rapid changes. 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 (e.g., Wilson and Power 2018) are not typically compiled despite the fact that they are vital for most coastal modeling applications.

Meeting such challenges, and delivery of a high-accuracy national coastal elevation dataset, spanning 50 m below to 20 m above mean sea level, has relevance well beyond that of the waves community, significantly improving our ability to model other hazards such as tsunamis and storm surges, 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 recognized for some time (COAG 2006) and its prioritization here again recognizes this. International programs such as the Nippon Foundation–GEBCO Seabed 2030 (Mayer et al. 2018) illustrate the widespread coastal, shelf, and ocean mapping applications required to support justification of this priority task at the national scale.

2) Improved understanding of extreme sea states. An ability to accurately measure, 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. Australia is a continent that experiences a range of wave climates, including extreme conditions. The southern coast of Australia faces the Southern Ocean, one of the most consistently rough oceans in the world (Young 1999; Cardone et al. 2014; Young and Donelan 2018). On both the northeast and northwest coasts the wave climate is mostly benign but punctuated by intense tropical cyclones which generate extreme waves. The central east coast is impacted by decaying tropical cyclones from the north and intense east coast lows that develop in the western Tasman Sea.

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, for example, WAVEWATCH III (Tolman and WAVEWATCH III Development 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); better understand wave measurements, particularly for extremes; extend the duration, spatial density, and accuracy of satellite data; and refine extreme value statistical projections.

3) Maintain and enhance the in situ buoy network. 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 seven different agencies, predominantly state governments (Queensland, NSW, and Western Australia), the Bureau of Meteorology, and industry-contributed data (Pilbara Ports, Woodside, and ESSO). The depth of deployment for these buoys ranges from 10 to 125 m. This is a disconnected network, in that each custodian operates their set of buoys independently, with little coordination between agencies.

The global network of in situ buoys is dominated by the U.S. and Canadian networks in the northern Atlantic and Pacific Oceans and buoys in the European shelf seas. In situ wave observations are particularly sparse in the Southern Hemisphere. The Data Buoy Cooperation Panel (DBCP) has identified that in situ wave observations in the Southern Hemisphere are urgently needed to support maritime safety services, calibration/validation of satellite wave sensors, and a range of other activities (DBCP 2015).

While the Australian network has a relatively broad coverage, some notable gaps are present. Greenslade et al. (2018) analyze the CAWCR wind-wave hindcast (Durrant et al. 2014) to determine the extent to which Australia's waters are represented by the current distribution of wave buoys. They identify a number of gaps, including eastern Tasmania and the Northern Territory coastline.

Recent developments have seen the emergence of smaller and lower-cost wave buoy instruments (e.g., Spoondrift Spotter; Smit et al. 2017). Several Australian research groups and state agencies have purchased these devices to support process studies and event monitoring and to assess performance, but longevity, accuracy, and comparability (Swail et al. 2010) have not yet been demonstrated for a sustained observation system.

4) Improved data access and sharing. As noted above, the publicly available Australian wave buoy network is operated by a number of different agencies, some state-based, some federal, and some provided by private industry. As a consequence, it can be a cumbersome and time-consuming process to acquire a set of wave observations for any national- or regional-scale study. 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 (portal.aodn.org.au), which has commenced the process of seeing the public buoy data, in both real-time and delayed mode, being made more accessible to the Australian marine data user community.

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, and now the ESA Seastate CCI program. Continued effort, however, is required. The IMOS SRS Surface Waves subfacility is addressing this challenge, to strengthen Australian capability in wave remote sensing, support calibration/validation efforts in the Australian/Southern Hemisphere region, and facilitate uptake of data among local users.

The accessibility and sharing of bathymetry data are also an issue. This has been challenging in the past due to the absence of a nationally coordinated program. AusSeabed (ausseabed.gov.au) is a national initiative established to facilitate the collaborative collection and update of seabed mapping data within Australia's maritime jurisdiction and provides access to various existing bathymetric datasets.

5) Ensemble and probabilistic wave modeling and forecasting. In recent years, weather forecasting techniques have shifted from strongly deterministic methods to approaches in which probabilities are explicitly included in the way forecasts are made and communicated. One of the key techniques in making this change has been to use an ensemble of forecasts rather than a single realization (NRC 2006).

