Ocean Extremes

A contribution to the theme –
'Dealing with climate change'
as part of the National Marine Science Plan white paper

Abstract

Ocean extremes considered in this paper are:- (i) extreme sea levels due to storm surges and waves, their link to severe storms and circulation and their impacts on the terrestrial environments through coastal flooding and erosion and marine environment through enhanced turbidity and turbulence impacts on marine biodiversity and (ii) extreme ocean temperatures and their impact on marine biodiversity. This paper focuses on the biophysical science that underpins decision making for effective adaptation to extremes and climate change. The paper does not deal with ocean biochemistry changes or regional sea level rise which are each separate subtheme of this white paper although the strong connections with these disciplines are noted. The paper also does not deal with the socio-economic and policy aspects of adaptation - it is understood that such issues will be a focus of NCCARF over the coming 3 years.

Background

A changing climate can cause changes in the frequency, intensity, spatial extent, duration, and timing of ocean extremes [1]. Understanding the factors that cause extremes and their trends under present climate conditions is fundamental to determining impacts for the future. Furthermore, understanding the response of systems (physical, ecological and social) to extreme events is essential to managing and adapting to those extremes in the face of a changing climate [2].

Ocean extremes include those related to sea level (e.g. storm surge and wind-waves) and their meteorological drivers (e.g. extreme weather events such as tropical cyclones and other storm events), coastal currents and extreme temperature events. Also relevant are the physical and biological consequences of extreme events and compound events, which may not be considered notable in isolation but combine with other factors to cause extreme impacts. Examples include moderate storm surges that combine with high waves, high tides and/or sea level rise [3], or high rainfall coinciding with high coastal sea levels[4], [5] to increase the frequency or extent of coastal flooding. Extreme ocean temperatures during marine heatwaves occurring in an already warming climate, coupled with decadal climate variation, can be disastrous for marine ecosystems [6],[7].

Shifting ocean temperature extremes alter habitat, impact ecosystem health and cause changes in abundance of marine species through local extinctions for species already living close to their upper and latitudinal expansions or shifts. Tropical marine species that are already living close to their upper thermal limits will be most affectedInteractions of temperature, ocean acidification, and hypoxia narrow thermal ranges and enhance sensitivity to temperature extremes in organisms such as corals, coralline algae, mollusks, crustaceans, and fishes [7]. Increased ocean temperatures can intensify coastal storms leading to larger storm surges, waves and coastal impacts [8].

The topic of ocean extremes is therefore highly multidisciplinary involving consideration of processes operating in the oceans, atmosphere, coastal waters and the terrestrial environment. The following lists the large number of institutions and agencies that are primarily involved in this research.

	Research Group	Funding	Key References
Coastal Sea-Level Extremes including storm surge, coastal sea level, inundation	CSIRO O&A ACE CRC UNSW WRL BoM Griffith U UWA UQ Macquarie Uni	CSIRO DOTE DFAT State Govt Local Govt WAMSI, ACE CRC, BNHCRC NSW OEH	[9], [10],[11],[12],[13],[14],[15],[16],[3]
Wind-Waves	CSIRO O&A Swinburne UWA BoM Macquarie UNSW WRL	CSIRO DOTE DFAT ARENA O&G ARC BoM State Govt NSW OEH	[17],[18],[19],[20],[3],[21]
Tropical Cyclones	BoM CSIRO O&A U Melb, UWA UTAS, Macquarie	ARC	[22], [23],[24],[25]
Compound (including coincident) Extremes	U Adelaide CSIRO L&W	GA	[5], [2] , [4], [26]
Tasman Lows	BoM Macquarie Uni	NSW OEH	[27]
Coastal Erosion	CSIRO O&A UNSW WRL UQ Macquarie Uni	DOTE GA State Govt Local Govt	[28],[29],[30],[31],[32],[33], [34]
Ocean Temperature Extremes and impacts	U Melb CSIRO O&A UWA IMAS	ARC	[6],[35],[36]
Coastal Adaptation	CSIRO L&W; CSIRO O&A U. Sunshine Coast NCCARF UNSW WRL Macquarie Uni	DOTE CSIRO GA State Govt Local Govt NSW OEH	[31],[32],[33],[34]

