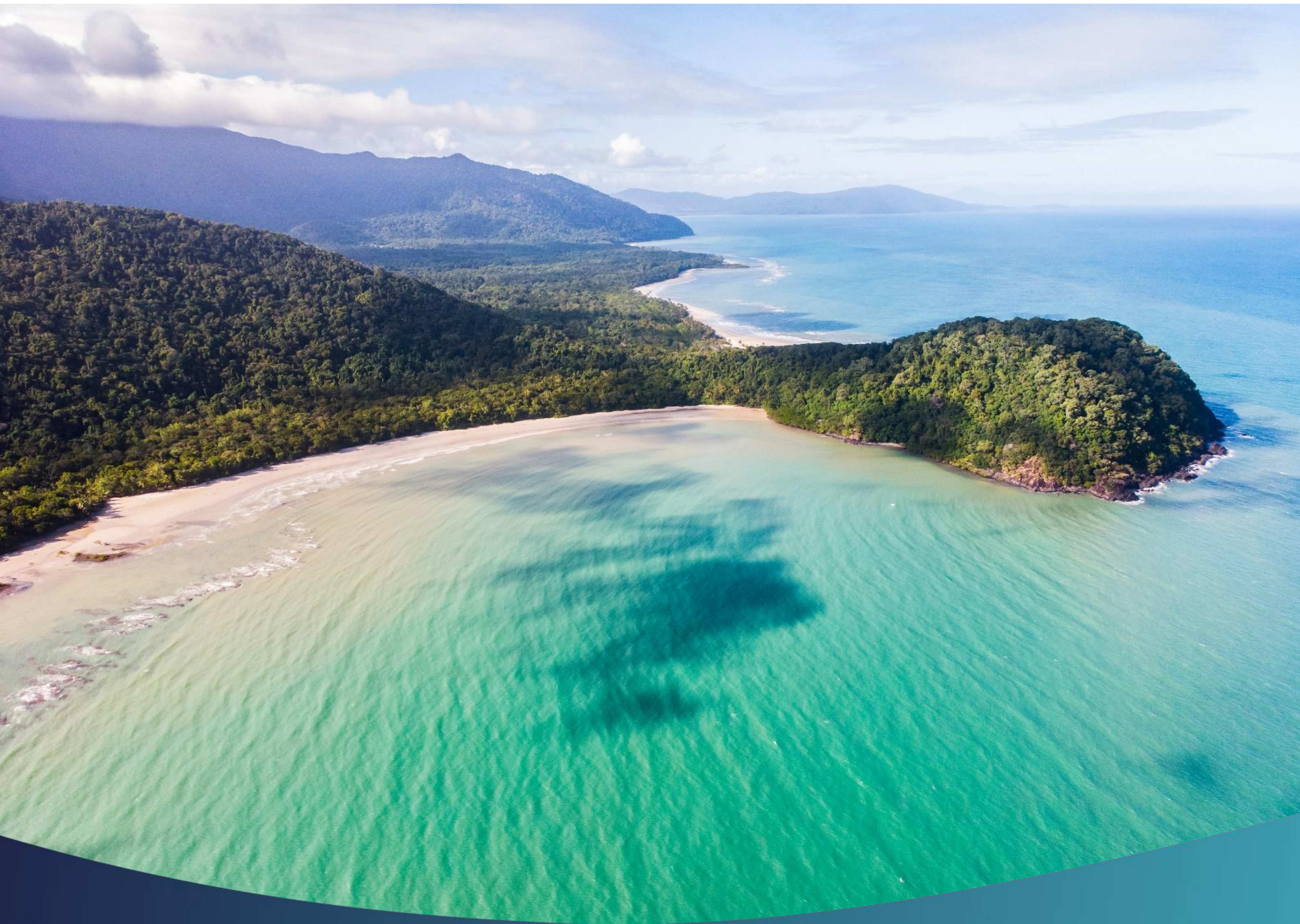
# Base Hydrodynamic Model

## Eramurra Solar Salt Project

METOCEAN
An O2Marine company



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# Version Register

| Version | Status | Author | Reviewer | Approver | Date |
|---|---|---|---|---|---|
| Rev A-D | O2Me Internal use only | A. Zulberti | S. Morillo | - | - |
| Rev D | For client and 3rd party review | A. Zulberti | S. Morillo | S. Morillo | 06/Jul/2022 |
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# Changes from Previous Versions

Changes beyond amendment of typographical and formatting errors, or adjustment of text for clarity are listed below.

| Section | Change |
|---|---|
| Whole report | From Rev D to Rev 0: Incorporated edits and comments from client and third-party review of draft rev D, as summarised in O2Me's Technical Note T220008 (Rev 0). |
| Whole report | Rev 0 to Rev 1: Client technical comments addressed in O2Me's Technical Note T220035 (Rev0) |

| Section | Change |
|---|---|
| 4.2.2 | Rev 1 to Rev 2: Clarified the approach to the comparison of local wind measurements from two stations. |
| Whole report | Rev 1 to Rev 2: Client technical comments addressed in O2Me's Technical Note T220092 (Rev1) |

# Acronyms, Abbreviations and Definitions

| Acronyms & Abbreviations | Definitions |
|---|---|
| 3D | Three-Dimensional |
| ADCP | Acoustic Doppler Current Profiler |
| AWAC | Acoustic Wave and Current Profiler (a Nortek-branded instrument) |
| BOM | Bureau of Meteorology |
| DSDMP | Dredging and Spoil Disposal Management Plan |
| AEDT | Australian Eastern Daylight Time |
| AWST | Australian Western Standard Time |
| Dp | Peak spectral wave direction |
| ECMWF | European Centre for Medium-Range Weather Forecasts |
| EIA | Environmental Impact Assessment |
| ENSO | El Niño Southern Oscillation |
| ESSP | Eramurra Solar Salt Project |
| GA | Geoscience Australia |
| GLpa | Gigalitres per annum |
| ha | Hectare, an area of 10,000 square metres |
| HAT | Highest Astronomical Tide |
| HD | Hydrodynamic |
| Hs | Significant Wave Height |
| IOD | Indian Ocean Dipole |
| LAT | Lowest Astronomical Tide |
| LS | Leichhardt Salt Pty Ltd |
| MEQMMP | Marine Environmental Quality Monitoring and Management Plan |
| MHWN | Mean High Water Neap |
| MHWS | Mean High Water Spring |
| MLWN | Mean Low Water Neap |
| MLWS | Mean Low Water Spring |
| MS | Ministerial Statement |

| Acronyms & Abbreviations | Definitions |
|---|---|
| MSL | Mean Sea Level |
| Mtpa | Million tonnes per annum |
| O2Me | O2 Metocean |
| PVD | Progressive Vector Diagram |
| RANS (equations) | Reynolds Averaged Navier Stokes (equations) |
| RMSE | Root mean square error |
| TC | Tropical Cyclone |
| TD | Tidal Dominated |
| TL | Tropical Low |
| Tp | Peak spectral wave period |
| WA | Western Australia |

# Executive Summary


This report presents the setup and validation of a hydrodynamic and spectral wave model of the Western Pilbara coastline, herein referred to as the *base hydrodynamic model* or more simply as *the model*. The model is used to support environmental studies associated with the Eramurra Solar Salt Project (ESSP) by providing boundary conditions for smaller numerical environmental studies. The smaller studies include dredge plume modelling, bitterns discharge dispersion modelling, and tidal inundation modelling simulations within Regnard Bay, E of Cape Preston. The scope of this report is to demonstrate that the model domain and forcing are fit for the purpose of driving such studies, and that the dominant circulation mechanism are adequately resolved by the model.

The model solves the 3D primitive equations, is built on a compilation of the best available local and regional bathymetric information, and is forced by state-of-the-art global tide and atmospheric models. Measured wind and waves are used to force the smaller Regnard Bay domain. Local - i.e. within or immediately offshore of Regnard Bay - validation data consisted of water-levels, ocean currents and spectral wave parameters described in O2Me (2022c and 2022d). The quality of the available bathymetric information both in Regnard Bay and the shallows south of Barrow Island is the major limiter to model performance. Limitations of the model with respect to periods of extreme atmospheric forcing are also discussed.

The model is demonstrated to reproduce the complex tidal flows, seasonal drift currents, the prevailing high-frequency sea-waves, and swell waves despite uncertainty in the bathymetry within Regnard Bay and across the Pilbara Shelf more generally. The model resolves the shallow water tidal constituents that lead to asymmetries in the along-shore coastal tidal currents W and E of Barrow Island, as well as the major asymmetries in tidal currents in the vicinity of the ESSP (the NCP05 observation site). The model qualitatively captures the water level setup and the associated currents under tropical storms (e.g. TL-08U).

Overall, the model is evaluated as being fit for the purpose of deriving boundary conditions for environmental studies in the Cape Preston region.

