Hindcast surface gravity wave modelling

Theme: Hydrodynamic Modelling

WAMSI Westport Marine Science Program

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ABOUT THE MARINE SCIENCE PROGRAM

The WAMSI Westport Marine Science Program (WWMSP) is a $13.5 million body of marine research funded by the WA Government. The aims of the WWMSP are to increase knowledge of Cockburn Sound in areas that will inform the environmental impact assessment of the proposed Westport development and help to manage this important and heavily used marine area into the future. Westport is the State Government's program to move container trade from Fremantle to Kwinana, and includes a new container port and associated freight, road and rail, and logistics. The WWMSP comprises more than 30 research projects in the biological, physical and social sciences that are focused on the Cockburn Sound area. They are being delivered by more than 100 scientists from the WAMSI partnership and other organisations.

FUNDING SOURCES
The $13.5 million WAMSI Westport Marine Science Program was funded by the Western Australian Government, Department of Transport. WAMSI partners provided significant in-kind funding to the program to increase the value to >$22 million.

DATA
Finalised datasets will be released as open data, and data and/or metadata will be discoverable through Data WA and the Shared Land Information Platform (SLIP).

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Contents

The WAMSI Westport Marine Science Program is a $13.5 million body of research that is designed to fill knowledge gaps relating to the Cockburn Sound region. It was developed with the objectives of improving the capacity to avoid, mitigate and offset environmental impacts of the proposed Westport container port development and increase the WA Government's ability to manage other pressures acting on Cockburn Sound into the future. Funding for the program has been provided by Westport (through the Department of Transport) and the science projects are being delivered by the Western Australian Marine Science Institution.

1 Hindcast surface gravity wave modelling

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Project

Theme 5.2a – Surface gravity wave modelling

Executive Summary

Westport requires a surface gravity wave model configured for local conditions to simulate wind and swell waves in Cockburn Sound. The primary scope of this project was to establish, integrate and validate a high resolution local spectral wave model for Cockburn Sound and to provide a 10+ year hindcast of the wave climate in Cockburn Sound. This report presents the wave model set-up and validation.

To achieve the aims of this project we used the Wind Wave (WWM-III) spectral model, an opensource code without any license constraints. The multi-decade global spectral wave model (WW3) outputs were used as boundary conditions. The WWM-III spectral model for Cockburn Sound is solving complex wave dynamics formulated on the unstructured finite element method and model grid with variable spatial resolution; the smallest elements distributed in the complex coastal environment. Results from the WA regional wave model was archived an hourly temporal resolution and full spatial grid providing a multi-year source for any additional locally – nested high resolution wave modelling studies requiring spatial resolution higher than 200 m. We simulated 13 years (2010 - 2022) of wave dynamics using the constellation of the global to regional Western Australian (WA) spectral models and validated the results at the available wave buoys. For Cockburn Sound, we set up an additional high resolution wave model nested inside our regional WA model with the spatial resolution up to 5 m inside the smallest element. This local model was configured to realistically capture features of the local area, for example the shipping channels. Results from the Cockburn Sound high resolution model was validated using field measurements from Project 5.1. The 13 year hindcast model of wave parameters (significant wave height; mean wave period; zero-crossing wave period; mean wavelength; mean wave direction; directional spreading; peak wave direction; peak directional spreading; wave-induced bottom orbital velocity) were output at hourly intervals which are now available through the WAMSI/WESTPORT data repository (https://catalogue.data.wa.gov.au/org/western-australian-marine-science-institution).

2 Introduction

Detailed understanding of the wind-wave climate within coastal regions is necessary for a variety of applications including coastal development, sediment transport and coastal erosion. Due to absence of long-term measurements of wave parameters within many areas, wind-wave characteristics are generally predicted using numerical models. This technique can be used to numerically simulate surface gravity waves (sea and swell) and predict wave energy from the ocean environment to coastal regions. These simulations consider atmospheric wind forcing, non-linear wave interactions, wave reflection, refraction and diffraction and frictional dissipation, as well as output statistics describing wave heights, periods, and propagation directions. Such wave hindcasts (historic conditions) and wave forecasts (future conditions) are extremely important for resolving many coastal processes including port operability; sediment transport; ecosystem modelling; dredge spoil dispersion and benthic habitat distribution.

The aims of Project 5.2 were to:

1. Configure a high resolution, validated local wave model for the Cockburn Sound region to accurately simulate wave parameters (wave height/period/direction). The model is to be compatible with other models, to be fit-for-purpose for both hindcast and forecast modelling and suitably configured to be integrated into the modelling platform being developed by WWMSP Theme 1 (Ecological modelling).
2. Complete wave modelling for decadal hindcast period to provide suitable boundary conditions for a port and channel operability model – in accordance with the requirements provided by Westport's Supply Chain Integrated Design consultant.

Over the past two decades, a number of spectral wind-wave models, known as third-generation models, have been developed globally. These models solve the spectral action balance equation without any *a priori* restrictions on the spectrum for the evolution of wave growth. They are based on the wave action balance equation with sources and sinks, and incorporates formulations for the deep-water processes of wave generation, dissipation and the quadruplet wave-wave interactions. In shallow water, these processes are supplemented with dissipation due to bottom friction, triad wave-wave interactions and depth-induced breaking.

Cockburn Sound is a semi-enclosed embayment that is relatively sheltered from the open ocean through the presence of Garden and Carnac islands and Success and Parmelia Banks. Due to these topographic constraints, the wave forcing is mainly through locally wind generated waves (periods < 8 s) and swell waves generated from distant storms (periods > 8 s). The longest periods of waves may originate in the Atlantic Ocean offshore from Brazil. Data obtained from the Stirling Channel (on the southern end of Kwinana Shelf) indicated the highest swell period energy was at 15 s and wind wave energy was at 3.5 s (Figure 1).

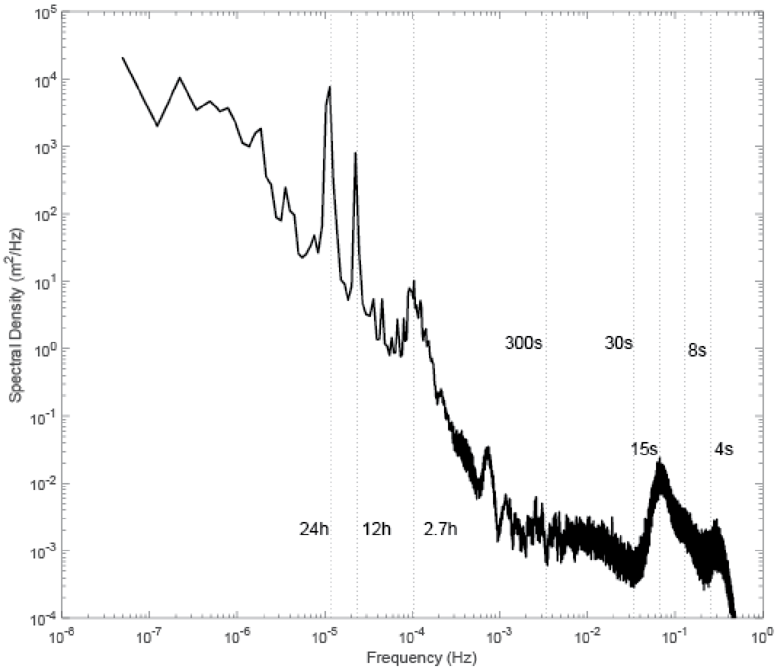

Figure 1. Wave spectrum from Stirling Channel (Kwinana shelf) using data collected by Fremantle Ports. Highest energy is at swell period of 15 s.

3 Materials and Methods

3.1 The Model: Wind Wave Model (WWM-III)

For this project we used the Wind Wave spectral (WWM-III) model (Roland et al., 2009, 2012). The model has very similar attributes to the Simulating Waves Nearshore (SWAN) model (same inputs and outputs), uses an unstructured grid but is more computationally efficient. This allows for the long, multi-decadal simulations to be undertaken, with high computational efficiency.

All wave models compute the evolution of the wave spectrum (energy in different frequencies) from one location to another in the ocean, by solving the Wave Action Equation (WAE):

Local evolution in time + [propagation + turning of the waves] = generation + exchange of energy - dissipation

This equation is written for different wave components (typically 24 directions x 32 frequencies), and these equations are coupled by the terms:

- "turning of the waves" (energy from one direction is shifted to energy from another direction)
- "exchange of energy": the different wave trains permanently exchange energy between them and with currents
- dissipation: the dissipation of one wave component is a complex function of the energy of all components
- generation: the amount of energy given by the wind to one wave train can also depend on the other wave trains

WWM-III solves the 2D wave spectrum equation (Wave Action Equation):

$$\frac{\partial N}{\partial t} + \nabla_x(XN) + \frac{\partial}{\partial \sigma}(\dot{\theta}N) + \frac{\partial}{\partial \theta}(\dot{\sigma}N) = S_{tot}$$

Where the wave motion index is defined as:

$$N_{(t,X,\sigma,\theta)} = \frac{E_{(t,X,\sigma,\theta)}}{\sigma}$$

where E represents the variance density of sea level elevation; σ is the relative fluctuation frequency; and θ is the direction of fluctuation. Wave propagation from deep to shallow water is accompanied by complex nonlinear processes, such as bed bottom friction, wave breaking and tumbling, and wave energy input imposed by the boundary, which are considered in the source terms of the equations. WWM-III is configured into a triangular unstructured grid.

The WWM-III incorporates the framework of residual distribution schemes (Abgrall, 2006) within a hybrid fractional splitting method using a third-order Ultimate Quickest scheme in spectral space, similar to the WAVEWATCH III (WWIII) model (Tolman, 1992). The numerical schemes for wave advection from WWM-III have also been successfully implemented into the new version of the WWIII model (Ardhuin et al., 2009; Ardhuin et al., 2010; Ardhuin and Roland, 2012). The WWM model has been shown to successfully simulate ocean and coastal wave conditions across a range of locations and scales including small scales in the Adriatic Sea [Roland et al., 2009], the Gulf of Mexico (Kerr et al., 2013), the Bay of Biscay (Bertin et al., 2015), and the South China Sea (Babanin et al., 2011). It is also being used by CSIRO in Port Phillip Bay, Victoria to determine future changes in wave climate.

The University of Western Australia West Australian WWM-III numerical model setup uses an unstructured finite element grid with spatial resolution along the coastline of ~500m. The model incorporates 36 spectral bins in frequency domain and 36 directions in the setup. Boundary conditions were applied at the model open boundary using information from the global WW3 - GFS model at 3-hour intervals. Atmospheric forcing was applied on the ocean surface and was based on the hourly high-resolution ECMWF - ERA5 re-analysis, consistent within 10 years of simulation. The model system is detailed in Figure 2. The global model has a resolution of 55km which is used as the boundary conditions to run the WWM-III model at 500 m resolution. The model provided boundary conditions for the Cockburn Sound model that also includes the surrounding ocean.

Global models, by definition, cover large areas, and as such, have relatively coarse spatial resolution (~ 10 - 25 km), and are not capable of resolving small scale coastal/bathymetry features. They predict global wave dynamics at multi-km resolution by using global atmospheric model wind fields at a similar spatial resolution as forcing. These models have low spatial (~10-25 km) and temporal (~3 hourly) resolution.