Relevance

Ocean extremes have wide-reaching impacts on natural and human systems that extend from the continental shelf seas to the coastal terrestrial environment. Australia is a coastal nation and is therefore extreme sea levels are a particular concern.
Recent estimates by the Climate Council [37] are that almost 250,000 homes around Australia worth about $72 billion are vulnerable to a 1.1 metre rise in sea levels. Key infrastructure (road, rail, ports, airports, water and wastewater services, energy and communications), public assets (schools, hospitals, parks etc) and commercial assets swell the national sum that is at risk to about $226 billion. Future population and economic growth will put more assets in harm's way. A high proportion of these costs may devolve to local government.

Research into ocean extremes is relevant for Engineers Australia, the peak organisation for professional engineers, which provides definitive guidance for good practice in hydrology, water resources, hydraulics and flood estimation via the publication Australian Rainfall and Runoff. This document is presently being revised and updated to incorporate recent research and considerations of climate change. Engineers Australia also provides guidance for ecologically sustainable engineering and management of the coast including adaptation responses to climate change [53], [54], [55].

The impact of extreme ocean temperatures on Australia's unique ecosystems (e.g. [38],[39],[35],[40]) are potentially significant for a number of industries. These include Australia's aquaculture and fisheries industry, worth about $2.23B and tourism industry both of which rely on a healthy, productive marine environments.

Attributes of waves such as extreme wave height, power and direction and the influence of climate variability and change on these attributes is relevant to a range of stakeholders including coastal managers, coastal councils, coastal engineers, the oil and gas industry and the renewable energy industry. The emerging ocean renewables sector and Oil and Gas Industries, need to understand effects of variability and change of extremes for platform/device design on planning horizons of decades.

DFAT programs benefit from better scientific understanding of climate extremes to assist with emergency response to disasters and adaptation planning activities for Australia's regional neighbours. Small Island Developing States in the region are particularly vulnerable to oceanic extremes that affect safety and food and water security [41]. In the context of long term changes in climate and sea level, these locations may become unliveable thereby creating environmental refugees.

A range of other beneficiaries of oceanic extremes research include all tiers of Australian government, coastal planners, insurance/reinsurance agencies, the transport sector (e.g. shipping, airports, rail and road) and associated facilities, the tourism sector, energy industries, emergency management agencies, coastal councils, offshore industries, such as shipping, fishing and oil and gas industries, the defence forces and search and rescue agencies.

Science needs

Significant physical, environmental and socioeconomic impacts are realised through extreme events and so improved understanding of many aspects of extreme events is needed to address the significant risks they pose to the Australian community. Major scientific questions are posed below with discussion of the science needs. The strong linkages between the 'Sea level and ocean heat and freshwater content' and 'Ocean biochemistry changes' subthemes to this white paper are also noted.

- Historical changes in extreme sea levels and extreme waves need to be better understood

Current observational records of waves and sea levels are sparse in space and time. This hinders reliable assessments of present climate risk and trends in these variables. Understanding how extremes of these variables relate to natural modes of climate variability (e.g. El Nino Southern Oscillation) and climate change (i.e. detection and attribution) is important to better constrain projections of future changes and reduce uncertainty. Greater research efforts are needed to address these issues. Geohistorical studies of coastal evolution and paleoclimate wind-field reconstructions are also relevant since they can highlight the much larger variability in wave climate change and range of coastal responses over longer historical periods (e.g. [42],[43],[44])

- Causes of extreme impacts need to be better quantified

Extreme impacts may be the result of a number of influences including natural variability, climate change and other anthropogenic factors. For example changes in shoreline position may be due to natural climate variability [45],[46],[21] rising sea levels or changed coastal conditions due to human development. Attribution of extreme observed events to multiple causes (i.e. fractional attribution of risk) provides an important foundation for mitigation and adaptation to extreme events.