A third-party review of O2 Metocean's nested modelling approach to environmental impact assessment of the ESSP commissioned to Dr R Steedman (metocean and environmental business consultant with over 40 years' experience), confirmed that the base hydrodynamic model of Regnard Bay provides a reasonably reliable estimate of the Regnard Bay coastal circulation and turbulent diffusion (friction) processes. Dr Steedman's findings are included in Appendix B of this report.

# Contents

# Tables

# Figures

# 1. Introduction

## 1.1. Project Overview

Leichhardt Salt Pty Ltd (LS) propose to construct and operate the Eramurra Solar Salt Project (ESSP), a solar salt project to extract an average of 5.3 million tonnes per annum (Mtpa) of high-grade salt (sodium chloride ($NaCl$)) from seawater, using a series of concentration and crystalliser ponds and processing plant, transport corridor, stockpiling and export from the Cape Preston East Port (the Project). The concentration and crystalliser ponds will be located on Mining Leases.

The export of salt is proposed to be via a trestle jetty. The jetty and associated stockpiles will be located at the Cape Preston East Port approved by Ministerial Statement (MS) 949. Dredging of the proposed channel and berth pocket will be undertaken as part of this Proposal. Dredge material will either be disposed of at one or more offshore disposal locations, or onshore within the Ponds and Infrastructure Development Envelope. The Cape Preston East Port jetty and associated stockpiles are excluded from the Proposal.

Bitterns will be transported by pipeline attached to the trestle jetty structure and discharged via a diffuser located off the trestle jetty.

The Proposal is located in the western Pilbara region of WA, approximately 55 km west-south-west of Karratha. The summary project description is detailed in the Table 1, with key physical and operational elements of the ESSP identified in Table 2.

Table 1: Short Summary of the Proposal.

| | |
|---|---|
| **Project Title** | **Eramurra Solar Salt Project** |
| **Proponent Name** | **Leichhardt Salt Pty Ltd** |
| **Short Description** | Leichhardt Salt Pty Ltd (LS) is seeking to develop a solar salt project in the Cape Preston East area, approximately 55 km west-south-west of Karratha in WA (the Proposal). The Proposal will utilise seawater and evaporation to produce a concentrated salt product for export.<br><br>The Proposal includes the development of a series of concentration and crystalliser ponds and processing plant. Supporting infrastructure includes bitterns outfall, drainage channels, product dewatering facilities, desalination plant and/or groundwater bores, pumps, pipelines, power supply, access roads, administration buildings, workshops, laydown areas, landfill facilities, communications facilities and other associated infrastructure. The Proposal also includes dredging at Cape Preston East Port and either offshore disposal of dredge material or the onshore use of dredge material within the Ponds and Infrastructure Development Envelope. |

Table 2: Location and proposed extent of physical and operational elements.

| Element | Location | Proposed Extent |
|---|---|---|
| Physical Elements | | |
| Pond and Infrastructure Development Envelope – Concentrator and crystalliser ponds. Process plant, desalination plant, administration, water supply, intake, associated works (access roads, laydown, water supply and other services). | Figure 2 | Disturbance of no more than 14,300 hectares (ha) within the 20,160 ha Ponds Development Envelope. |
| Marine Development Envelope – Seawater intake and pipeline, dredge channel, bitterns pipeline, outfall diffuser and mixing zone. | Figure 2 | Disturbance of no more than 90 ha within the 790 ha Marine Development Envelope. |
| Dredge Spoil Disposal Development Envelope – Disposal location for dredge spoil. | Figure 2 | Disturbance of no more than 320 ha within the 4,605 ha Dredge Spoil Disposal Development Envelope. |
| Operational Elements | | |
| Bitterns discharge | Figure 2 | Discharge of up to 8 Gigalitres per annum (GLpa) of bitterns within a dedicated offshore mixing zone within the Marine Development Envelope. |
| Groundwater abstraction | Figure 2 | Abstraction of no more than 0.5 GL pa from the Ponds or Infrastructure Development Envelope. |
| Dredge Volume | Figure 2 | Approximately 314,000 $m^3$ |

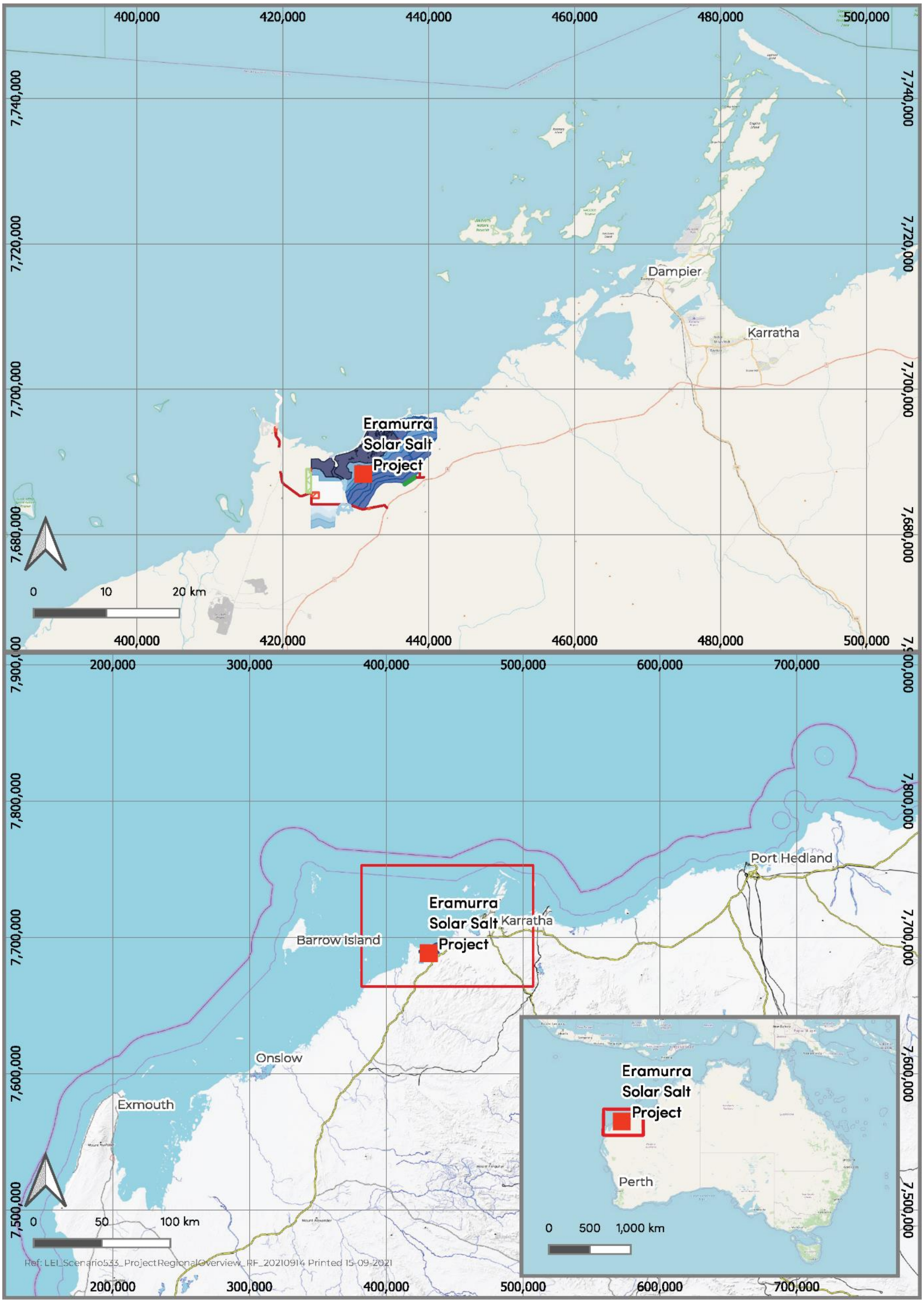


Figure 1: Regional Overview.