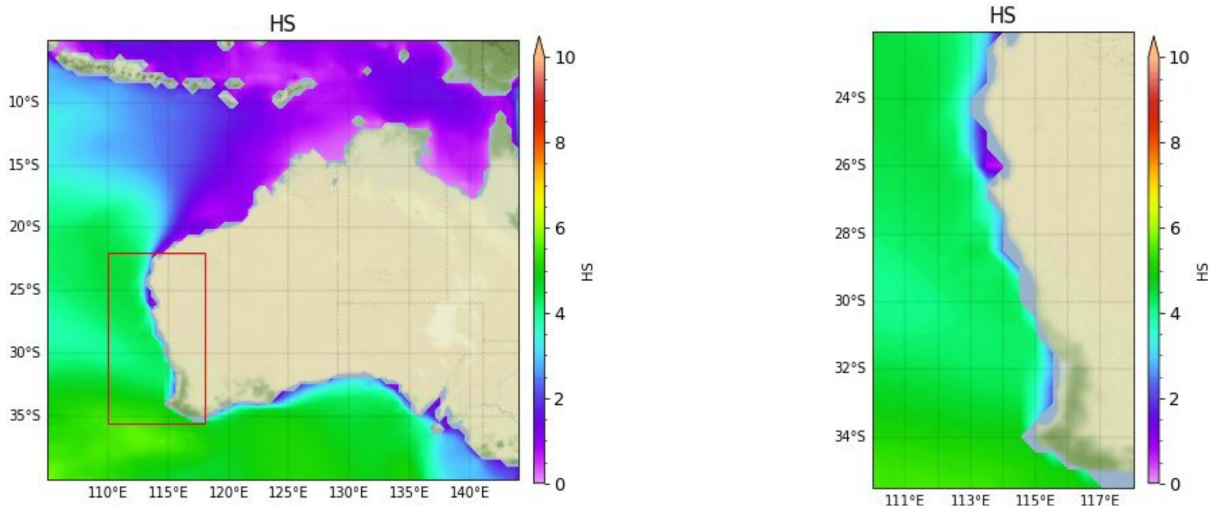

Figure 2. Significant wave height from the global WW3 wave model at 0000 UTC on 25 July 2020.

A first step in the model construction was to acquire the outputs from the global WW3 spectral wave model for the 2010-2022 period and create a subset for the Australian region (Figure 2). The locally archived WW3 database holds all necessary variables in the netCDF format (Hs, fp, dir, spr, t02 in WW3 terminology) needed to perform the downscaling (i.e. to provide boundary conditions for the local UWA West Australia (WA) spectral wave model).

To estimate more realistic wave dynamics apart from those already available inside the global models, a locally nested regional wave model needs to be setup. A crucial requirement for this is to resolve local bathymetry and coastline features, as well as to include a better physical parameterisation of wave interactions. At the first step, the regional models use global model boundary conditions defined at the open boundary and are forced with regional or the same global atmospheric forcing. In that sense, we setup and validated the regional WA unstructured – finite element spectral wave model (based on Roland et al. 2012: https://schism-dev.github.io/schism/master/index.html) using available field measurements along the WA coastline. This spectral regional wave model (Figure 3) can resolve major features along the WA coastline within up to 200 m horizontal resolution. It is based on the advanced spectral wave model formulation with source terms that includes non-linear interactions, wind wave growth and dissipation via white capping, bottom friction and wave breaking, as well as non-linear 4-wave interactions using Discrete Interaction Approximation (DIA), and Lumped Triad Approximation in shallow waters. It uses a time implicit advection scheme as currently available in the WW3 model. For coastal applications this resolution and model setup would suffice. However, for Cockburn Sound, we required an even finer model, nested inside the WA regional wave model to resolve complex bathymetry and coastal features in the area of interest (Figure 3).

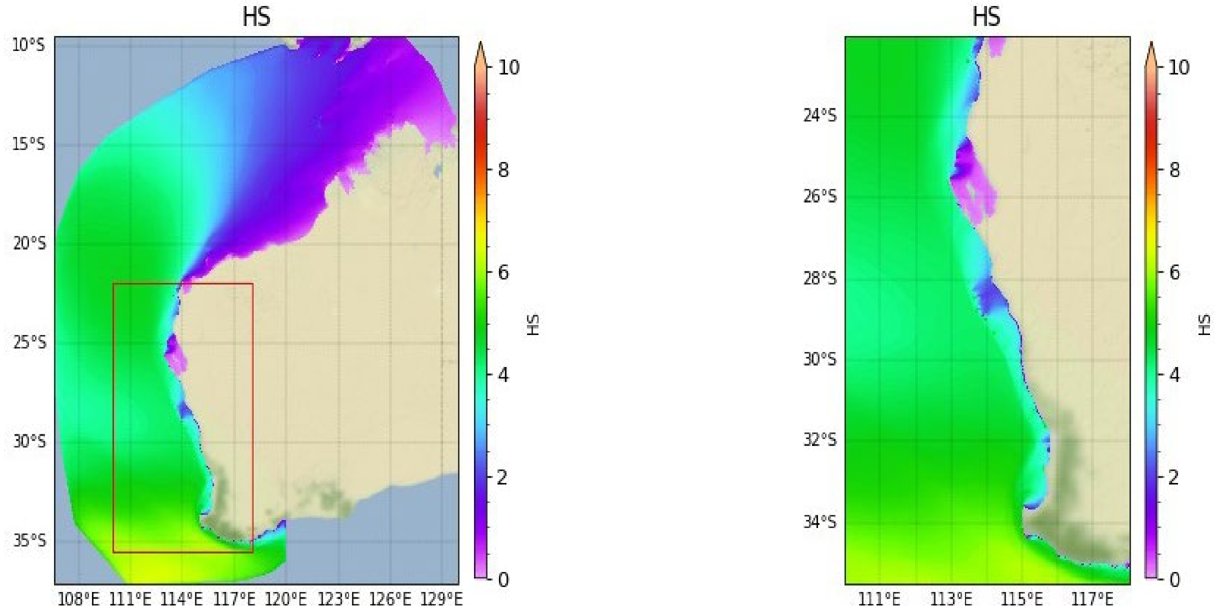

Figure 3. Regional WA spectral wave model and significant wave heights (left) and zoom to WA coastal region (right).

3.1.1 High resolution local wave model.

To develop a wave model capable of resolving the high variability in the local bathymetry, capturing the interactions between the island and reef systems, and include realistic wave energy spreading and dissipation, we setup another level of nested spectral model inside our regional WA model. It is important to note that to adequately generate wind induced waves, spatially and temporally, we needed a fine scale wind forcing (atmospheric model capable of resolving interactions between the ocean and the land – important for the sea-breeze coastal system). To that end we used 2-way nested WRF-ARW atmospheric model providing local winds at the 2 km spatial and 1-hour temporal resolution.

The simulations during the period 2010- 2022 were made using a 2-way coupled system available within the SCHISM 3D hydrodynamic - wave modelling framework. This allows for inclusion of sea level (e.g. tidal and non-tidal water levels) and ocean currents to the spectral wave model and the wave dynamics back into the hydrodynamic model. This framework is a part of the advanced setup, available within SCHISM modelling system and is fully integrated inside the UWA nested Regional Ocean Modeling System (ROMS) ocean model for the Perth region (at 500m spatial resolution). This required considerable computing resources, and therefore all simulations were performed on the Pawsey - Setonix supercomputer.

Aiming to capture possible wave effects due to a long dredged channel together with the rapid change in the bathymetry (Figure 4) we used fine unstructured model mesh consisting of 102304 nodes and 193924 elements with up to 5 m horizontal resolution at shallower regions (Figures 4, 5, 6).

The Cockburn Sound local spectral wave model was run in hindcast mode over the period 2010-2022 (13 years) and all critical wave variables were output at hourly intervals for each numerical mesh node. The variables are listed on Table 1.

Table 1. Wave parameters output by the spectral wave model.

Parameter	Name of parameter	Units	Comments
Ocean time	Time	gregorian	'seconds since 1858-11-17 00:00:00'
Ocean time_str	Time string	gregorian	e.g. 2022-01-01 00:00:00
lon	longitude	degree	
Lat	latitude	degree	
HS	Significant wave height	m	
TM01	Mean wave period	s	
TM02	Zero-crossing wave period	s	
TPP	Peak wave period	s	
WLM	Mean wavelength	m	
DM	Mean wave direction	degree	
DSPR	Directional spreading	degree	
WLM	Mean wavelength	m	
LPP	Peak wavelength	m	
PEAKD	Peak wave direction	degree	
PEAKDSPR	Peak directional spreading	degree	
UBOT	wind-induced bottom orbital velocity	ms^{-1}	

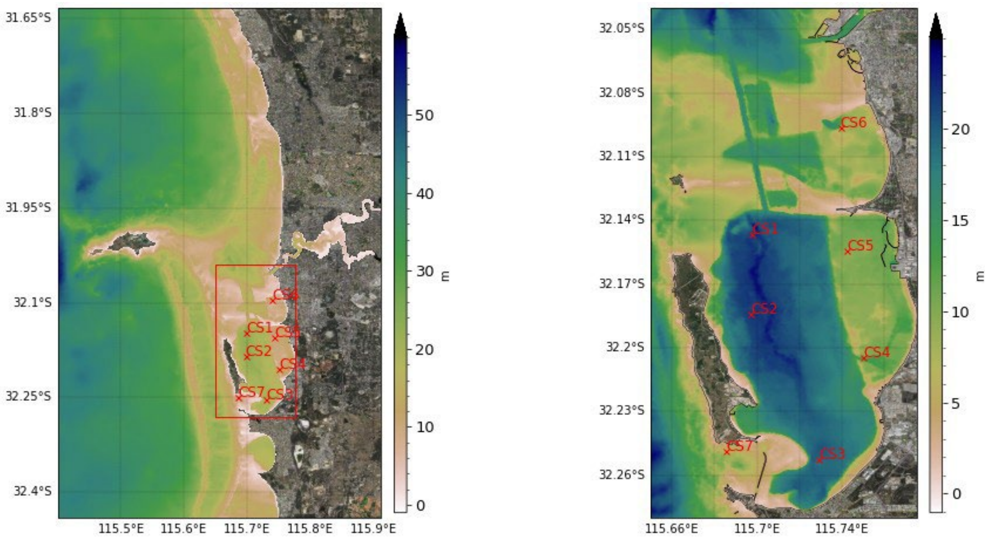

Figure 4. Local high resolution wave model bathymetry (left) and zoom to the area of interest with mooring stations (right). Note different colour scales on the figure. All features on the figures are actual model mesh depths.

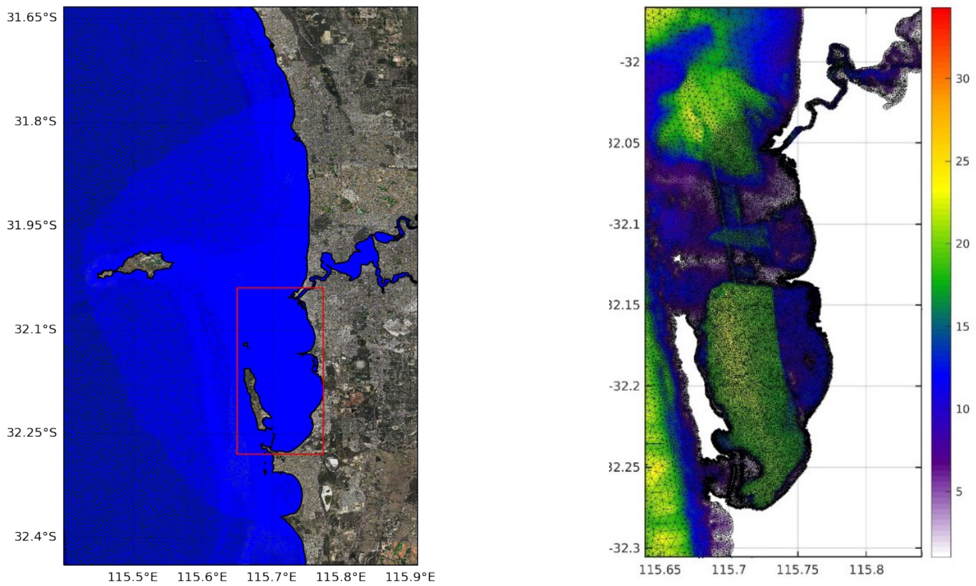

Figure 5. Unstructured - finite element mesh of the local wave model for the whole domain (left) and zoom at the area of interest (right).