- Improved understanding of severe weather events (e.g. tropical cyclones and East Coast Lows) in the context of climate variability and change.

Ocean extremes such as waves and storm surges and coastal impacts such as erosion and inundation are caused by severe weather events. Therefore improved theoretical understanding of the relationship between severe weather events and climate is needed to improve modelling capability and reduce uncertainty in climate model projections of changes to the frequency, intensity and region of influence of severe weather events in the future. Also important is the sequencing of storm events which can determine the severity of the impacts. Paleoclimatic studies can also shed light on the larger variability in storm systems over longer historical time periods (e.g. [47], [48], [49], [50])

- Projections of future changes to waves and surges

The most recent IPCC assessment assigns low confidence to projections of changes to waves and storm surges caused by severe storms [51]. This is due to the limited number of studies, limited regional coverage (in the case of storm surges) and large uncertainties in model projections. Additional effort is needed to quantify future changes and their uncertainties through enhanced and coordinated modelling efforts.

- How will compound events influence extreme impacts?

Extreme impacts may be influenced by multiple dependent variables. Obvious examples include high waves with extreme water levels and/or catchment floods combined with high tides and storm surge, various combinations of which may share the same causal mechanism [5], [3], [4]. Other examples, include episodes of high ocean temperatures and the occurrence of tropical cyclones, both of which are influenced by climate variability (e.g. ENSO), which could have profound impacts on marine ecosystems such as coral reefs. The present likelihood and future changes to compound events such as these are poorly understood [2].

- How will shoreline position (i.e. erosion & deposition) respond to changing mean sea level and extreme events such as storm surges and waves along different coastal types (e.g. sandy beach, rocky and coral reef coastlines, estuaries and coastal waterways?)

Erosion assessments to date have been largely based on a simple Bruun rule calculation because of its ease of application, but the accuracy of this simple approach has been questioned [52] and use of more sophisticated probabilistic and risk based approaches recommended [53]. Considerable effort is needed to develop and test additional models and methodologies for modelling shoreline change within the coastal compartment framework.

- Extreme ocean temperatures change and ecological impacts

Examples of recent ocean temperature extremes [6] and their impacts on marine biodiversity [35] have been recently documented. Further research is needed to establish future ocean temperature extremes and their impacts on unique marine ecosystems around Australia to identify host ecosystems that are particularly vulnerable and need protection. Development of improved forecast tools for extreme ocean temperature events to support management of reefs and fisheries is essential [54].

- What is the influence of ocean extremes on estuaries and coastal water ways?

The number and value of properties and assets that may be impacted by ocean extremes within estuaries is at least an order of magnitude higher than those on the open coast. Storm surges and sea level rise are generally translated unattenuated from the open coast into harbours, bays and estuaries. The wave setup that occurs with high waves breaking close to shore can also be translated in part across tidal entrances and into estuaries leading to an additional increase in extreme water level. The interactions in space and time of tide, surge, wave setup and catchment flooding make the risk assessment of extreme water levels and inundation within estuaries one of high complexity. Significant research has been undertaken [55], [56], [4] but much more is needed.

- What new types of extreme events can be expected?

A changing climate may cause new types of extreme events to occur in regions where they have not previously been experienced. Examples include movement of weather systems into new regions, algal blooms, unusually cold summers/warm winters, shifts of monsoon seasons. Analysis of climate model simulations and targeted impact model studies provide a means to assess the likelihood of new types of extreme events occurring.

- What are the likely impacts of extreme events beyond Australia’s borders?

Small island developing states in the Pacific and Indian Oceans experience hazards from ocean extremes that are specific to their particular coastal morphology. An example is severe inundation and saltwater contamination of freshwater supplies and food crops due to remotely-generated swell waves [41] with such events having led to widespread disasters [41]. Enhanced research efforts that include quantifying these present risks and predict future changes to these risks are needed to ensure appropriate disaster planning and adaptation to extreme events is undertaken in the region. These risks equally apply to various Australian islands such as those in the Torres Strait.