Ensemble systems aim to provide not only a forecast of future conditions, but also the likelihood of that forecast. Traditionally, an ensemble forecast is created through perturbing initial conditions and evolving a number of dynamic models in time from those initial conditions. 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, for example, *there is a 40% probability that significant wave height (Hs) will exceed 5 m*, or, *the Hs that has a 5% probability of being exceeded is 7.4 m*. These sorts of probabilistic forecasts can be very useful for decision-making. However, education on the use of probabilistic forecasts is vital so that end-users fully understand their meaning and are able to maximize their potential in decision-making.

Ensemble systems require very large computational resources and so are mostly run by centers 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 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 on the northwest shelf of Australia (Zieger et al. 2018).

The main research issues for ensemble systems, in addition to the education of users noted above, relate to the development of techniques to perturb the forecasts, in order to improve the skill and spread of the ensemble and provide more reliable and accurate probabilistic forecasts. Given the extensive computational requirements, research into aspects such as how best to make use of newly developed hardware and/or computing protocols (e.g., cloud computing) is also necessary.

Tier 2 priorities

6) Advancement of remote sensing capabilities to measure wave conditions in coastal environments. Satellite remote sensing (SRS) can generally provide good-quality open-ocean observations (noting that new sensors require validation and calibration), but 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, for example, Satellite with Argos and AltiKa (SARAL) incorporates a relatively small antenna beamwidth that reduces the size of the altimeter's footprint, allowing wave estimates closer to the coast. The future SWOT mission with its wide-swath altimeter also has potential application for resolving nearshore wave fields.

In addition to SRS, waves are retrieved from other remote sensing platforms [i.e., shore-mounted platforms, unmanned aerial vehicles (UAV), 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.

Fewer than ten shore-mounted video systems [Autonomous Real-Time Ground Ubiquitous Surveillance (ARGUS) or similar] are deployed in Australia, and distribution is very sparse, focused on the Sydney and Gold Coast beaches, with two systems recently installed on the Western Australian coast. This system has many applications predominantly focused on morphological change in the littoral zone—quantifying storm-driven shoreline change and measurement of surfzone bathymetry, among others.

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.

Wind waves can facilitate or moderate the ocean surface currents in two major ways. The first is via the Stokes drift due to the nonlinear nature of surface waves. The second is via the transfer of energy to the currents through wave-breaking and other processes in the ocean-interface system. These processes are further complicated by the fact that waves and wave breaking have features of a random process on the two-dimensional ocean surface. Wave-induced surface currents, therefore, will have features of two-dimensional turbulence behavior.

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, parameterized in some way, can account for surface currents resulting from the wind forcing. Wind tangential stress does indeed generate surface currents directly, but for wind speeds greater than 7.5 m s^{-1} most of the wind stress goes to generating wind waves (e.g., Kudryavtsev and Makin 2001). Under these conditions, only a small component of the surface current is directly related to the local wind, so a parameterization based on local wind stress is not entirely appropriate—see Babanin et al. (2017) for a recent review of the wave–current interaction problem.

8) Long-term beach/coastline monitoring. The ability to quantify and model contemporary and future coastline variability and change at a range of time scales offers the very real potential to inform and guide future development and economic growth around Australia's open coastlines. 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. While there is some overlap here with obtaining nearshore bathymetry and topography data (section "Enhanced and updated nearshore and coastal bathymetry"), this priority focuses specifically on the nature of the shoreline over long periods of time.

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, and largely uncoordinated. As a result, the coverage and sustainability of these observations is unsecured, incomplete, inadequate, and largely inaccessible.

Fundamentally, and irrespective of the coastline modeling 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.

9) Nearshore modeling and forecasting. The nearshore zone defines the critical interface between the land and ocean, containing a large diversity of coastal environments (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, and security. To effectively manage coastal regions requires a detailed understanding of nearshore processes and, in particular, an ability to predict changes.