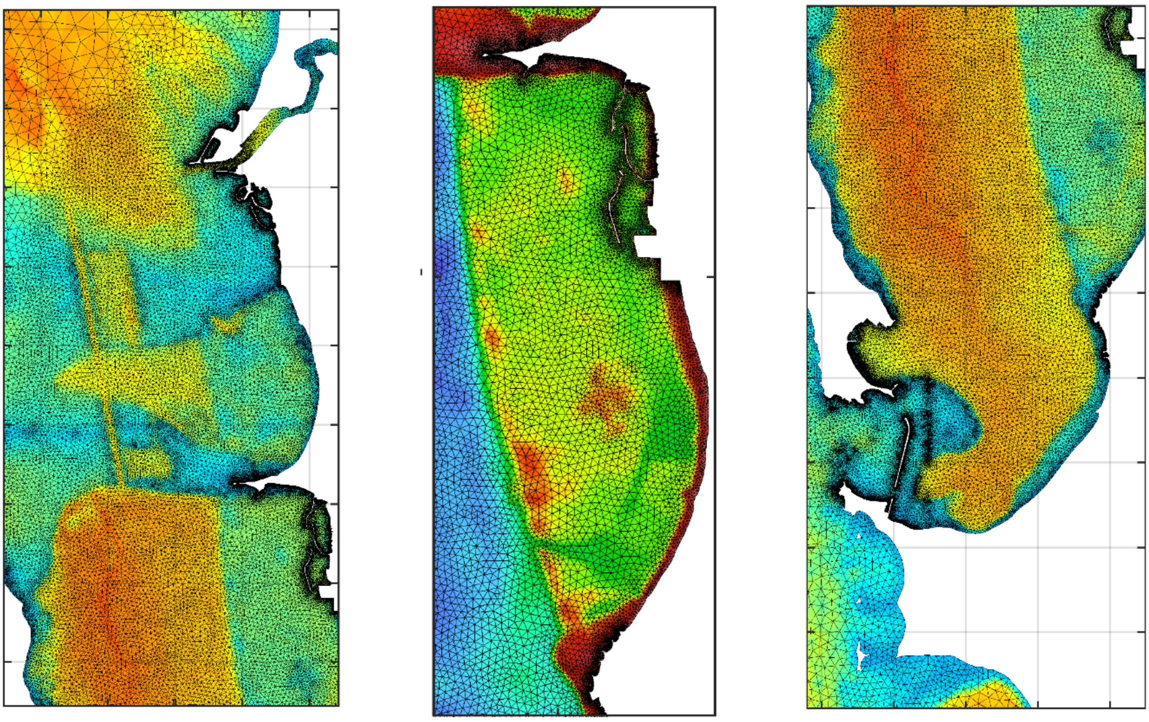

Figure 6. UWA Cockburn Sound model grid with zoomed views of Success and Parmelia Bank, Kwinana Shelf and southern Cockburn Sound. The minimum resolution is 5 m.

3.2 Field measurements for model validation

In order to validate the Cockburn Sound local spectral wave model, all critical wave variables at each numerical mesh node were output at hourly intervals. Simulations covered the period of the measurements in the Cockburn Sound (Project 5.1) waters providing a unique data set for the model validation.

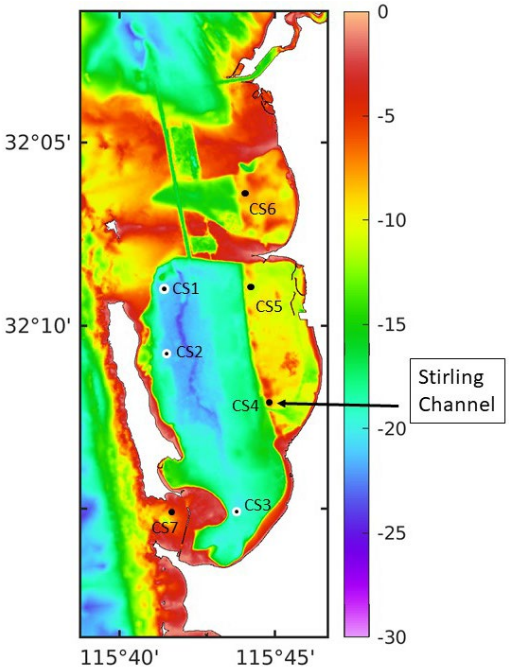

Figure 7. Map locations of the mooring sites for wave measurements.

Long-term data from a Digi-quartz pressure sensor operated by Fremantle Port Authority were available from Stirling Channel (Figure 7). These data were collected continuously at 2 Hz at a nominal depth of 2.5 m located on a channel marker where the mean water depth was ~10 m. The data were analysed as 1-hour bursts to extract non-directional wave parameters (H_s, H_{max}, mean period) that were compared with the model output in 2022. Time series of significant wave height and mean period for 2022 are shown on Figure 8. Time series show a typical wave climate from the Perth coastal region with higher waves during winter associated winter fronts and lower variable wave heights during the summer due to sea breeze conditions. Note that the maximum significant wave height recorded on 1 August of 2.3 m corresponded to the highest wave heights recorded during a winter storm since 2010.

Over the period April 2021 to August 2022, UWA collected directional and non-directional data from 7 mooring locations around the Sound as part of Project 5.1 of the WWMSP (Figure 7). These moorings were deployed for 4-6 week periods in water depths ranging from 5 m (CS7) to 20 m (CS1). The primary aim of these deployments was to collect hydrodynamic data for circulation model validation. Specifically, for the wave model validation we used mooring sites equipped with the capability to measure directional and non-directional (CS-1 CS-4 and CS-6) waves. All these measurements were based on the Acoustic Doppler Current Profilers (ADCP. RDI workhorse or Nortek) instruments in case of directional, and RBR Solo pressure loggers for non-directional waves. In this task we didn't perform any dedicated and more advanced data analysis.

In the study region three wind systems dominate: sea breezes; storms (wind speeds >15 ms^{-1}), and calm periods (wind speeds <5 ms^{-1}). Local sea breezes superimposed upon synoptic southerly (meteorological convention) winds, with maximum speeds often >15 ms^{-1}, are prevalent in austral spring and summer (September-February). The unusually strong alongshore sea breeze results from the interaction of the local sea breeze generated due to the synoptic pressure system and the land–sea temperature gradient and promote strong vertical mixing and surface currents. During a typical sea breeze day, the wind speed in the morning is usually low (5 ms^{-1}) and directed offshore (easterly). The wind direction then typically changes to south/south-westerly around late morning/early afternoon, and steadily increases to speeds 10-15 ms^{-1}. The maximum wind speed is generally reached by the late afternoon/early evening. Storm systems are most frequent during winter (June-August), associated with the passage of frontal systems with maximum wind speeds > 25 ms^{-1}. Winter storms have a typical pattern with strong north/north-westerly winds blowing for 12 to 52 hours, followed by a period of similar duration when winds turn south/south-westerly. Maximum wind speeds are from the north-west. Summer storms have southerly winds over a period of 3-4 days that are enhanced by the sea breeze system in the afternoon. Calm wind conditions are mainly observed during autumn and winter (March-August; between winter storm fronts) and are characterized by low wind speeds (<5 ms^{-1}). These wind conditions are reflected in the wave record. During the sea breeze conditions (Jan-Mar) and (Oct-Dec), the wave heights are smaller (0.5-1.0) and undergo diurnal variation as reflected in higher 'noise'. During winter months, the wave heights are larger with the peaks corresponding to passage of storm fronts. The lower wave heights between the storm peaks reflect calm conditions.

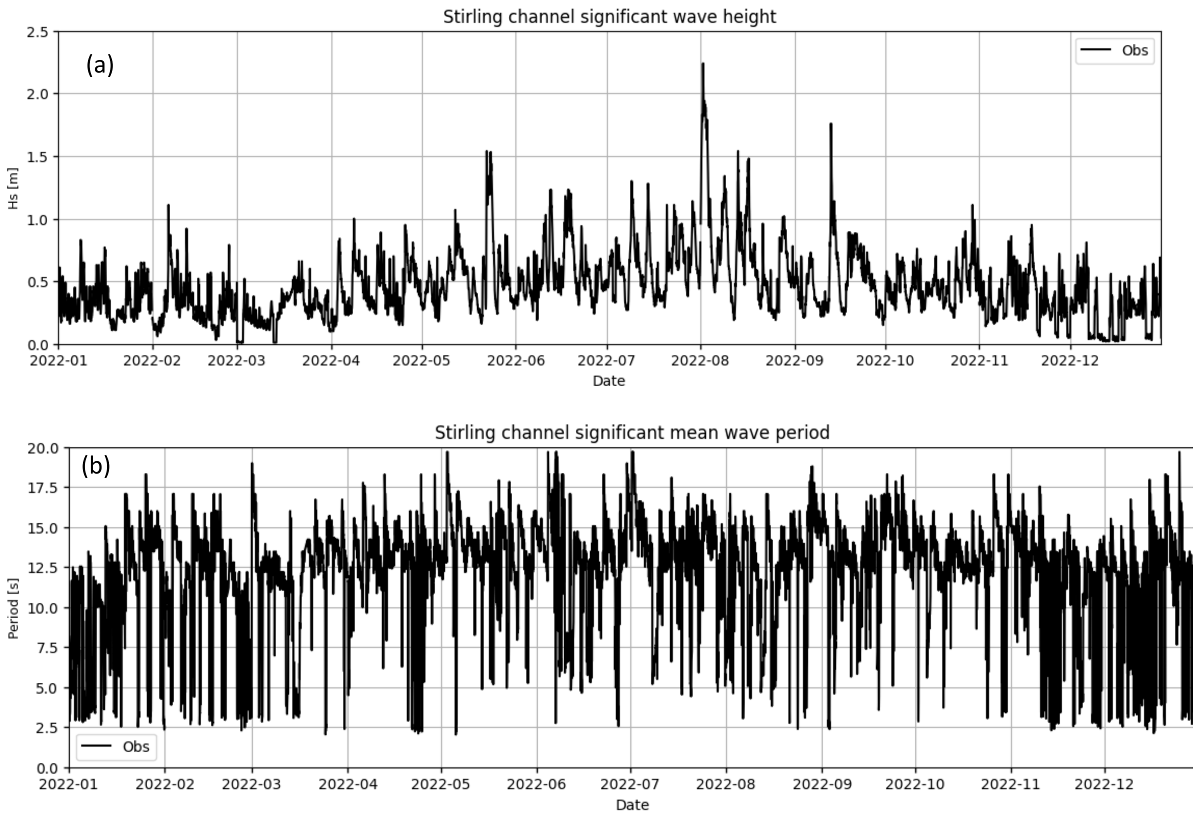

Figure 8. Time series of (a) significant wave height; and (b) wave period measured in Stirling Channel in 2022.