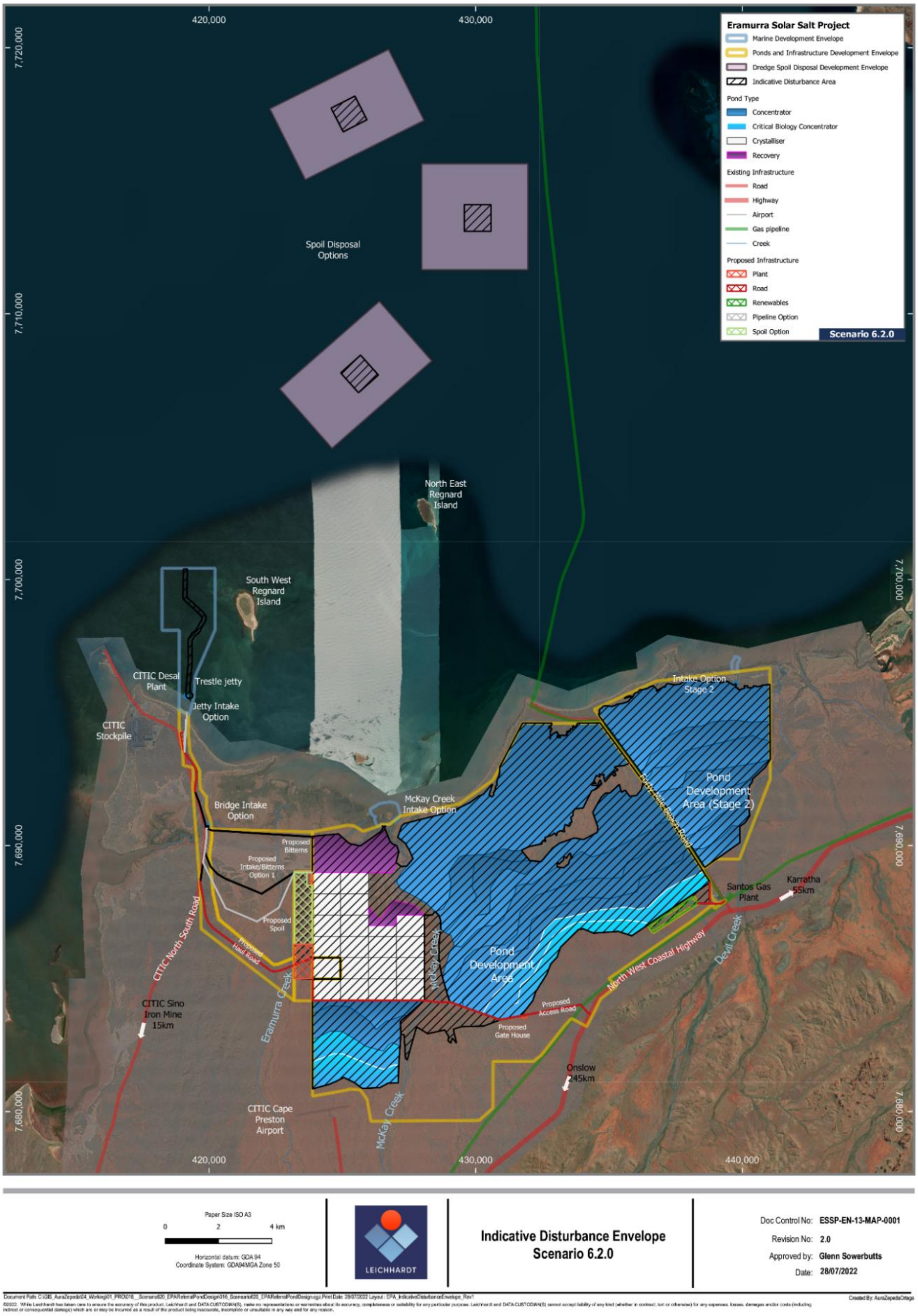


Figure 2: Development Envelopes.

## 1.2. Objective

The objective of this report is to present the validation of a base hydrodynamic and spectral wave model of Regnard Bay that will support the environmental impact assessment of the ESSP.

## 1.3. Scope

The scope of this report is to demonstrate that the modelling approach chosen is adequate to resolve the dominant hydrodynamics in the immediate vicinity of the ESSP. The primary focus of this document is to demonstrate that the selection of domain size and model forcing are appropriate for driving environmental studies, namely:

- Modelling of sediment plumes generated by dredging and dredge spoil disposal [O2 Metocean (O2Me) 2022b];
- Modelling the fate of bitterns released by bitterns outfall (O2Me 2022e); and
- Modelling of the changes to tidal inundation patterns associated with the construction of the salt ponds (O2Me 2022g).

Modelling methods including transport calculations, mesh refinement, model nesting, alternate vertical discretisation schemes etc. that are specific to the environmental studies above are covered in the standalone reports for these studies, and thus excluded from this report.

The outcomes of these modelling studies, and subsequent environmental packages, will in turn inform:

- Preparation of a Dredging and Spoil Disposal Management Plan [DSDMP, O2 Marine (O2M) 2022a];
- Marine Environmental Quality Monitoring and Management Plan (MEQMMP, O2M 2022b); and
- Benthic Communities & Habitat - Cumulative Loss Assessment (O2M 2022c).

## 1.4. Exclusions and Limitations

Quality of available data is a limitation of any modelling exercise. After a desktop review, bathymetry and wind-fields used in this study were relied upon as the best available information. Manipulation of wind-fields, pressure fields and bathymetry were excluded, and the limitations of any errors noted in text as appropriate.

## 1.5. Definitions and Conventions

Directional convention: Throughout this report, wind and wave directions will assume the standard meteorological convention of 'coming from', while currents will retain the standard oceanographic convention of 'flowing to'.

Directional Acronym Conventions: When describing the directionality of metocean parameters (such as wind, waves and currents), acronyms for direction are used in the report. For example, a wind direction may be described as SSE instead of a south-southeast. The exceptions to this convention include:

- when describing direction within a header;
- when describing a proper noun (such as 'Southwest Regnard Island' or 'Southwest Trade Winds'); and
- when describing the direction that is not related to measured data or metocean parameters (such as describing a location for example 'southern Australia').

‘**Significant wave height**’ (Hs) often refers to the average height of the highest ‘one third’ of the wave heights in each wave record . Here, ‘significant wave height’ values were calculated as four times the square root of the zeroth moment (integral) of the power spectrum, Hm0. Note that the wave datasets discussed were calculated using the spectral calculation of significant wave height (Hm0) and unless explicitly stated as otherwise, all references to wave heights are for significant wave height.

‘**Old Sea**': Over inner continental shelf regions, local wind forcing of sea can be ‘interrupted’ by several mechanisms:

- blocking by offshore reefs, islands and peninsulas;
- refraction of wave energy away from the line of the forcing winds;
- sudden drops in wind speed; and
- rapid changes in wind direction.

Each of these mechanisms takes the growing sea away from the line of direct wind forcing, at times before the nonlinear interaction terms can transform the wave energy into swell. These remnant sea states therefore do not fall into the category of either sea or swell, and have been termed “old sea”.

## 1.6. Reports of Relevance

Reports listed in Table 3 have been prepared to address specific items identified in the Environmental Scoping Document (ESD) (Preston Consulting, 2022) by means of hydrodynamic modelling. A base hydrodynamic model (O2Me 2022a) capable of reproducing ambient waves, currents, and water levels E of Cape Preston was validated with locally acquired data (O2Me 2022c, 2022d). The base model was then adjusted to answer specific questions related to the environmental impact assessment of the ESSP, namely:

- Dredge and dredge disposal plume dispersion modelling to assist with the assessment of impacts to BCH (O2Me 2022b);
- Bitterns discharge plume dispersion modelling to assist with the assessment of impacts to water quality (O2Me 2022e);
- Tidal inundation changes to assist with the assessment of impacts to inter-tidal habitats (O2Me 2022g); and
- Coastal re-adjustments post ESSP development using a modified version of the tidal inundation model to assist with the assessment of impacts to inter-tidal habitats (O2Me 2022f).

Table 3: O2 Metocean (O2Me) reports of relevance.

| Report number | Report title | Intext reference |
|---|---|---|
| R210323 ([1]) | ESSP: Base Hydrodynamic Model | O2Me, 2022a |
| R210324 | ESSP: Dredge Plume Modelling | O2Me, 2022b |
| R200219 | ESSP: Metocean Field Data Collection Programme: Data Report | O2Me, 2022c |
| R210389 | ESSP: Metocean Data Appraisal | O2Me, 2022d |

[1] This report

| | | |
|---|---|---|
| R210325 | ESSP: Bitterns Dispersion Modelling | O2Me, 2022e |
| R210391 | ESSP: Coastal Process Study to Support BCH Assessment | O2Me, 2022f |
| R210327 | ESSP: Tidal Inundation Modelling | O2Me, 2022g |

# 2. Oceanographic Context

The proposed ESSP is in Regnard Bay on the western Pilbara Shelf. In the sections below the physical settings for the Pilbara coast (regional setting) and Regnard Bay itself (local setting) are discussed. A thorough review of these processes is presented in the accompanying report O2Me (2022d).

## 2.1. Climate and Wind

The Pilbara is an arid region with pronounced wet and dry seasons, influenced by the Indonesian-Australian monsoon and the meridional migration of the equatorial and subtropical pressure belts. The wet season (November-April) is characterised by high temperatures, higher than average rainfall, and lower atmospheric pressures (over the land). The dry season (May-October) is characterised by warm temperatures, clear skies, limited thunderstorm activity, very low rainfall, and higher atmospheric pressures. Over 1991-2020 the maximum daily temperatures at Mardie (nearest long-term weather station to the ESSP) averaged 34.0 °C, with the monthly average peaking at 37.9 °C in January and falling to 28.3 °C in July (Figure 3).

During the dry season, winds are predominantly from the E to S, coincident with the Trade Winds (Figure 4) ([2]). During the wet season winds are predominantly W to SW (Figure 4). These seasonal trends are modulated year-round by a diurnal land-sea breeze system, which intensifies in the wet season.