Predicting nearshore processes remains a great challenge given 1) the highly nonlinear nature of the hydrodynamics, 2) the wide range of spatial and temporal scales that must be considered, and 3) the complexity of nearshore bathymetry that can also rapidly evolve. For most of Australia's coastline, 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. In sufficiently shallow water, groups of incident swell waves break in the surfzone, and through nonlinear transfers of the swell energy, a range of other flows are generated, including mean wave-driven currents, infragravity waves (with periods of 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, and potentially coastal inundation in extreme events (see the "Improved understanding and prediction of coastal wave impacts" section). The accurate characterization and prediction of these processes represents arguably the greatest challenge in nearshore hydrodynamic modeling.

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. 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, for example, 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).

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). However, the DA was not implemented when the operational wave modeling framework was transitioned from WAM to WAVEWATCH III. Part of the reason for this was that as numerical weather prediction (NWP) and wave models improve in accuracy (due to higher resolution, improvements to physical parameterizations, etc.) the incorporation of wave data assimilation becomes a lower priority compared to other possible wave model developments such as ensemble systems or coastal modeling. Indeed, the results of the present priority ranking have supported this.

11) Development of a standardized data and QA/QC specification for wave observations. Observations of the sea state can be presented in several forms, such as directional energy spectra or nondirectional wave parameters, depending on the level of processing of the "raw" sensor observations. This allows for many levels of variability in the type, quality, and reliability of the observations.

At present, within Australia one will encounter wave observations from a variety of sources and providers across the community, and these observations exist in many ad hoc legacy standards and data formats, and often with limited metadata. Metadata often lack the comprehensive information that is required to fully understand the measurements. This variability in the reliability, provenance, and quality standards of the data reduces the interoperability and usefulness of data. Standardization of the data and metadata will enable the necessary transparency and interoperability for the community to fully realize their value.

The process of maintaining data quality from a metocean device network relies on both quality assurance (QA) and quality control (QC). The QC processing of wave observations will differ according to the intended use of the data, for example, provision of real-time swell spectra versus long-term climatological studies. Understanding the limitations of wave data through provision of metadata is essential to ensure that data are used to their fullest potential and not used erroneously. As such, a QA/QC framework is complementary to metadata conventions. An established standard for a QA/QC framework is Quality Assurance/Quality Control of Real Time Oceanographic Data (QARTOD), developed by U.S. Integrated Ocean Observing System (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.

12) Better engagement of maritime industries with research. While there may be a perception that strong ties between industry and research could limit scientific independence and objectivity, better engagement will ultimately lead to enhanced decision-making. 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 direct pathway to application via a potential alternative source of funding beyond the public purse.

Within Australia, the Australian Research Council (ARC) Linkage Program incorporates a number of schemes that aim to promote collaboration and research partnerships between stakeholders in research and innovation, including higher-education institutions, government, business, industry, and end-users. Furthermore, a significant amount of research is directly 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.

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.

13) Improved understanding and prediction of 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 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 along Australia's open coastlines.

Wave runup by extreme wind waves impacting the coast can generate wave overtopping of natural sand dunes, engineered coastal protection structures, and rock platforms. Along much of Australia's sandy coasts the overtopping of dunes and resulting inundation of low-lying coastal land is relatively rare and tends to be localized, due to the prevalence of well-developed coastal barrier systems; however, it is highly relevant in regions where rocky shore platforms are present.

Accurate prediction of wave runup levels is critical to the engineering design of the crest level and stability of coastal protection structures. For coastal planning and management the prediction of maximum wave runup determines the landward limit of beach and dune coastal erosion that is anticipated during storm wave events.

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, and second, through morphological change in nearshore areas. Morphological change will result from 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 and could potentially lead to chronic erosion.

Study of changes in future wave climate is a relatively new field. The first time waves were included with any rigor within an Intergovernmental Panel for Climate Change assessment was in the Fifth Assessment Report in 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 Programme sea level conference (Stammer et al. 2017). To date, the wave climate community has largely focused on the effects of changes in atmospheric circulation on wave climate. While some robust features of change are apparent—for instance, the projected future trend toward increased wave heights in the Southern Ocean, of relevance to activities along Australia's southern and western coasts—considerable uncertainties exist with the future wave climate projections (Hemer et al. 2013; Morim et al. 2018).