4 Results

4.1 Model validation

4.1.1 Validation of West Australian model

UWA Western Australia Wave Modelling System has been set-up to provide continuous wave forecasts since 2011 and covers most of the WA coastline from Albany to the Kimberley (Figure 3). The model has been validated using the wave buoys along the WA coast and we provide comparison of observed and predicted wave heights at the Rottnest Island wave buoy as Figures 9 and 10. For the period 2010 to 2019 the correlation between the predicted and observed wave height was 0.86 (Figure 9) and for the period March 2019 to November 2020 the correlation was 0.92 (Figure 10). These high correlations between observed and predicted values provide confidence that the model is able to provide accurate boundary conditions for the higher resolution Cockburn Sound model.

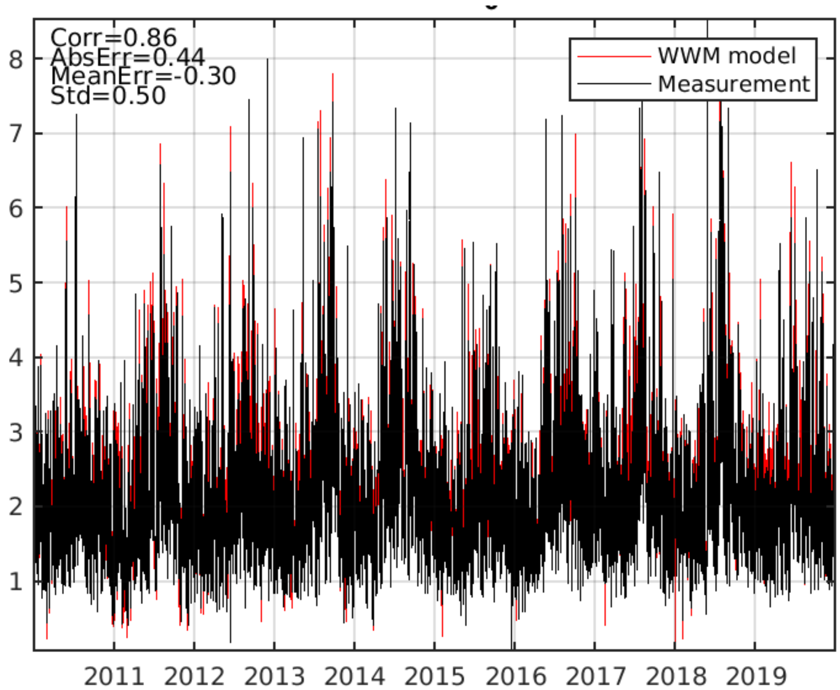

Figure 9. UWA Western Australia Wave Modelling System validation: significant wave height at Rottnest Island comparison between observations and predictions for 2010-2019.

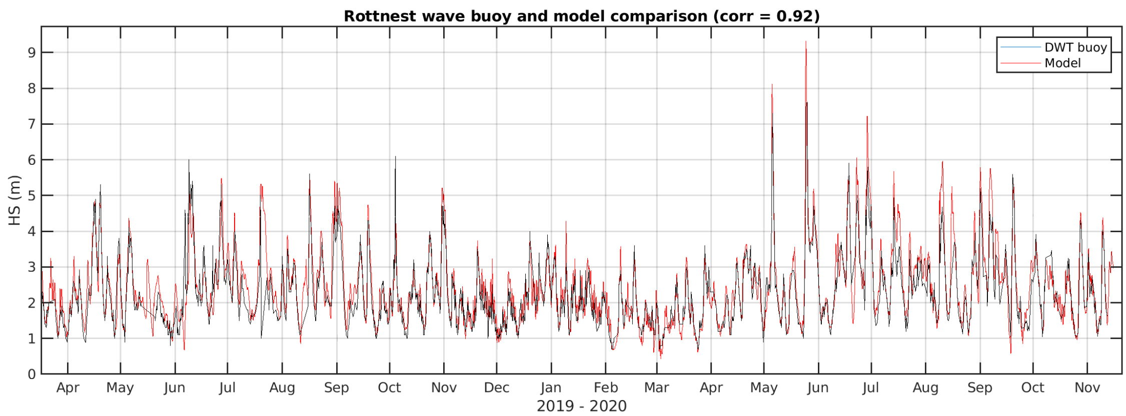

Figure 10. UWA Western Australia Wave Modelling System validation: significant wave height at Rottnest Island comparison between observations (Department of transport wave buoy) and predictions (red line) for 2019-2020.

4.1.2 Cockburn Sound Model: validation using Stirling Channel data

Data acquired in Stirling Channel is ideal for model validation as it included a whole year of data at hourly intervals and included typical sea breeze cycles as well as a large storm that recorded the highest wave heights since 2010. Over the whole year there was very good agreement between the observed and predicted wave parameters for both significant wave height and wave period (Figure 11). For the significant wave height, the model slightly underestimated the wave heights during storm peaks whilst overestimating wave heights under low wave conditions (e.g. December 2022; Figure 11a). Under low wave conditions (e.g. December 2022) the predicted wave periods were higher than the measured under certain conditions (Figure 11b).

The time series with measured and predicted significant wave heights was examined to isolated periods of sea breezes and storm events (Figure 12). Under sea breeze conditions, the model consistently overestimated the measured values by 0.1-0.2m most likely due to slightly higher wind forcing (Figure 12a). There was a good correspondence between the observed and predicted significant wave heights during storm events with the model reproducing the peaks in the storms (Figure 12b).

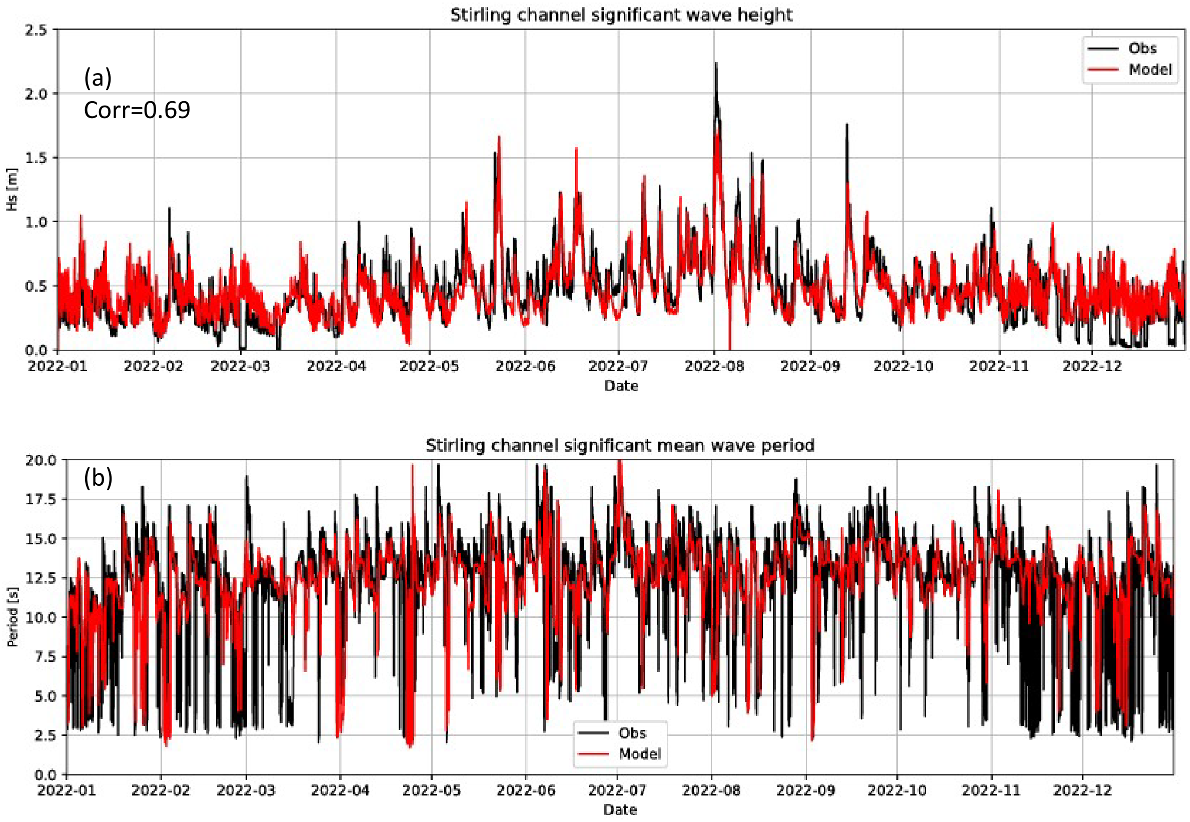

Figure 11. Time series of observed (black line) and predicted (red line) wave parameters at Stirling Channel in 2022: (a) significant wave height; and (b) wave period.

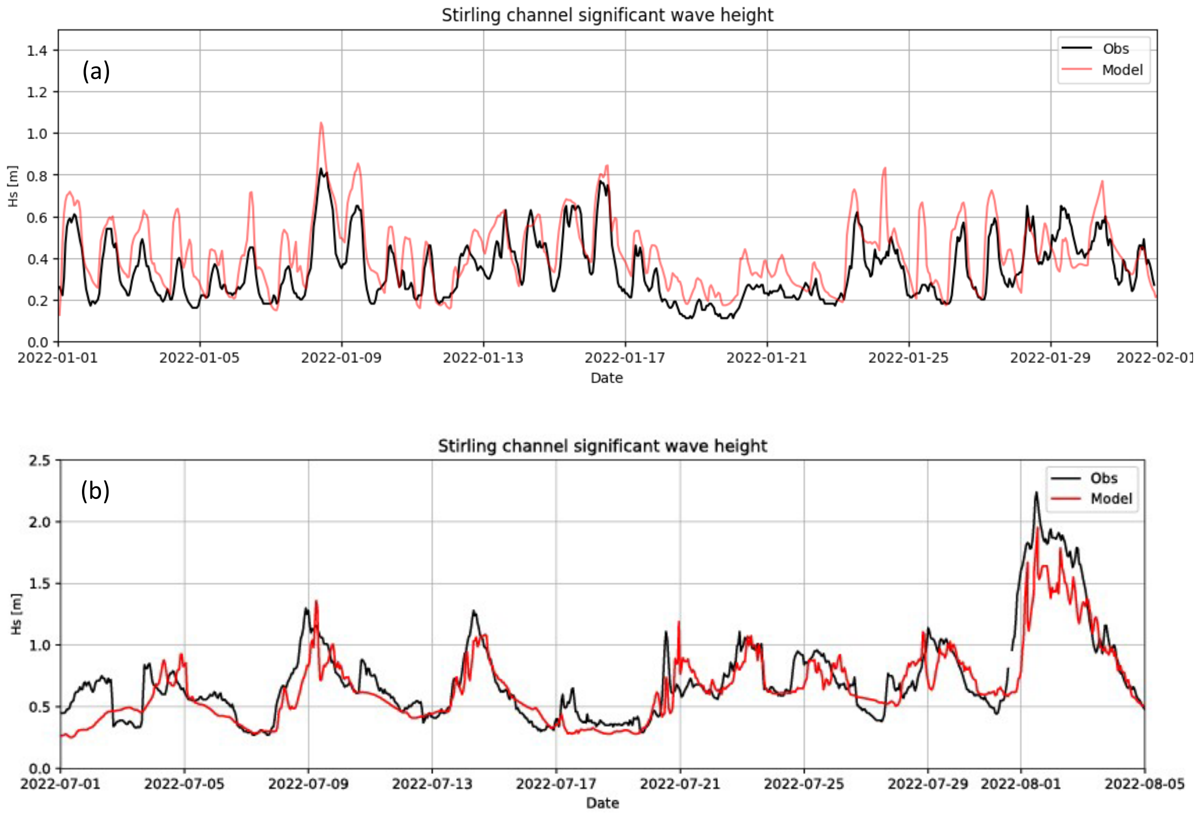

Figure 12. Time series of observed (black line) and predicted (red line) significant wave heights at Stirling Channel: (a) January 2022 associated with sea breeze events showing diurnal variability; and (b) during the storm of 1 August 2022.