The region is exposed to tropical storms and cyclones during the wet season. The Karratha to Onslow coastline is the most-cyclone prone section of the Australian coast (Figure 5), with one cyclone making landfall every two years on average. Cyclones affecting the Pilbara typically form in the tropical waters between the Kimberley and the Timor Sea and intensify as they propagate westward and poleward (Figure 6). In addition to tropical storms, troughs of low pressure also bring rain, strong winds, and sharp changes in wind direction.

The annual average rainfall is only 315 mm, though this value can be exceeded in a single day during an extreme tropical storm. The mean monthly rainfall has a bimodal distribution with one peak in February and a second peak in June. Tropical storms dominate this first peak, while frontal systems from the S can contribute to the rainfall in the middle of the year. Very little rain falls between August and October (Figure 3).

[2] Data from European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 model, described in Section 4.2.1.

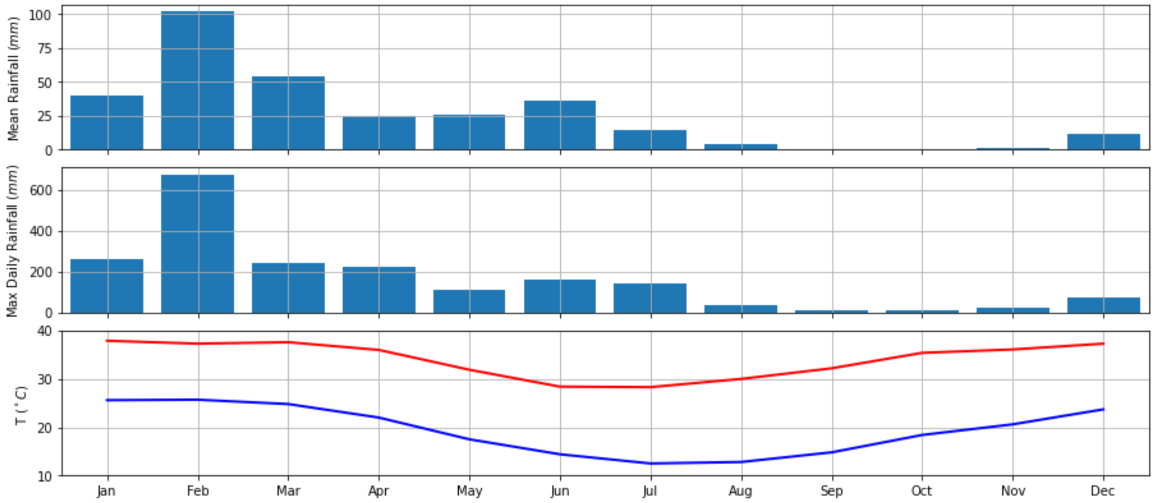


Figure 3: Climate Statistics for BOM Mardie weather station over ten years of 1991 to 2020. Top: mean monthly rainfall. Middle: maximum daily rainfall per month. Bottom: monthly mean maximum daily temperature [red] and monthly mean minimum daily temperature [blue].

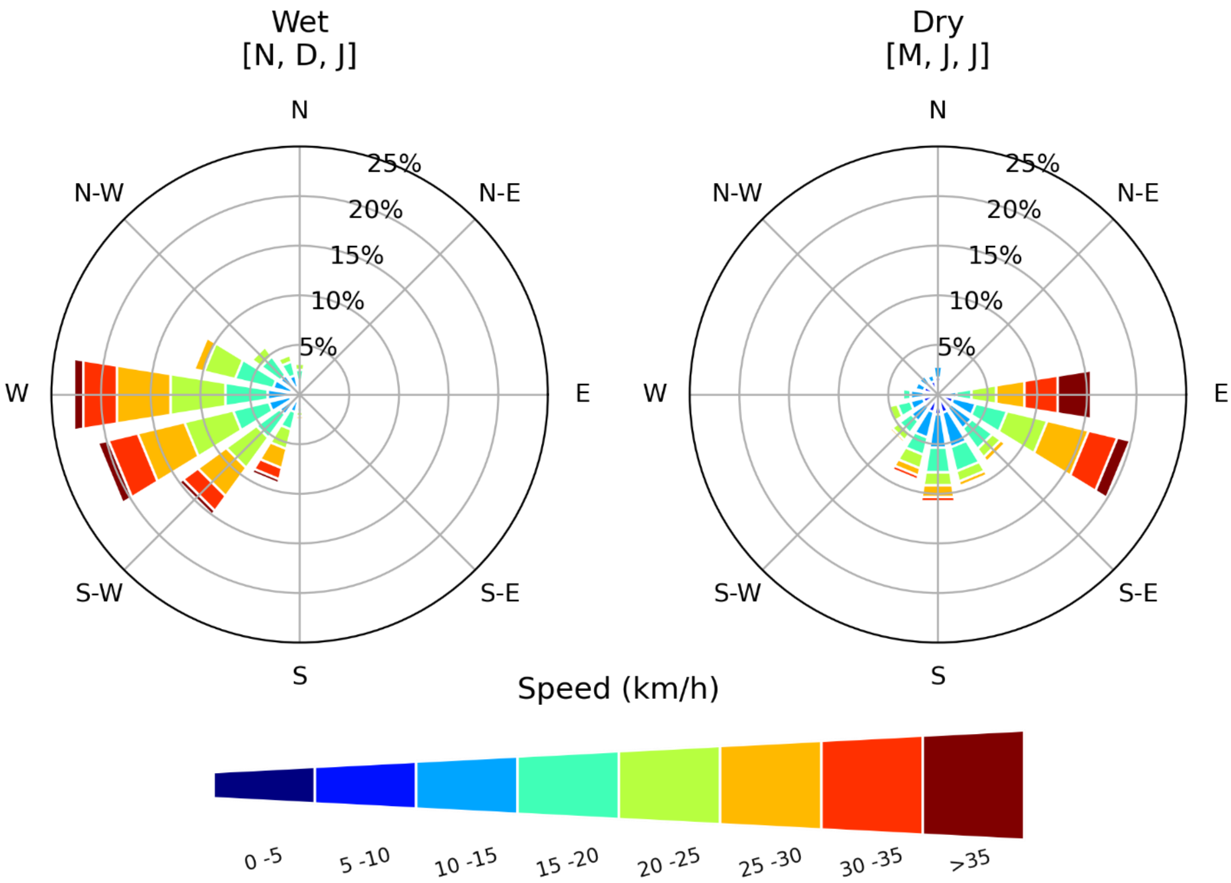


Figure 4: Wind Rose plots for wet (left) and dry (right) seasons based on analysis of the 10 years of ERA5 modelled data (2011-2020) from near Cape Preston. Note that the months selected are to present general seasonal behaviour, not to define the wet and dry seasons. ERA5 model is described in Section 4.2.1.