15) Improved modeling of swell propagation. Swell refers to wind-generated waves that 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 and recreational activities and can also have a major impact on offshore platforms and operations. While integrated parameters such as Hs are generally well forecast by third-generation wave models such as WAVEWATCH III, the energy distribution across the wave spectrum is often poorly described. In particular the low-frequency swell component can be poorly predicted, in terms of both 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.

To better understand the modeling problem, the evolution of swell should be measured along its propagation path, which can be thousands of kilometers 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. 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 modeling community.

Discussion

We have presented 15 priorities for wind-waves research, which have been identified via an extensive stakeholder engagement process across the Australian marine research and industry sectors. These priorities, while derived from an Australian perspective, are likely to be widely applicable to the needs of other marine communities internationally. However, in some instances, an Australian bias is likely evident.

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, a figure expected to increase (Australian Bureau of Statistics 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), and residential property ($41–63 billion) (DCCEE 2011). No less significantly, the cultural and economic value of beaches is also well recognized and helps define the Australian way of life. For example, the NSW government has ranked beaches in its top four most valuable natural resources (Gillespie and Clarke 2005).

A possible issue that arises when attempting to prioritize research activities is the need for a certain level of categorization of the activities, and the possibility that different categorizations might produce different results. An example in the present case is number 14, "Improved understanding of the effect of future climate variability and change on coastal areas." Under the final categorization 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 categorization.

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 1) research activities to increase our understanding (e.g., extreme sea states), 2) tasks or community-based activities (e.g., data sharing), and 3) 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 et al. (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 top-ranked priorities 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-focused 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 Fig. 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.

Interestingly, it can be seen that the priorities fall into three clusters. The first cluster includes the major infrastructure activities (bathymetry, wave

Table 1. Summary of the top-ranked research priorities. Priorities marked with an asterisk refer to items designated as "research." See "Discussion" section 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 the in situ buoy network
4	Improved data access and sharing
5	Ensemble and probabilistic wave modeling 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 modeling and forecasting
10	Development of wave data assimilation
11	Development of a standardized 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 modeling of swell propagation

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-focused activities. A second cluster includes research-enabling activities that do not 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 modeling, and nearshore modeling). 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.

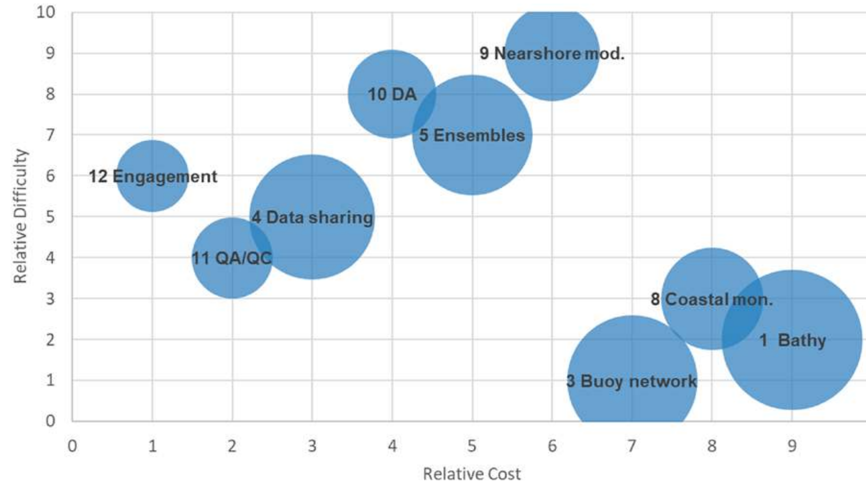

Fig. 1. An assessment of the "feasibility" of each priority. The size of the circles and the numbers within the circles represent the priority rank as listed in Table 1. Relative cost ranges from 1 (low cost) to 9 (high cost) and relative difficulty ranges from 1 (low difficulty) to 9 (high difficulty).

Importantly, this figure can give an indication of the "low-hanging fruit," that is, 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. Number 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 the "Improved data access and sharing" section.

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 organizations as to how they might prioritize 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.

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