Scatterplots of between measured and predicted wave heights for significant wave heights are shown on Figure 13 and the plots also indicate good correspondence. There is an even spread of points across the 1:1 line for both hourly data (Figure 13a) and the daily maxima (Figure 13b). The correlation coefficients between measured and predicted significant wave heights were 0.69 and 0.77 for the hourly (n=8760) and maximum daily data (n-365), respectively

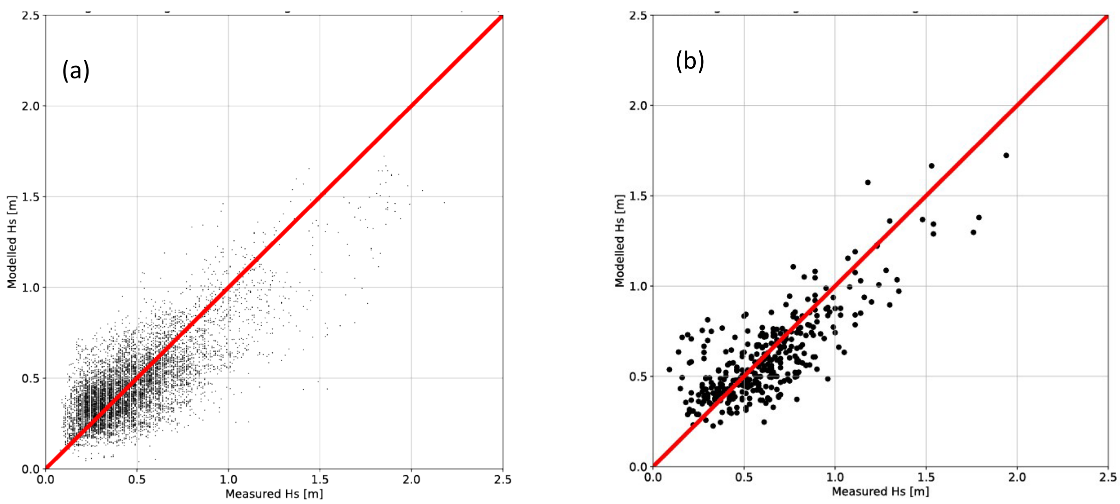

Figure 13. Scatter plots of observed and predicted significant wave heights at Stirling Channel in 2022, showing (a) hourly data (8760 data points); and (b) daily maxima (365 data points).

4.1.3 Cockburn Sound Model: validation using moored data

A range of sensors were deployed in Cockburn Sound to acquire data on hydrodynamic processes including surface gravity waves in 2021-2022. The aim of these deployments was to collect current meter and stratification data but also included sensors to record directional and non-directional data using ADCPs and pressure sensors. The instruments were deployed at the seabed in water depth of 10-20 m. The fluctuations in pressure due to the waves decrease in amplitude with increasing water depth. Thus, pressure fluctuations under long-period waves can be readily felt, and measured, at depth, but pressure fluctuations under short-period waves (e.g. those due to locally generated waves from sea breeze) may not actually penetrate to the same depth. Waves have a range of periods and heights and the fluctuating pressure at depth is also made up of many components, the long-period components being less attenuated than the short-period components. Therefore, consideration should be given to comparing wave parameters from pressure sensor in deeper water.

Time series of observed and predicted significant wave heights for three different periods show different outcomes (Figure 14). The 3 periods include (1) sea breeze dominated period (Nov-Dec 2021) with strong diurnal variability (Figure 14a); (2) a summer period with a southerly storm with some diurnal variability (Figure 14b); and (3) a storm system in June-August 2022 (Figure 14c). For sea breeze generated waves, when compared to the ADCP measurements (at 10 m depth) the model under-predicts the higher waves whilst over-predicting the lower waves. However, the model reproduces the diurnal variation (Figure 14a). A similar pattern is observed for February 2022, but the model correctly reproduces the summer storm on 7 February (Figure 14b). For the winter storms the model overpredicts the RBR pressure sensor located at 10 m water depth (Figure 14c).

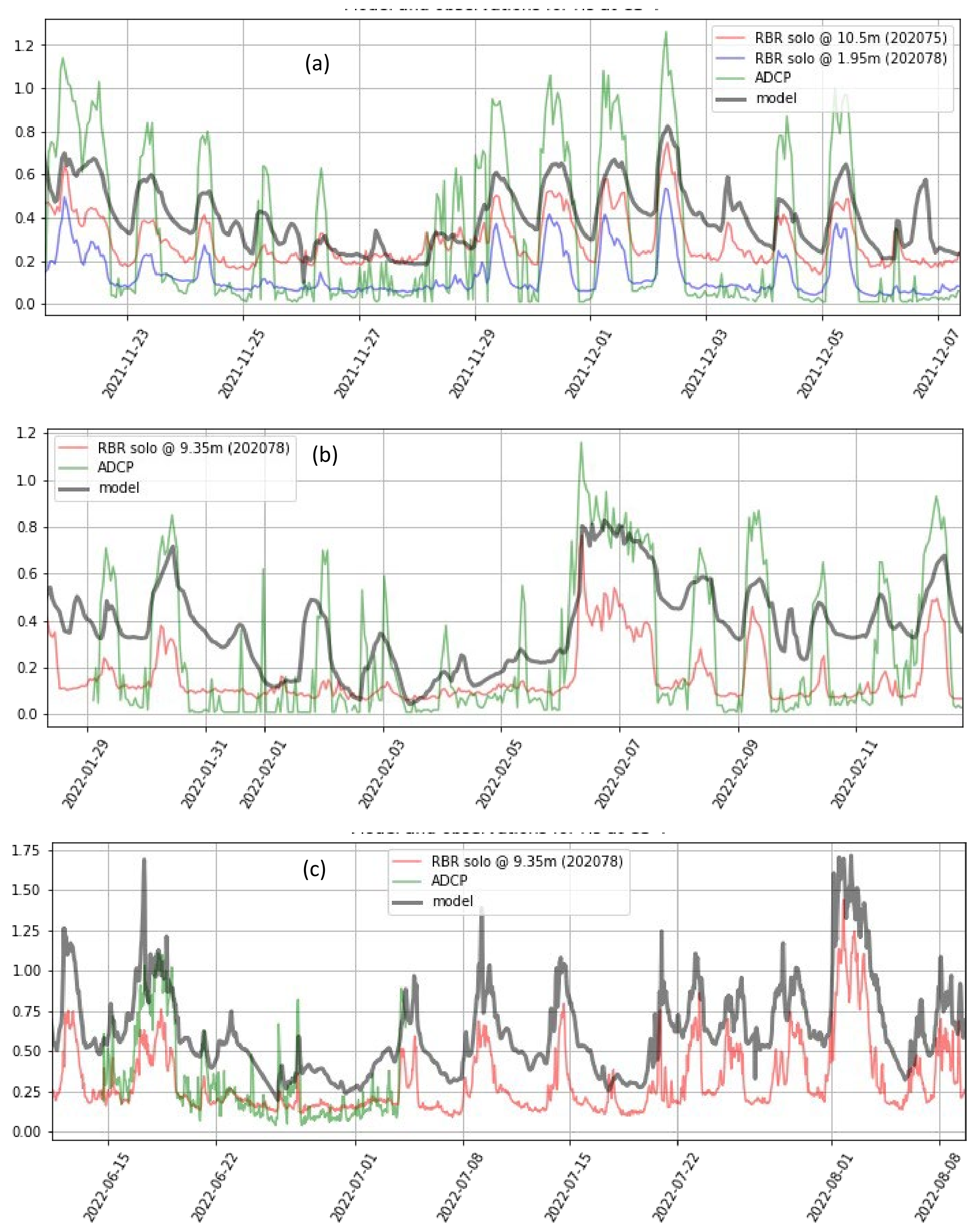

Figure 14. Time series of significant wave heights at Station CS4: (a) November-December 2011; (b) January-February 2022; (c) June-August 2022

4.2 Hindcast 13-year wave climate.

In this section we describe the wave model output for the 13-year hindcast for Stirling Channel location (Figure 7). Time series of significant wave height, peak wave period and mean wave direction (Table 1) were examined. For hourly values there were a total of 113,854 values for each wave parameter (Figure 15).

Time series of significant wave height indicated the seasonal signal with higher waves during winter and lower waves during the summer (Figure 15a). There was also a strong year-to-year change with lower annual significant wave height in 2010 and 2015 and annual higher significant wave heights in 2020 and 2021 (Figure 15a). Over the 13-year record, there was also a trend of an increase in significant wave heights since 2015. This trend is also present in other stations in south-west Australia, such as the Rottnest deep water station (Figure 9). The year-to-year changes are more prominent when we examine the daily and monthly maxima significant wave height (Figure 16).

The seasonal pattern is also present for the peak period with higher periods during winter (swell waves) and lower periods during summer (local sea breeze generated waves) (Figure 15b). Similarly, for wave direction (Figure 15c), the swell direction (~300^o) is almost constant whilst during the summer the direction was mainly between (225^o and 300^o).

As expected, and like many other processes in nature, the distribution of significant wave height and peak period both displayed a Rayleigh distribution (Figures 17a, b). The median significant wave height and peak period based on 113854 hourly values were 0.46m and 13.3s, respectively. In contrast the wave direction was dominated by the direction 300^o-310^o when almost 40% values were in this segment indicating the dominance of this wave direction (Figure 17c). This is also illustrated in the wave rose where the direction ~300^o dominated (Figure 17d).

The year-to-year changes in wave parameters can be further examined by comparing the annual time series for 2010 (low waves) and 2022 (high waves). In 2010, the wave heights were low with relatively few storm systems (Figure 18a). A similar pattern was present for peak period and mean direction (Figures 18b, c). In contrast, the 2022 wave heights were higher and there were many peaks in the significant wave heights indicating a higher number of storms during winter (Figure 19a).