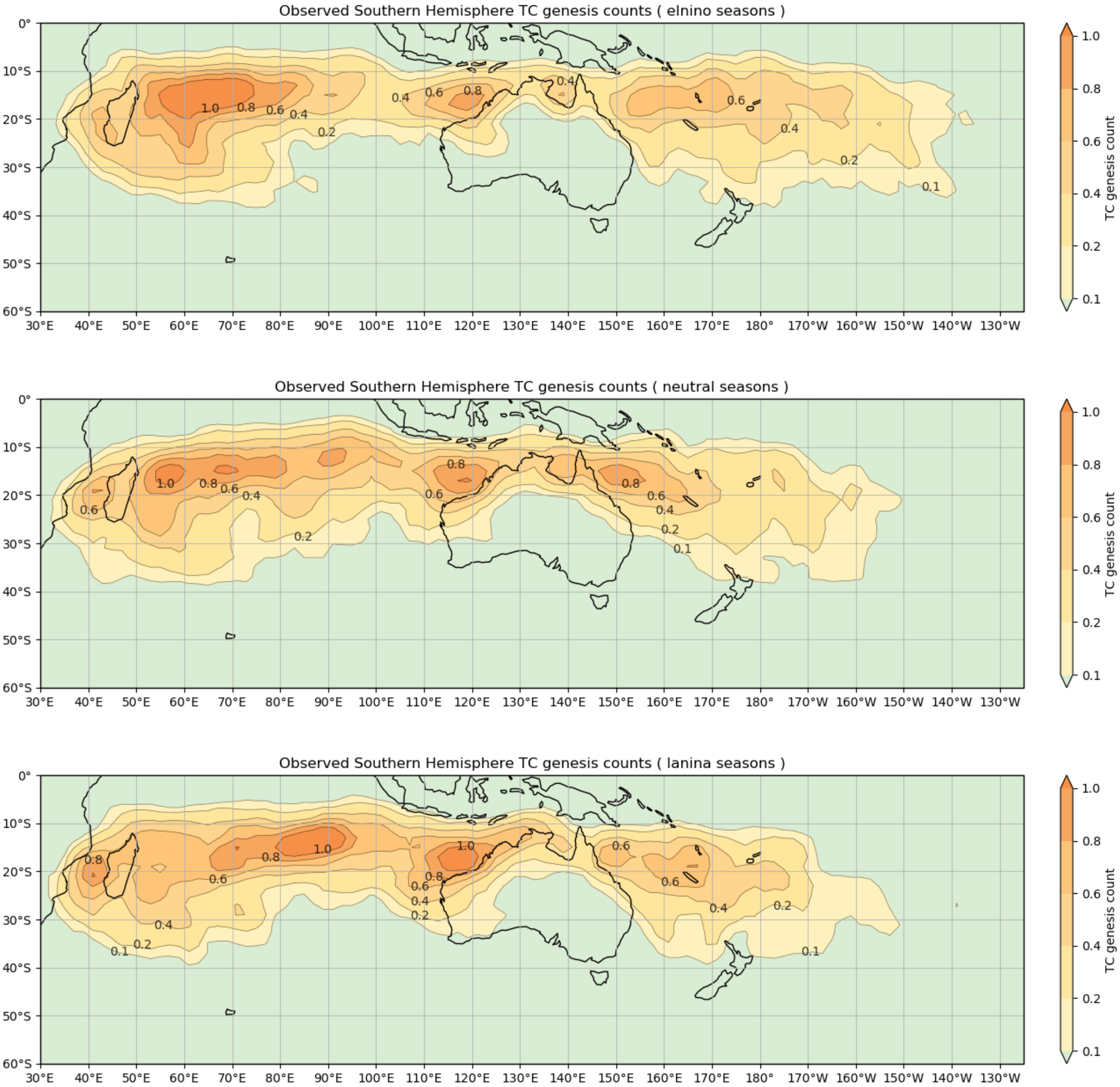


Figure 5: Tropical Cyclone occurrence for El Niño (top), Neutral (middle) and La Niña (bottom) seasons (source: BOM).

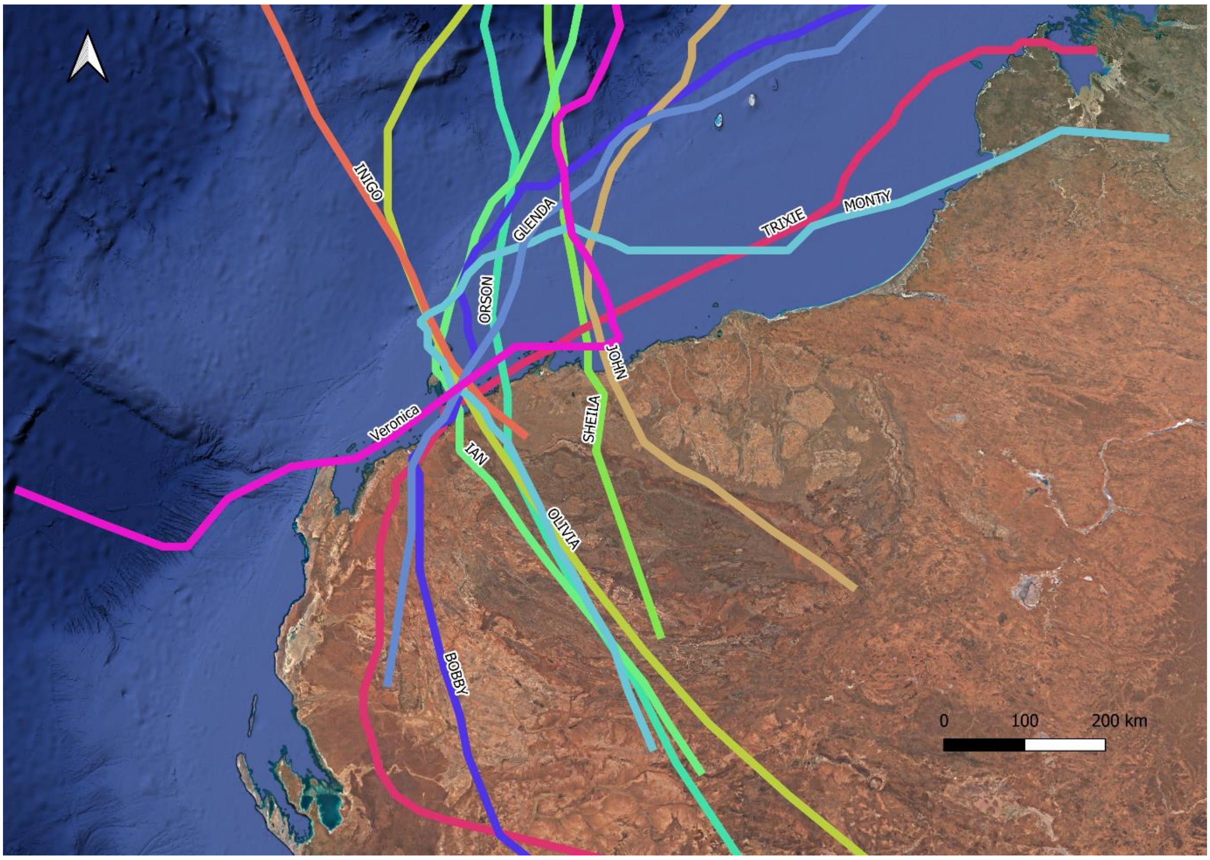

Figure 6: Tracks of notable cyclones impacting Cape Preston.

### 2.1.1. Drivers of climate variability

Over short timescales (i.e. decades), the main driver of interannual climate variability in Northern Australia and the Pilbara region is the El Niño Southern Oscillation (ENSO). The Southern Oscillation Index (SOI) is one indicator of the state of the ENSO, with large positive conditions (see Figure 7, blue region) indicating La Niña conditions, large negative values (Figure 7, red region) indicating El Niño conditions, and intermediate values (Figure 7, white region) considered neutral. The positive phase of ENSO, known as La Niña, is characterised by a strengthening of the trade winds over the tropical Pacific. This intensification drives more warm water over the western Pacific, leading to less stable atmospheric conditions and increased rainfall over northern and eastern Australia, warmer than average conditions over the Cape York Peninsula, and cooler than average conditions over southern Australia. The negative phase, El Niño, has approximately opposite effects. Compared to the Pacific coast, the effects of ENSO over the Pilbara coast are less dramatic, and often less consistent, though La Niña years are linked to an increase in both the number and intensity of tropical cyclones in the Pilbara, despite distance from the direct effects of the Pacifica Ocean trade winds.

The Indian Ocean Dipole (IOD) is another empirically defined oscillation which impacts interannual climate in the Indian Ocean, modulating the effects of ENSO. A negative IOD reflects an intensification of the standard atmospheric circulation in the upper Indian Ocean. This is associated with warmer ocean temperatures and increased atmospheric instability over northern Australia, reinforcing La Niña conditions. Conversely, a positive IOD reflects a weakening or disruption to this circulation, associated with a more stable atmospheric conditions over northern Australia, reenforcing the effects of El Niño.

The contemporary warming trend in the ocean and atmosphere (global warming) are another source of long-term climate variability, though significant effects are generally measured (and predicted) over timescales larger than the life of many engineering projects.

### 2.1.2. Temporal context of the present observations

The ENSO and IOD states for the current deployment period is shown in Figure 7 and Figure 8, respectively, with respect to longer term records of the indices. The 2020-2021 wet season was characterised by mild La Niña conditions and a neutral IOD, while the 2021 dry season was characterised by neutral ENSO conditions and a mild negative IOD.

Despite the presence of La Niña, cyclone impacts in the Pilbara Region were very mild during the 2020-2021 cyclone season. The only storms reaching cyclone classification were TC Marian (21 February – 9 March 2021), and the interacting systems Seroja (3 – 12 April 2021) and Odette (3 – 10 April 2021), though each of these reached full intensity far to the W of Cape Preston. In addition to these extreme events there were numerous other weaker tropical storms in the region (e.g. TL02U 6 – 12 December 2020; TL08U 15 – 23 January 2021, and TL12U 28 January – 5 February 2021). In many cases unnamed low-pressure cells located very close to Cape Preston had a more direct influence on local winds than more distant tropical storms. (O2Me, 2022d)

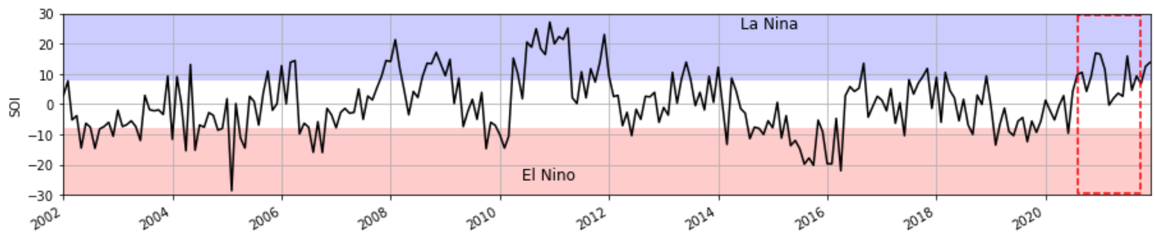


Figure 7: Monthly Southern Oscillation Index (SOI) from 2002 to 2021 (source: BOM).