Perspective

Sea Level Observations
In Australia, a set of high quality tide gauges that are monitored for land motion are maintained by the Bureau of Meteorology to provide information on long term sea level changes. Additionally sea level data is also available from tide gauges operated by state authorities such as ports and catchment authorities. Australia also funds a network of high quality gauges throughout the South Pacific. The high quality Australian and South Pacific observations feed into the international GLOSS programme.

Wave Observations
Wave monitoring in Australia is undertaken by state authorities and the data coverage is patchy. For example, the NSW coast is well sampled, yet the southern Australian and Tasmanian coastlines (which experience considerable swell from the southern ocean) are poorly sampled. Additionally many of the existing wave buoys record only wave height and period and not wave direction. In some regions of Australia such as the northwest shelf, wave buoys may be operated by the oil and gas industry but the data is not readily available to the research community.

Modelling of Waves and Extreme Sea Levels
For extremes research, many tide gauge records, particularly those in the tropics, are too short to provide reliable estimates of extreme sea level occurrence, because the meteorology causing extreme sea levels (e.g. tropical cyclones) are of relatively small scale and of low temporal frequency to be adequately sampled by the available gauges. Modelling is needed to enhance extreme sea level information at locations not sampled by tide gauges (e.g. [15],[16],[57]) and further efforts to improve the resolution and representation of the processes in models would be beneficial.

Underpinning coastal modelling efforts is the need for sustained funding into atmospheric modelling to ensure improvements in the representation of extreme weather events that provide the forcing for extreme sea levels and waves. Improved modelling of geophysical processes would also support research into extreme impacts from compound events. For example a better understanding of the timing of potentially coincident events (e.g. peak river flow and storm surges [4] could reduce the number of 'conservative' assumptions embedded in statistical models of compound events.

Future Projections of Waves and Extreme Sea Levels
Recent IPCC reports assign low confidence to regional projections of waves and storm surge. For waves, this is because to date studies on past wave climate change and future projections on a global scale are only just emerging as part of an international coordinated program between relevant international agencies (the Coordinated Ocean Wave Climate Intercomparison Project, COWCLIP [17]), which is led by Australia with funding from the Australian Climate Change Science Programme (ACCSP) and endorsed at the international level by JCOMM and WCRP. Continued effort is needed to obtain maximum benefit from this project.

For storm surge the 'low confidence' in projections reflects the limited number of regional studies available, which are largely not comparable because of the different assumptions, models or climate change scenarios that have been used. A similar international coordinated effort is needed for storm surge modelling across key international agencies responsible for this work to develop more robust storm surge projections under future climate conditions. The extent to which these coastal extreme events vary over longer time-scales remains an open question, but in some instances, shoreline position may be more vulnerable to changes in these processes than sea-level.

WCRP has identified a number of scientific 'Grand Challenges' (http://www.wcrp-climate.org/index.php/grand-challenges) as priority areas of research that focus on modelling, analysis and observations. Two of these Grand Challenge topics ('Climate Extremes' and 'Regional Sea Level Rise') have adopted extremes in sea levels and waves and shoreline response as important areas for future research providing the opportunity for enhanced engagement at the international level.

Coastline Monitoring and Modelling

The NCCARF-funded research project [31] provides a comprehensive overview of the various methods that may be applied to assess risk and adaptation to climate change on the Australian coast. More recently GA with DOTE funding mapped at Primary and Secondary scales the geomorphic compartments of the Australian coast [32]. Tertiary scale case studies for individual beaches on the East coast [34] and West coast [33] demonstrated best practice methodologies (ranging from deterministic to probabilistic) for the assessment of coastal erosion hazard and shoreline movement within an adaptive management framework.