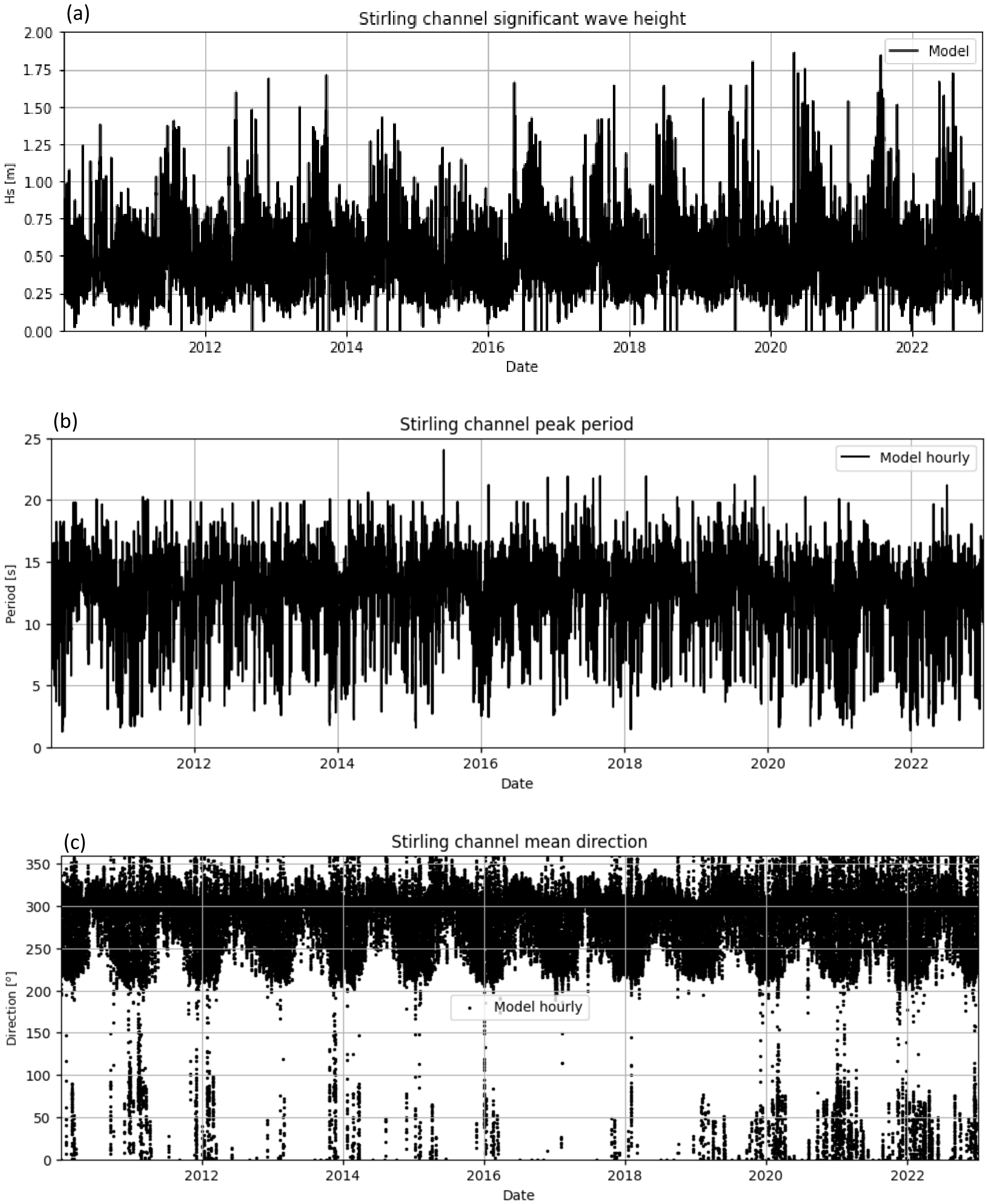

Figure 15. Time series of predicted hourly wave parameters at Stirling channel for the period 2020-2022: (a) significant wave height; (b) peak period; and (c) mean direction.

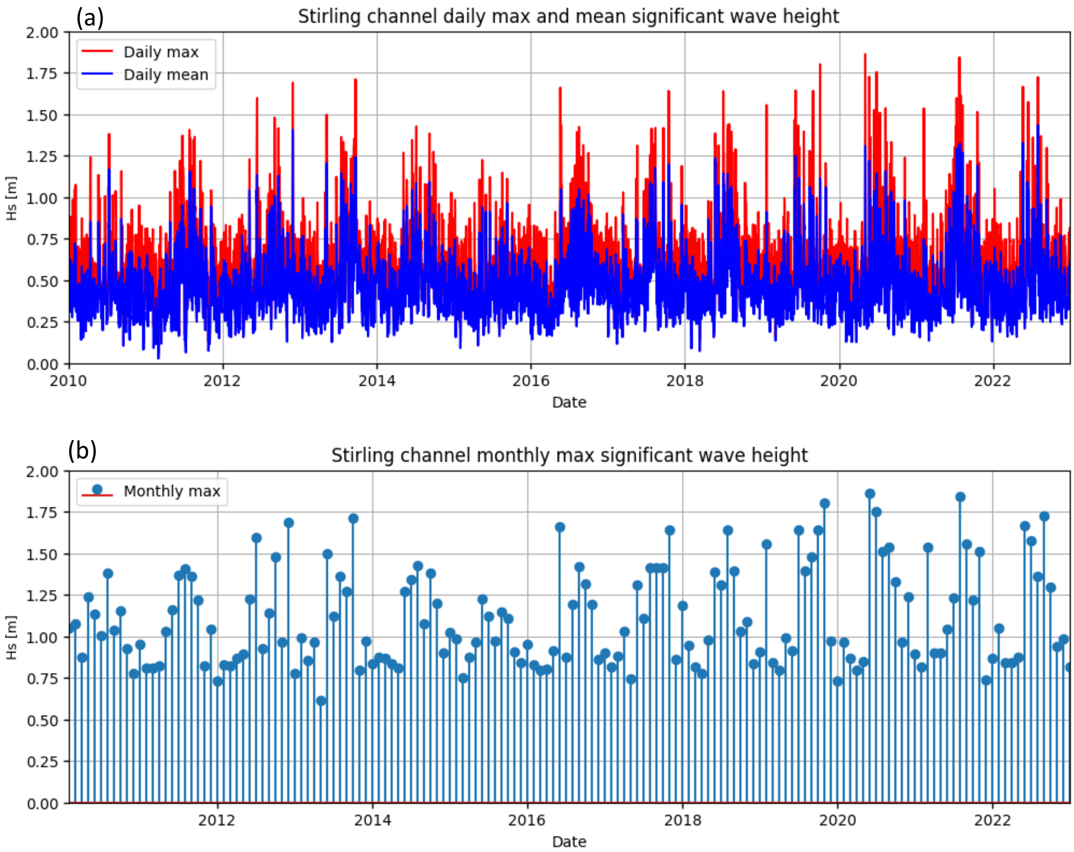

Figure 16. Time series of (a) daily maxima and mean; and (b) monthly maxima in significant wave height at Stirling channel for the period 2020-2022.

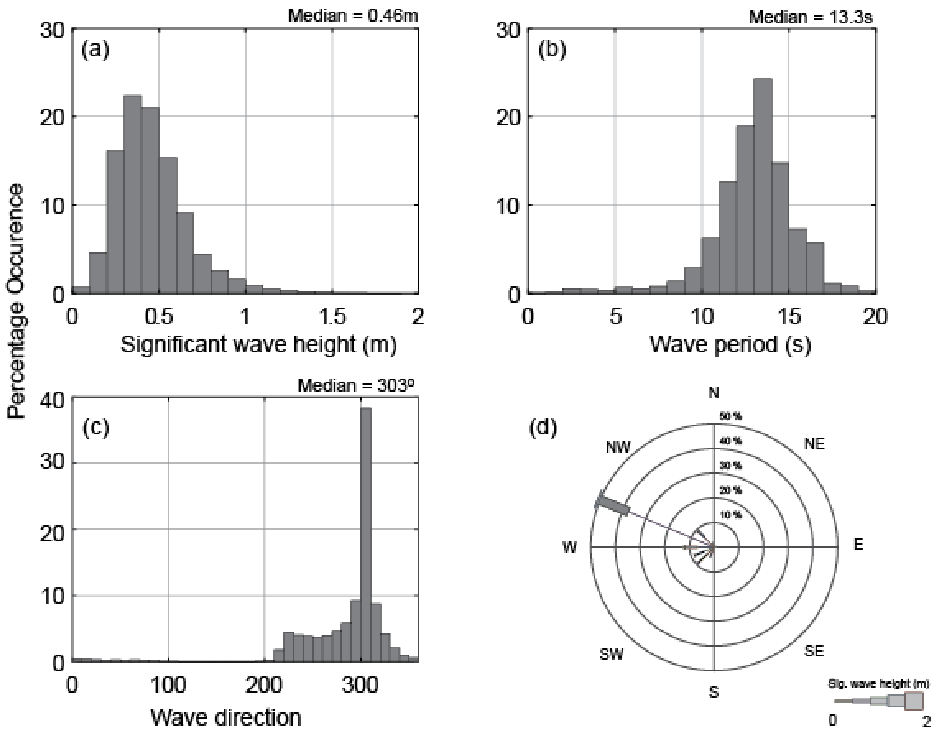

Figure 17. Distribution of predicted hourly wave parameters at Stirling Channel for the period 2020-2022: (a) significant wave height; (b) peak period; (c) mean direction; and, (d) the wave rose.

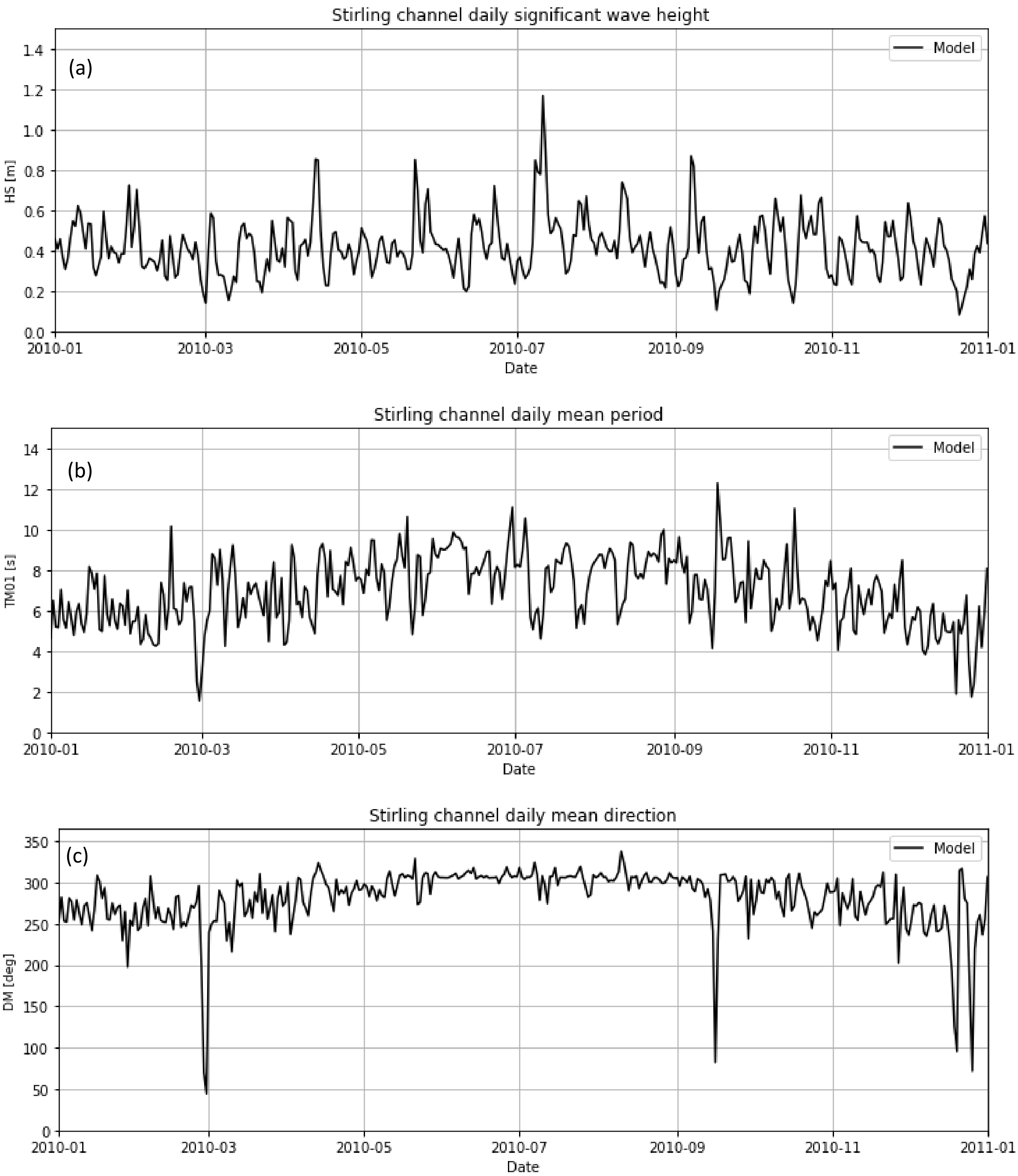

Figure 18. Time series of predicted daily mean wave parameters at Stirling Channel for 2010: (a) significant wave height; (b) peak period; and, (c) mean direction.