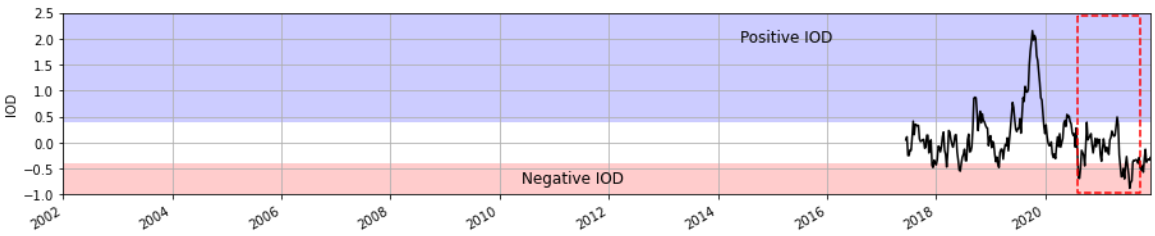


Figure 8: Monthly Indian Ocean Dipole Index from (IOD) 2017 to 2021 (source: BOM).

## 2.2. Geomorphology

The Pilbara has a very broad continental shelf, ranging from around 100 km at the western extent to 300 km in the E. To the W (i.e. offshore from Barrow Island) the shelf breaks gradually onto the Exmouth Plateau, while in the E (i.e. offshore from the Rowley Shoals), the shelf breaks much more rapidly into deeper waters. Barrow Island, the Montebello Islands, and the shoals to the S of Barrow are significant features of the inner shelf that influence waves, tidal currents, and wind driven circulation in the region. Between North West Cape and the Dampier Archipelago, many smaller islands lie inside the 30 m depth contour, providing further shelter for the coastline. These islands introduce heterogeneity in the ambient hydrodynamic conditions along the coast, which in turn promotes heterogeneity in marine habitat.

Regnard Bay is bound by Cape Preston to the W and the Dampier Archipelago to the E. Offshore, the bay is bound by a series of islands (e.g. Southwest Regnard, Northeast Regnard and Eaglehawk Islands), the line of which mark a step change in bathymetry from the relatively shallow bay to the deeper waters offshore. Cape Preston has been extended and fortified by the construction of the Cape Preston marine offloading facility. The consequences for sediment fluxes into the bay are described in O2Me (2022f).

Lebrec et al. (2021) characterise the seabed between the Regnard Islands and the 20 m isobath as a submerged strandplain. The authors do not characterise the bay itself, though the satellite derived bathymetry product of Lebrec et al. (2021) indicates several distinct systems of ridges within the bay. The region behind (i.e. to the S of) Southwest Regnard Island is particularly shallow, which is expected to introduce complex friction controlled tidal flows through the channel to the W, where the trestle jetty, dredge channel, and bitterns discharge are proposed to be constructed (Figure 1).

The mainland Pilbara coastline is characterised by extensive beaches, mud flats, mangroves and tidal creeks seaward of an ancient hard-rock terrain. Marine sediments are delivered and deposited through the action of wave and tides, while terrigenous sediments are delivered to the coast episodically through flood plains and river deltas – the largest river within Regnard Bay being the Maitland River to the E of the proposed site. Island coastlines are predominantly rocky marine sediments. *Cape Preston East* has a beach coastline as far as the sandbar connecting *Great Sandy Island* to the cape. Behind this sand bar the shoreline consists of tidal creeks, mangrove habitat and extensive algal mats. Cyclones, and the associated extreme high-water levels, waves, and freshwater discharge are likely to be a significant driver of coastal geomorphic changes in the region (Eliot et al. 2013).

### 2.2.1. Available bathymetric data

The Geosciences Australia dataset provides a reasonable estimate of the deeper waters off the shelf break and has been used in many numerical studies of the Eastern Indian Ocean (Rayson et al., 2021; Gong et al., 2019). Digitised Nautical Charts offer improved estimates over much of the inner and mid-shelf, but there are many dynamically important 'unsurveyed' areas. For example, there are large significant unsurveyed areas around the shoals S of Barrow Island, where strong frictional effects exist (Condie and Andrewartha, 2008) that potentially influence coastal hydrodynamics elsewhere in the domain. Further, the bulk of Regnard Bay itself is unsurveyed in these charts. The Lebrec et al. (2021) satellite derived product is a high-resolution dataset spanning from the Gascoyne to the Kimberly region (Figure 9) to supplement the lower resolution GA and nautical chart datasets. In addition to these publicly available data, LS possess a merged product which offers very high-resolution data in the vicinity of the primary marine components of the project.

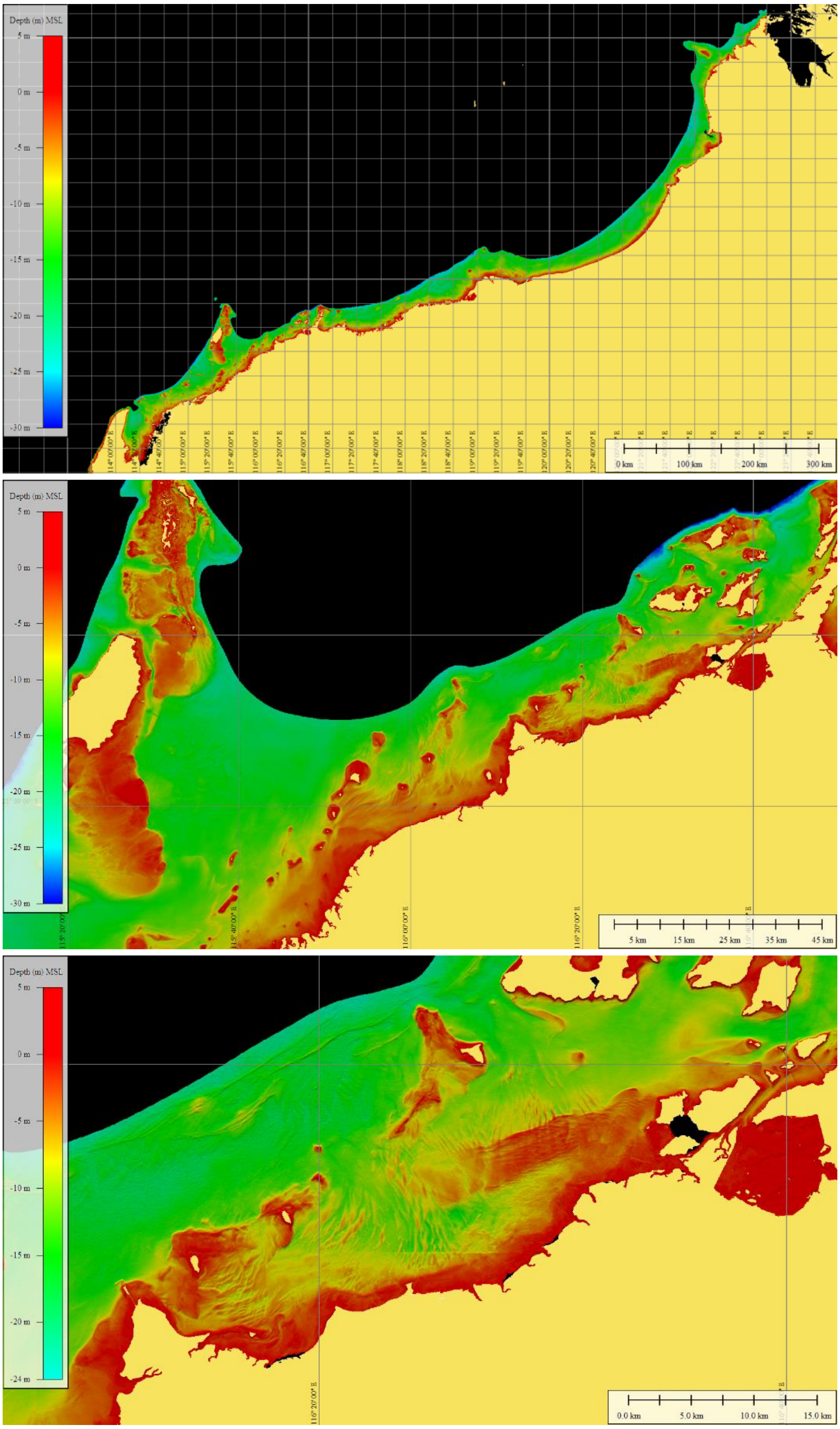


Figure 9: Lebrec et al. (2021) satellite derived product. Top panel: full dataset. Middle Panel: zoomed view from Barrow Island to Burrup. Bottom Panel: zoomed view in the vicinity of Regnard Bay.