To improve research into shoreline change including detection and attribution studies, improved shoreline modelling, and understanding the dependence between different variables that contribute to extreme impacts, nearshore and shoreline monitoring needs to be substantially increased. This includes measurements of coastline position, nearshore waves (possibly via a network of wave-enabled HF radar), sea levels and currents. Also needed for coastal modelling is land elevation and coastal bathymetry and terrestrial inputs such as rainfall run-off.

To meet these needs, establishment of a Coastline Observatory (utilising latest technological instrumentation and on ground quality control) at 15 or more representative coastal shoreline sites chosen from the Coastal Compartment mapping information [31] is highly recommended. The information from the representative Coastline Observatory sites is essential to the establishment of benchmark data for testing the performance and reliability and ultimately the acceptance of existing and new coastal process modelling systems.

Ocean Temperature Extremes

Marine heat waves are emerging as a topic of great interest and research effort internationally. Australia hosts a range of unique marine ecosystems from tropical coral reef communities to temperate kelp forests, and these ecosystems are under threat from the combined impacts of global warming and changes to the frequency and magnitude of marine heat waves. Australia has the opportunity through its highly-skilled scientific community, to become a clear leader in research, monitoring and prediction of marine heat waves with both national benefit and international value .

Emergency management

The costs of recovery from extreme events and disasters can be devastating to an economy if the magnitude of the hazard, impacts and risks are underestimated [58]. The effectiveness of emergency management in dealing with extreme events and minimising loss of life and property/infrastructure is reliant upon scientific information on the likely occurrence, severity and timing of extremes. Improving the accuracy, reliability and robustness of the various methods and models for simulating biophysical processes, impacts and quantifying adaptation responses is needed to support emergency management.

Realisation

To support research efforts into ocean extremes there is a need to increase observational data both temporally and spatially.

Sea Level Observations

It is important that sea level observations receive sustained funding to ensure that the network is maintained into the future. Long sea level records are also lacking in Australia with only two locations where records extend back to the late 1800's. While additional long records exist at several other locations in Australia, they have not been digitised and quality controlled. Where possible, the existing network should be boosted by digitising older chart records. Such efforts could link into international efforts on data rescue such as occurs within ACRE (Atmospheric Circulation Reconstruction over Earth) [59]. This initiative is looking to expand its efforts into rehabilitation of marine observations.

Wave monitoring

Understanding historical variability of wave climate extremes is severely limited by an inadequate national wave observing network. While in some instances the near-shore wave climate is well understood (e.g., NSW), availability and distribution of accessible, long, directionally resolving wave records is very limited. Coordination of current, predominantly state-based, wave network should be considered a priority.

Satellite Observations

Increased exploitation of satellite observations of wind, waves and sea levels over recent decades provide increased data coverage spatially. Computer reanalyses [60] and data reconstructions [61], [62], [21] provide a representation of the data at regular spatial resolution and stretch further back over time and therefore provide a valuable source of 'pseudo-data' for science research. However such products need to be maintained, refined and updated from time to time, and then reassessed against available observations before they can be used for research purposes. Activities that boost the spatial and temporal coverage of these data sources also require resourcing.

The southern ocean is an important source region for midlatitude extremes but is least covered by observations. A comprehensive database of relevant satellite observations, formatted, validated and calibrated throughout the decades of observations should be undertaken in the short term and where possible, in situ observations in the Southern Ocean be increased, particularly since a significant part of this Ocean is the area of Australia's responsibility.

Wave and Surge Modelling

Efforts to improve confidence in future wave climate changes through the efforts of the Coordinated Ocean Wave Climate Intercomparison Project [16] must continue to obtain maximum benefit from this endeavour. A similar effort is needed for storm surge modelling across key international agencies responsible for this work to develop more robust storm surge projections under future climate conditions.

Atmospheric drivers of ocean extremes

Better understanding of what causes extreme ocean events under baseline (i.e. current climate) conditions is needed as a foundation for understanding future changes, using both theory and models. Therefore strong connections are needed with the atmospheric research community. Similarly understanding of changes in extreme storms and their impacts could benefit from strong linkages to the Paleoclimate research community.