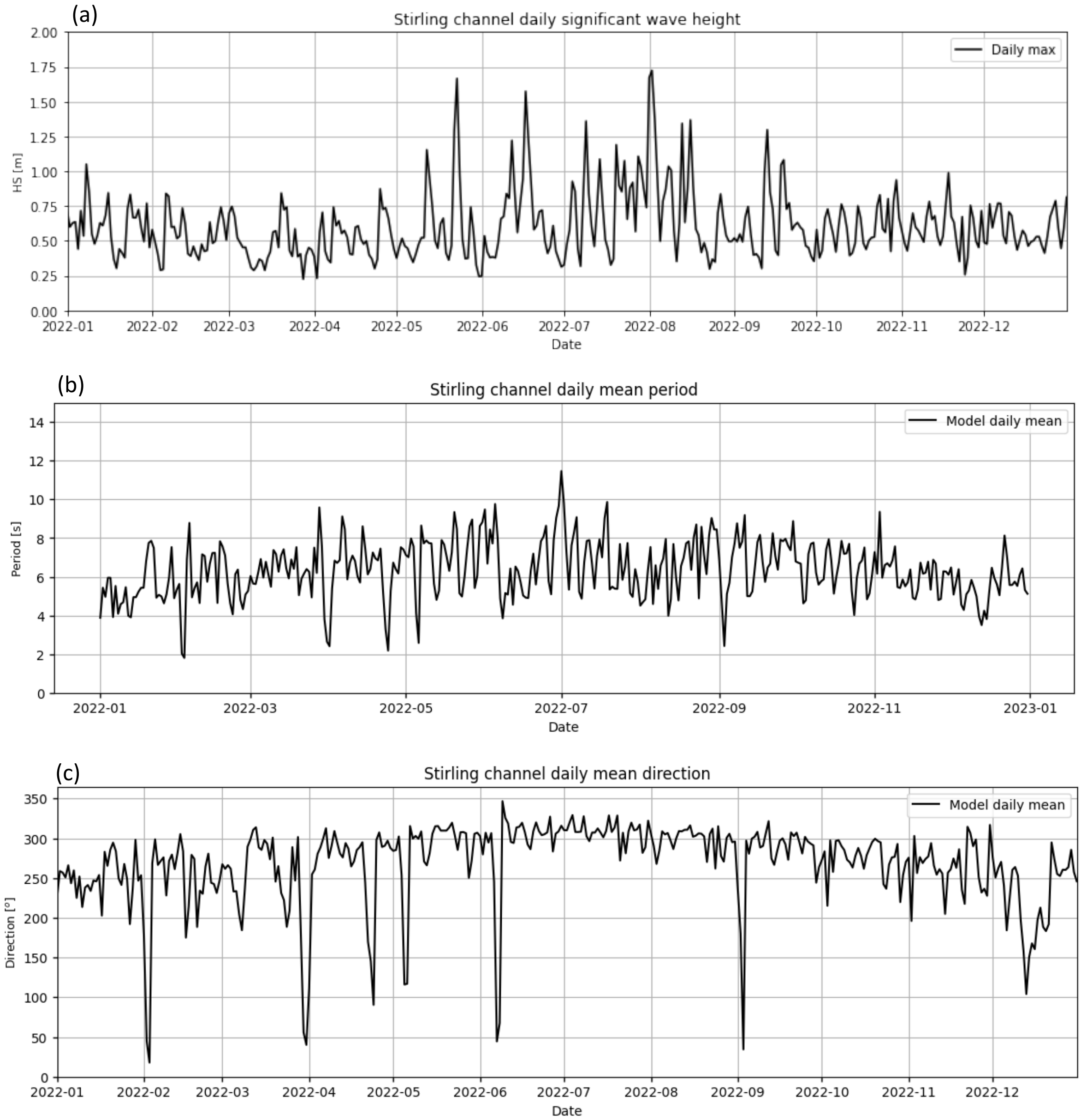

Figure 19. Time series of predicted daily mean wave parameters at Stirling channel for 2022: (a) significant wave height; (b) peak period; and (c) mean direction.

4.3 Storm: July/August 2022

To illustrate complexity and spatial variability of the wave model output, we examine the extreme storm event that occurred during 30 July to 4 August 2022 (Figure 20). The maximum wave height measured at Stirling Channel was 2.2 m at 22:00 on 1 August (Figure 20). During this storm, Perth coastal waters experienced one of the largest waves recorded at the Rottnest wave buoy, >10 m for significant wave height. To illustrate this storm within Cockburn Sound we demonstrate the different nesting systems used for this project: (1) The global coarser resolution WW3 model shows the spatial extent of the storm extending across offshore region of south-west Australia (Figure 21); (2) The nested WA regional model used the WW3 data as boundary conditions to create a higher resolution on the continental shelf and slope of WA (Figure 22). The maximum offshore wave heights were > 10 m, off the southwest Australian coast. (3) higher resolution Cockburn Sound that included high resolution atmospheric model forcing using 2km resolution (Figure 23)

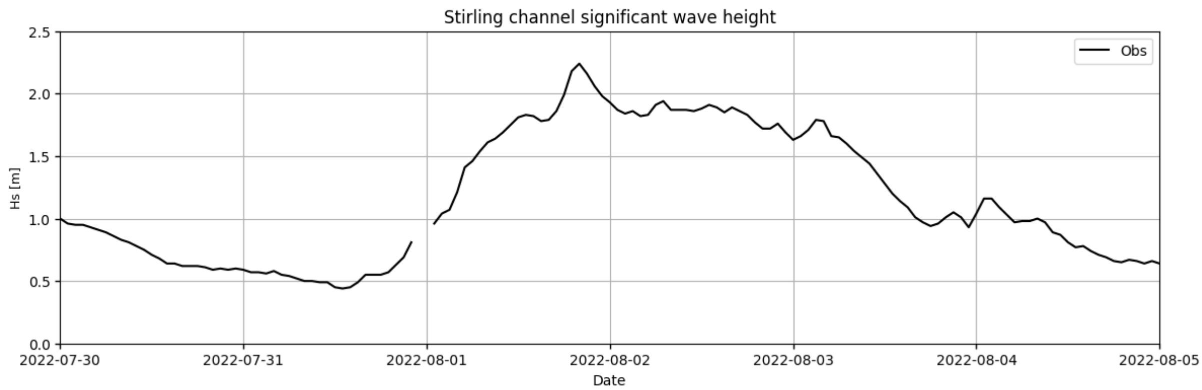

Figure 20. Global WW3 model solution for significant waves during the 2 August 2022 storm.

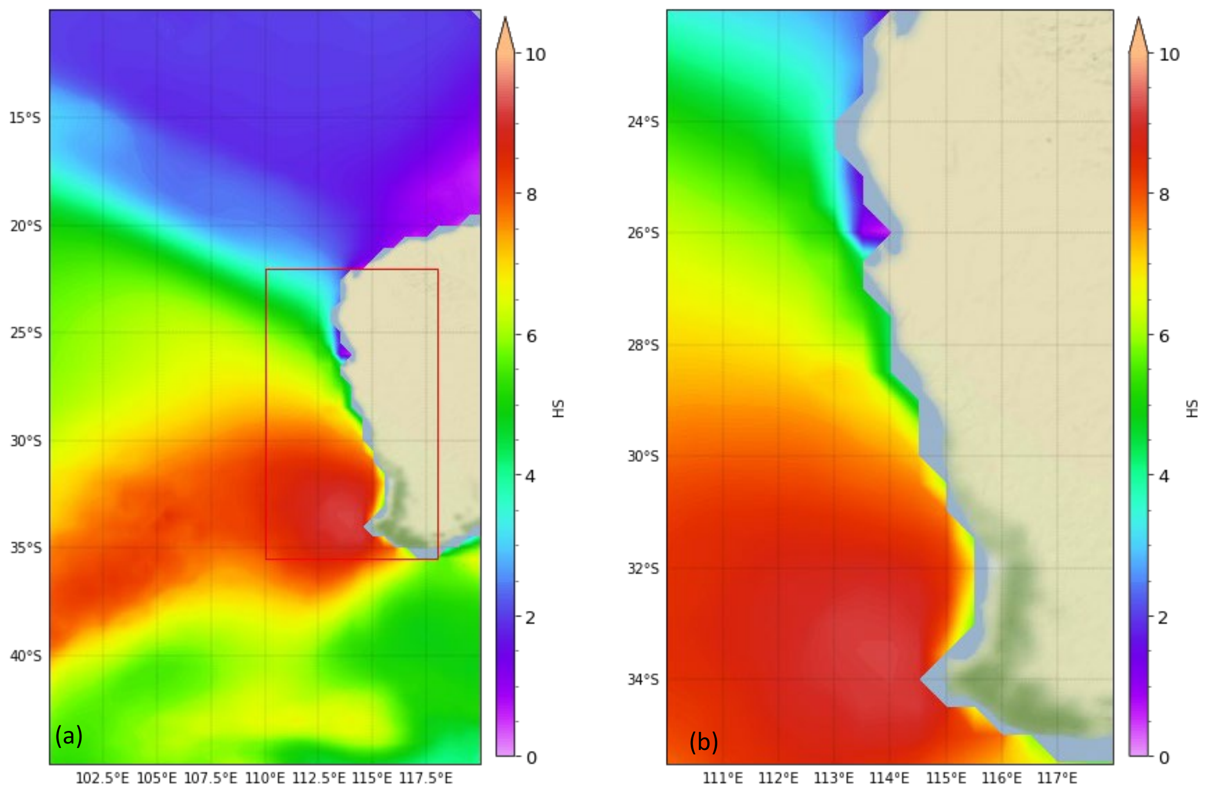

Figure 21. Global WW3 model output for significant wave height during the August 2022 storm at 0000 on 02/08/2022 UTC at (a) basin scale; and (b) zoomed to the WA coast.