## 2.3. Water levels

Water levels along the Pilbara coast are dominated by the semidiurnal lunisolar tides, with the eastern Pilbara classified as from macro-tidal, and the western Pilbara as meso-tidal (Table 4). At the proposal site the mean spring tide range exceeds 3 m and the maximum tide range is approximately 4.5 m. The presence of Barrow Island and the shallow waters to the S, strongly affect the westward propagation of semidiurnal and diurnal tidal energy, introducing complex non-linear tidal flows to the W of Barrow Island.

Wind, pressure and wave-setup in the Pilbara are typically low in comparison to the tidal variability, though they can be significant under tropical cyclone forcing, particularly in partially closed water bodies (i.e. marine embayment). Appreciable inundation of coastal areas occurs under these conditions, and wave action can be highly destructive. O2Me are not aware of any long-term records (i.e. measurements) of water levels within Regnard Bay to estimate peak storm water levels.

When the forcing of super-inertial (i.e. periods longer than ~2 days) coastal water-level fluctuations relaxes, the perturbation can become 'coastally-trapped' continental shelf waves (Provis and Radok, 1979). These waves propagate counter-clockwise for long distances around the WA coast, steered by Coriolis and the local bathymetry. The strength of such waves depends on the scale of the initial forcing, regional and local bathymetry.

Table 4: Nominal tidal planes at Dampier, Barrow Island, Onslow and Cape Preston [datum mean sea level]. Data source: Australian Coastal Vertical Datum Transformation (AusCoastVDT). Note that these data are provided here only as an indicator of variation along the Western Pilbara coast, they are not suitable for navigation.

| | Onslow [m] | Dampier [m] | Cape Preston [m] | Barrow Island West [m] | Barrow Island East [m] |
|---|---|---|---|---|---|
| HAT | 1.29 | 2.46 | 2.25 | 1.30 | 2.20 |
| MHWS | 0.85 | 1.76 | 1.71 | 0.89 | 1.50 |
| MHWN | 0.26 | 0.46 | 0.38 | 0.26 | 0.41 |
| MSL | 0 | 0 | 0 | 0 | 0 |
| MLWN | -0.25 | -0.46 | -0.38 | -0.25 | -0.40 |
| MLWS | -0.84 | -1.48 | -1.45 | -0.94 | -1.33 |
| LAT | -1.29 | -2.66 | -2.19 | -1.32 | -2.21 |

Shallow water effects on the barotropic tide are significant in some localities, particularly in coastal waters to the SW of Barrow Island. Here, barotropic energy flux is largely from the E, and interactions with frictional effects plus wave-wave interactions lead to non-linearities in water levels that are not well represented by tidal harmonics (Figure 10). Times of high water are marked by black dotted lines, and low water by red dotted lines in Figure 10. Non-linearities in the timeseries are evident by relatively sharp peaks around high water, and a shorter ebb than flood.

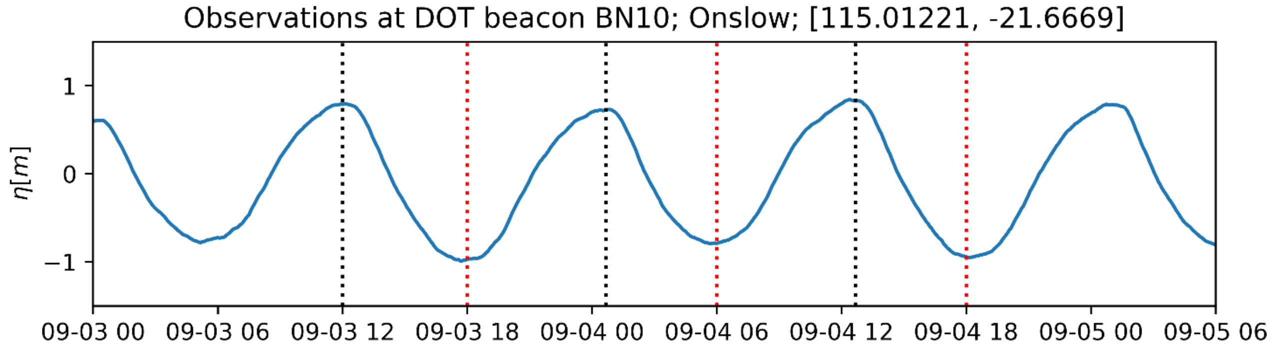


Figure 10: Short time window of observed water-levels at Pilbara Ports Authority's BN010 site (blue). Time shown in 'day-month 24-hour' format.

## 2.4. Ocean Currents

Instantaneous currents on the inner shelf are dominated by barotropic tides, with wind-driven currents, steric currents and continental shelf waves playing a lesser role (Godfrey and Mansbridge, 2000; Condie & Andrewartha, 2008; Ridgway and Godfrey, 2015; Sun and Branson, 2018, and the references therein). Persistent large-scale currents (e.g. the Holloway current) are typically constrained to waters depths greater than 100 m. Sub-tidal circulation is seasonally variable, and driven predominantly by winds (Condie and Andrewartha, 2008). During the wet season these low-frequency wind-driven currents typically flow towards the E, while in the dry season they typically flow towards the W.

Examination of current data gathered for the ESSP at sites shown in Figure 11 revealed that currents are dominated by tides, with a distinct semi-diurnal (twice daily) cycle, and a pronounced (~15 day) spring-neap cycle. Tidal ellipses are highly variable (between sampling locations) and are strongly controlled by local bathymetry. Though inspection of the full ESSP measurement period (15-months from July 2020 – November 2021), wind direction and near-surface current direction time history plots reveal the seasonality of wind drift currents, the speed manifestations are masked by the tidal currents. Vestiges of low frequency motions are only evident during periods of neap tides, and then only near-surface, as bottom friction is shown to rapidly attenuate near-seabed low frequency flows. Though small, the effects of seasonal drift currents and low frequency flows will be important to far field flushing of any releases into Regnard Bay.

Close-approach tropical lows were seen to have the strongest nontidal influence on local currents but then only when they occurred near neap tides. It is expected that future close-approach severe tropical cyclones will generate the strongest currents in Regnard Bay (stronger than tidal currents).

Though originally conjectured as being a potential issue for marine operations, no evidence was found of significant infragravity wave activity (swell-related sea level and slow drift current fluctuations on timescales of the order of 1 minute, the period of a swell group).

Evaporation over the expansive tidal mudflats would be expected to result in a persistent drainage of relatively high salinity water along the deepest channels in Regnard Bay (S Buchan, pers. comm). This process, however, was not detected in the limited measurements of near-seabed salinity and temperature from NCP05 and UNS05 (no strong lateral density gradients observed).