Coastline Observations and Modelling
Modelling of coastal change and impacts requires accurate data on terrain elevation in the coastal zone but also near shore bathymetry to enable satisfactory transformation of waves and storm surges from deep water onto the coast and within estuaries. Accurate terrain elevation data is increasingly available from airborne Light Detection and Ranging (LiDAR) surveys. For the coast Laser Airborne Depth Sounder (LADS) surveys can provide accurate nearshore bathymetric surveys but are more costly than LIDAR with limited coverage. Much of the available bathymetry for the Australian coast dates back to the 18th century. Around Australia, terrestrial LiDAR surveys are increasing but mostly limited to population centres. LADS surveys are more limited. The only state that has a complete seamless survey of elevation between around 10 m to -20 m elevation is the State of Victoria. For coastal compartments and estuaries of identified value and significance, funding and completion of accurate bathymetry for coastal risk assessment and effective adaptation is necessary.

Coordination of existing elevation data sets would be of benefit to the research community who often need to spend valuable resources tracking down and accessing available data and often duplicating efforts of others who have faced similar problems before them. A central repository for such data for the research community would increase efficiencies.

Surveys of shoreline change and monitoring of coastline processes need to be substantially increased. This includes measurements of coastline position, nearshore waves (possibly via a network of wave-enabled HF radar), sea levels and currents. Establishment of a Coastline Observatory (utilising latest technological instrumentation and on ground quality control) at 15 or more representative coastal shoreline sites chosen from the Coastal Compartment mapping information is highly recommended. The value of the longer term beach profile datasets from Moruya , Collaroy and-Narrabeen (NSW) is exemplified in the numerous Australian and international coastline modelling research publications based upon these data. The value and need for extended datasets at these and other locations as proposed in the Coastline Observatory is evident.

The information from the representative Coastline Observatory sites is essential to the establishment of benchmark data for testing the performance and reliability and ultimately the acceptance of existing and new coastal process modelling systems. Quality control, archiving and making the observatory data available to coastline modellers worldwide would be a key function of the observatory.

Resourcing and Coordination
The topic of ocean extremes is highly multidisciplinary. To ensure that the benefits of scientific endeavour are maximised, the various contributing disciplines and agencies involved in this research require adequately funding. Many of the groups involved in ocean extremes research are experiencing significant funding pressures resulting in significant time and effort chasing limited funding opportunities rather than maximising their effort on advancing the science. Limited funding availability creates a highly competitive environment that reduce collaborative efforts between agencies.

Funding arrangements for scientific research differs between universities and other government agencies and this has limited collaboration between these different organisations. For example, universities who obtain ARC funding cannot easily engage with government agencies such as CSIRO or BoM. A Centre of Excellence or CRC on Extreme Climate and the Marine Environment is recommended for higher consideration. Its focus should be (as in this paper) limited to the biophysical processes, impacts and adaptation responses to existing extremes and those of the future with climate change.

Additional comments

As noted previously, additional topics that are relevant to ocean extremes are dealt with in other sub-themes of this white paper and include regional sea level rise, and extreme impacts due to acidification.

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Attachments

(sub-themes of the 'Dealing with Climate Change' white paper)

1. Sea Level (incl. global and regional changes in sea level, ice sheet processes, climate modelling)

2. Ocean Extremes (incl. sea-level extremes, TCs, coastal adaptation)

3. Coastal Oceanography (incl. WBC, near-shore flows, shelf /open ocean interaction)

4. Ocean biogeochemistry (incl. carbon cycle, ocean acidification, marine chemistry)

5. Tropical oceanography (incl. ENSO, IOD, interactions with the subtropics atmosphere-ocean interactions, MJO)

6. Mid- to high-latitude oceanography (incl. the overturning circulation, heat and carbon storage, Southern Ocean processes, ocean-cryosphere interactions)

7. Paleoclimate (incl. proxies, ice/sediment cores, marine geology, modelling)

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