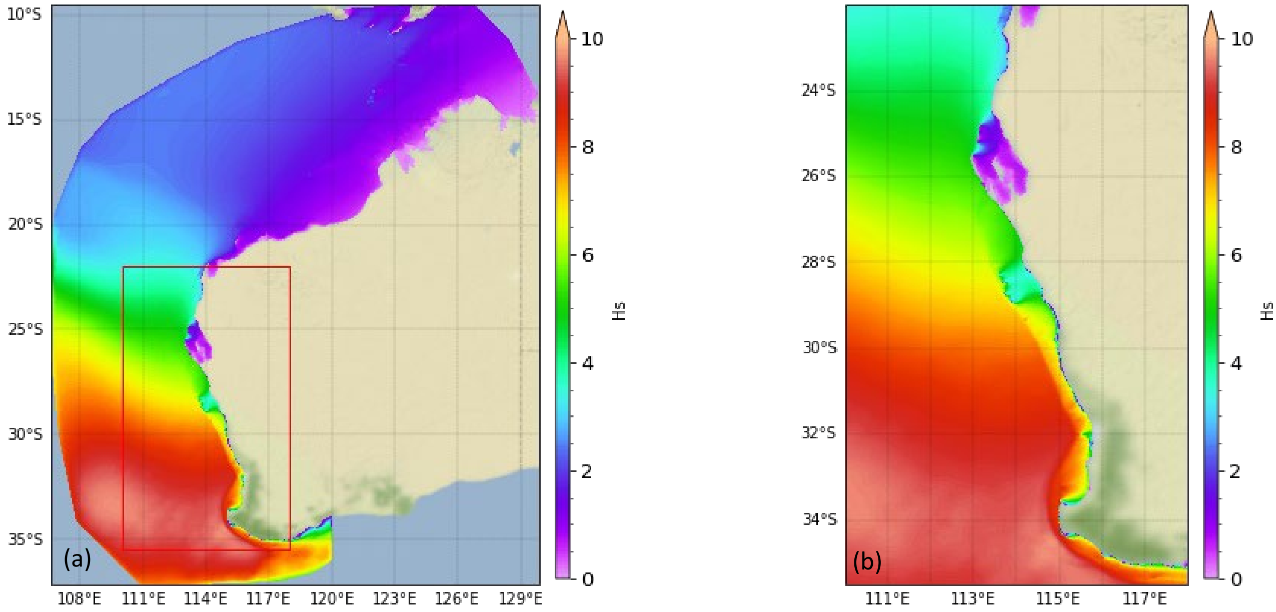

Figure 22. Global WW3 model output for significant wave height during the August 2022 storm at 0000 on 02/08/2022 UTC at (a) basin scale; and (b) zoomed to the WA coast.

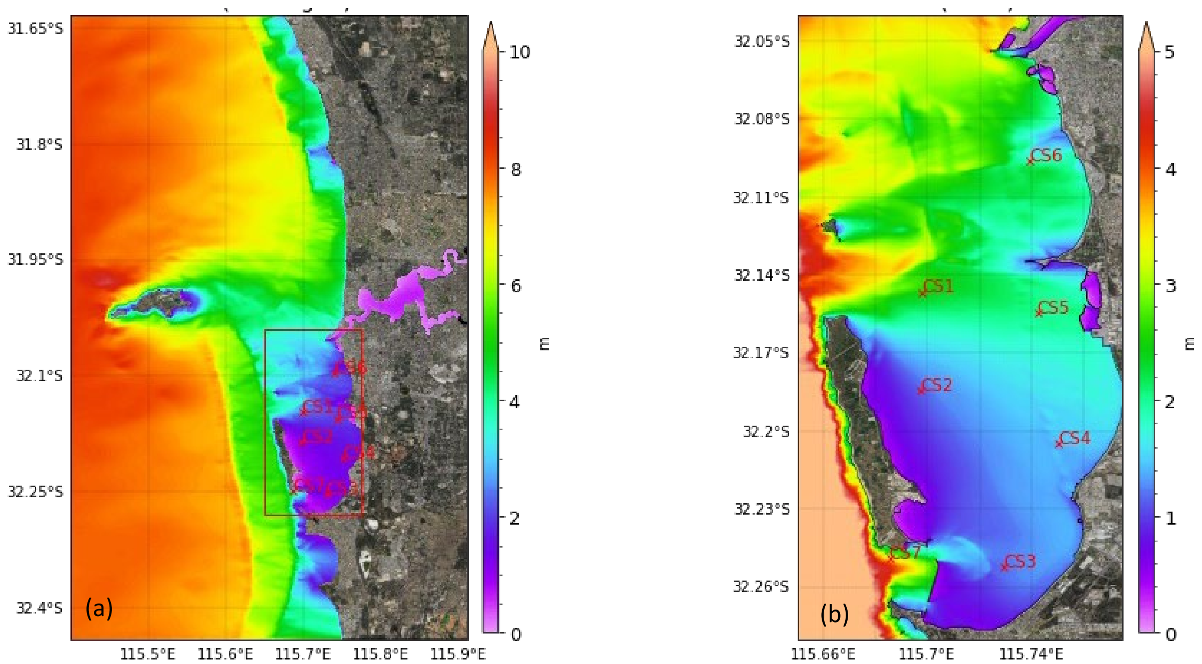

Figure 23. High resolution of WWM-III model output for significant wave height during the August 2022 storm at 0000 on 02/08/2022 UTC at (a) continental shelf scale; and (b) zoomed to Cockburn Sound.

The development of the storm inside Cockburn Sound is illustrated in snapshots of significant wave height and direction plots at 12-hour intervals (Figure 24). At 0000 01/08/2022, the storm was starting, and the wave heights are increased across the domain with higher wave heights offshore from Garden Island (~3m) compared to wave heights of ~ 1m in Cockburn Sound. The measured wave height at Stirling Channel was also 1 m (Figure 20). Over the next 12 hours (0000 01/08/2022; Figure 24a), the wave heights increased significantly with offshore wave height reaching 4.5 m and large gradients in wave heights in Cockburn Sound. The effect of Carnac Island on the refraction and diffraction is prominent with waves converging in the lee of the Island as a constant feature (Figure 24). The main input of wave energy into Cockburn Sound was between Garden and Carnac islands. The waves then propagated from a direction of 300^{o} towards the Kwinana Shelf and Stirling Channel (Figures 24b,c,d). In the subsequent snapshots the offshore wave height increased in height to >5 m, but wave heights within Cockburn Sound did not increase. By 0000 03/08/2022 (Figure 24e) the winds have changed and the waves inside Cockburn were approaching the Kwinana Shelf from a westerly direction (Figures 24e,f).

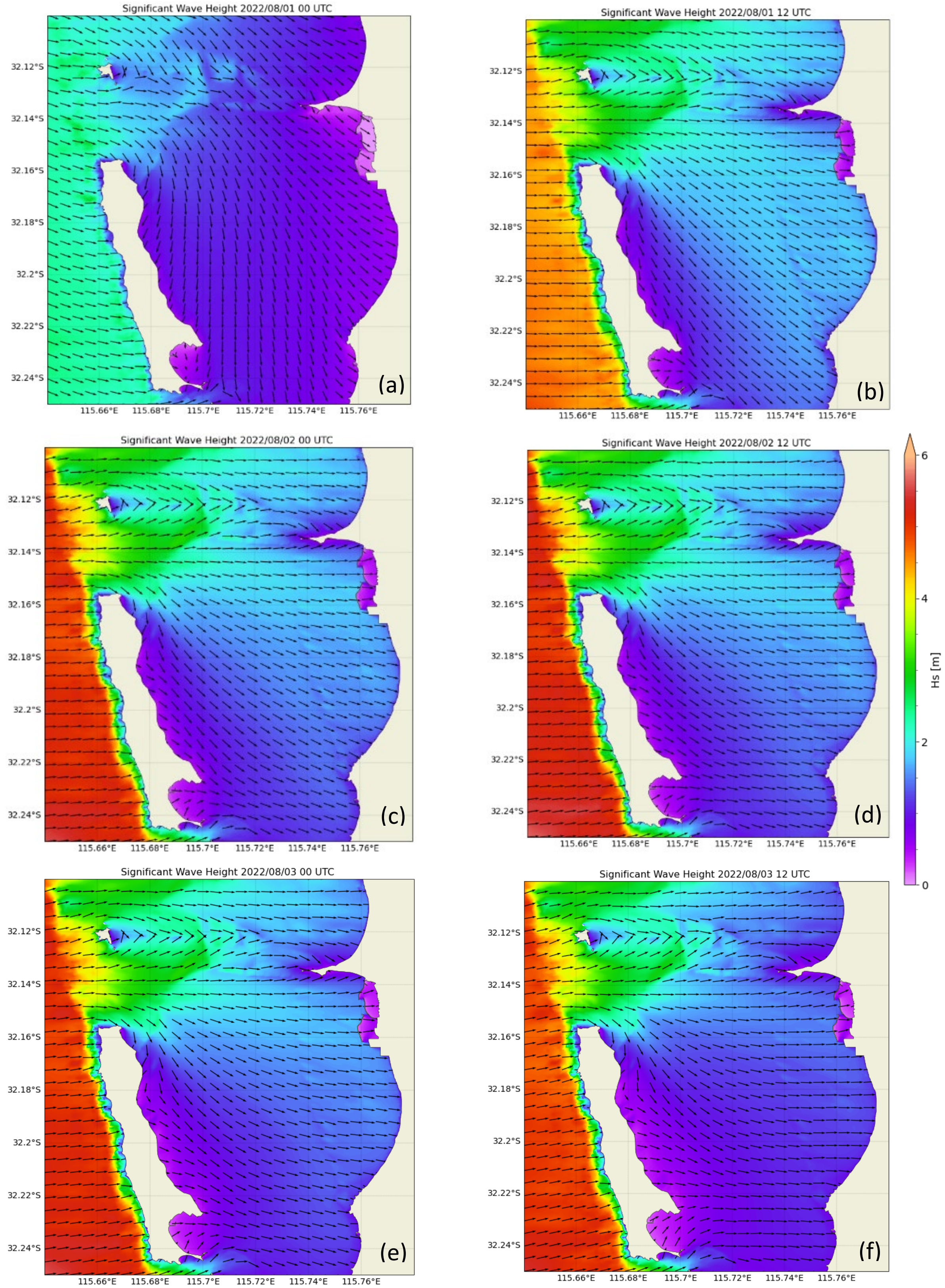

Figure 24. The spatial distribution of significant wave heights and direction in Cockburn Sound the August 2022 storm. (a) 0000 01/08/2022; (b) 1200 01/08/2022; (c) 0000 02/08/2022; (d) 1200 02/08/2022; (e) 0000 03/08/2022; (f) 1200 03/08/2022. For clarity the arrows representing wave direction are not plotted on every point output by the model.

5 Discussion

Spectral wind wave models use numerical techniques to simulate wave conditions in response to atmospheric forcing (e.g. surface wind field). The application of these models to shallow coastal regions with complex bathymetry such as Cockburn Sound, a nested modelling process is required to downscale ocean basin scale wave models (e.g. WW3) that simulate deep-water wave climates to the continental shelf scale and then onto the coastal regions to simulate wave transformation in shallow-water environments. All these models at different spatial scales simulate wave growth and propagation across a regular grid or irregular mesh, and output continuous time series (e.g. hourly) of wave parameters. When reliable atmospheric forcing data are available, spectral wind wave models are used to simulate coastal wave climates over extended periods. In this project, we used a high spatial (~5 m in shallow waters) and temporal (hourly) resolution unstructured wave spectral model, Wind Wave Model (WWM-III), to simulate the wave climate for Cockburn Sound and surrounding region. The model was nested within the basin scale WW3 model and a WA regional model. The regional and Cockburn Sound models were validated using field measurements from the Rottnest deep water buoy and Stirling Channel, respectively. A 13-year (2010-2022) hindcast of wave parameters output from the model, at hourly intervals, was successfully completed. The wave parameters include significant wave height, peak period, mean wave direction and bottom orbital velocity (for a full list Table 1).

6 Conclusions

A high spatial and temporal resolution wave spectral was developed for Cockburn Sound and adjacent region. A 13-year (2010-2022) hindcast of wave parameters output from the model is archived in the WAMSI/WESTPORT data portal (https://catalogue.data.wa.gov.au/org/western-australian-marine-science-institution) and is available to project participants.

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