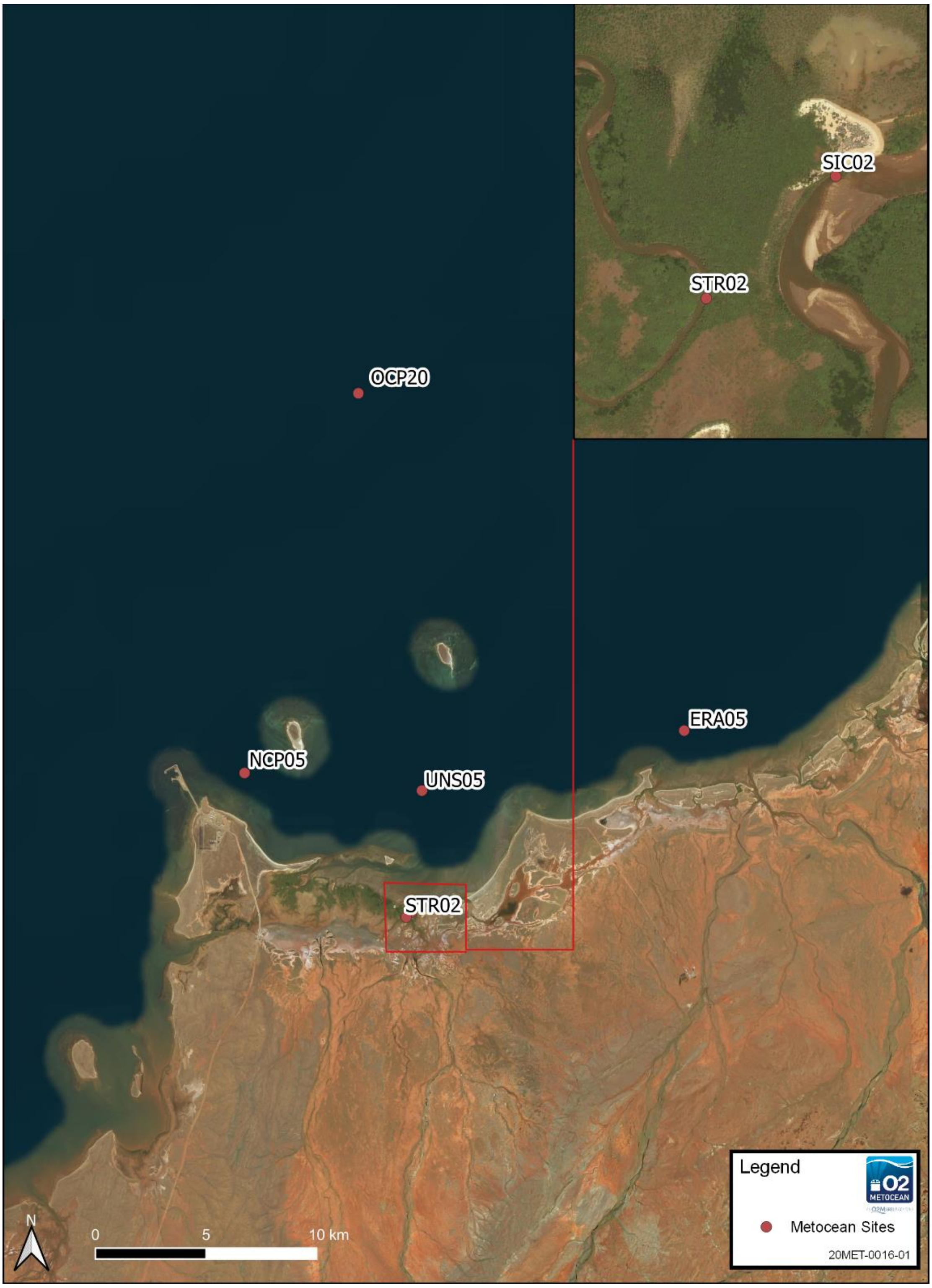


Figure 11: Study sites from (O2Me 2022c). Ocean current profiles were taken at all sites except STR02, and spectral wave observations were made at all sites except STR02 and SIC02.

## 2.5. Waves

The sea state of the southern NWS principally comprises contributions from:

- Southern Indian Ocean swell;
- Winter Easterly swell;
- "West Coast" swell;
- tropical cyclone swell;
- local wind-generated sea; and
- "old sea".

Each contribution is discussed in O2Me (2022d). A summary is presented next.

### 2.5.1. Southern Indian Ocean Swell

Southern Indian Ocean Swell is a perennial feature of exposed NWS waters. Typically, this swell arrives at the outer edge of the continental shelf from the S and SW, before refracting during propagation across the shelf, to become more W and even NW near-shore.

Southern Indian Ocean swell tends to be higher (typically 2 m in deep water) during winter than in summer (typically 1 m) because the generating storms move further N in winter. Swell periods are typically of the order of 12 to 16 seconds, though swell of 20 seconds period have been measured on the NWS.

### 2.5.2. Winter Easterly Swell

Where sufficient fetch is available (at least 200 km), the synoptic winter easterlies which prevail over all of the NWS may generate an E or NE swell of 6 to 8 seconds period.

Such swell will be of influence in the outer shelf portions of the mid NWS region (1 to 2 m height).

### 2.5.3. "West Coast" Swell

During summer, strong southerly diurnal coastal winds are a feature of the Western Australian coastline between Perth and the North West Cape. These winds generate sea, and the resulting dispersive swell refracts around the North West Cape and Barrow Island onto the NWS, producing a "burst" of swell passing the area off Dampier, near the edge of the continental shelf, several hours after midnight.

### 2.5.4. Tropical Cyclone Swell

Tropical cyclones will generate waves which propagate radially (roughly) out from the storm centre.

Depending upon such parameters as storm size, intensity, relative location and forward speed, tropical cyclones may generate swell of 6 to 18 seconds period from any direction, with heights ranging up to 15 m (depth permitting).

### 2.5.5. Local Wind-Generated Sea

Local wind-generated sea typically ranges in period from 2 to 6 seconds but may attain 7 seconds under very persistent forcing. Heights are extremely variable, ranging from 0 to 6 m under non-tropical cyclone forcing, and possibly exceeding $H_s > 10$ m under severe tropical cyclone forcing.

The direction of local sea would be the same as that of the generating wind, unless local bathymetric effects (refraction, diffraction, shielding ...) act to influence wave direction.

### 2.5.6. Old Sea

Old Sea may be generated by surges in either the summer NW Monsoon or the winter SE Trade Winds, in the deeper waters to the N of Cape Preston. In summer, old sea is refracted around the N extremities of The Monte Bello Islands to arrive at Cape Preston from the NNW. In winter, old sea is refracted around the N extremities of then Dampier Archipelago and arrives at Cape Preston from the NNE.

The prevailing (i.e. non-cyclonic) wave climate exhibits strong seasonality. Locally generated high-frequency wind waves dominate, although remotely generated wind-waves (i.e. "old sea") can be significant at times. These remote seas vary appreciably along the Pilbara coastal waters but typically have a NW aspect in the wet-season, and a NE aspect in the dry season.

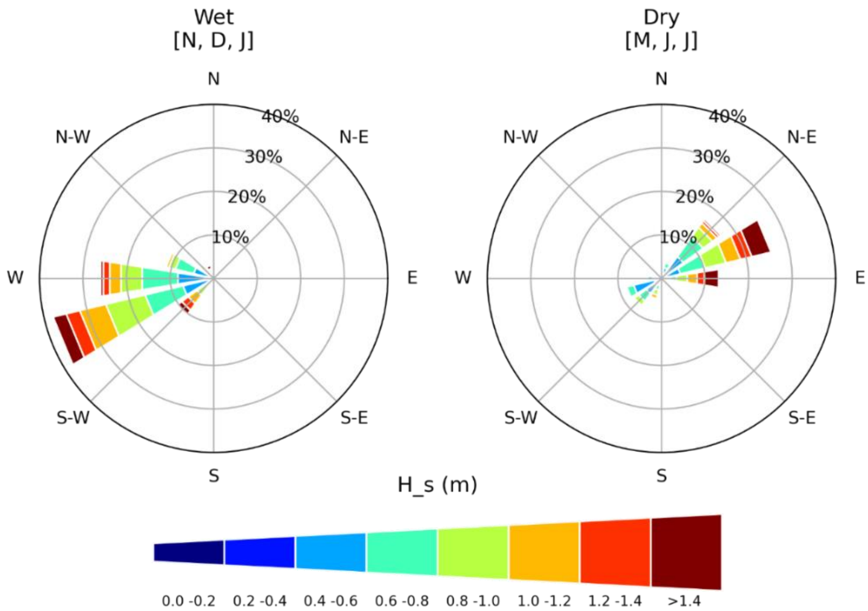


Figure 12: Wave roses for the wet (left) and dry (right) seasons based on analysis of the 10 years (2011-2021) of ERA5 modelled data from near Cape Preston, suitable for evaluating prevailing seasonal patterns. Note that the months selected are to present general seasonal behaviour, not to define the wet and dry seasons. The ERA5 model is described in Section 4.2.1.

# 3. Numerical model: overview

Modelling was conducted using DHI's MIKE FM three-dimensional (3D) suite of models. The MIKE FM hydrodynamic (HD) module solves the unsteady Reynolds-averaged Navier Stokes (RANS) equations (mass and momentum) and can be fully coupled with a surface wave-action equation. Spatial discretisation uses a finite volume approximation on unstructured horizontal grids with three-sided and four-sided polygons. The vertical coordinate in the hydrodynamic module can be discretised with either a sigma or combined sigma-z scheme. Alternately, the depth averaged equations can be solved without vertical discretisation.

The model incorporates non-hydrostatic and baroclinic pressure, though hydrostatic and barotropic assumptions can be used for increased efficiency and stability. Coriolis may be specified as fully variable, or by f-plane approximation. A two-equation ($k - \epsilon$) closure scheme is implemented for both horizontal and vertical eddy viscosities, or alternately a Smagorinsky formulation may be used in the horizontal. If required, air-sea fluxes, tidal potential and ice-coverage may be prescribed.

The MIKE suite of models incorporates several additional modules for transport of dissolved or suspended material. Coupled sub-grid near-field models are included (e.g. for ocean outfalls and sea-dumping), and far field diffusivities scale on the eddy viscosity from the hydrodynamic module.

The hydrodynamic module is 2-way coupled with a third-generation spectral wave-action model that uses a 2-dimensional (direction-frequency) formulation for the wave action spectrum[3] (e.g. Young, 1999). The model conserves action through shoaling, refraction, three-wave and four-wave interactions, accounts for growth through wind stress, and losses due to bottom friction, white-capping and depth-induced wave breaking. Two-way wave-current interaction is achieved through advection of the wave field and wave-induced bed-stress.

## 3.1. Bathymetry

The model bathymetry was a compilation of three datasets. The priority of datasets when compiling was:

1. Geosciences Australia (GA) 250 m gridded bathymetry product (not shown);
2. Lebrec et al. (2021) satellite derived data (Figure 9); and
3. Two versions of a high-resolution local bathymetry datasets provided by LS (Figure 13).

The full compiled dataset is presented in Figure 14. O2Me have compiled these datasets and performed spot validations against their own unpublished sounder observations within Regnard Bay, and pressure sensor recordings from the Eramurra Metocean observations (O2Me 2022c). O2Me found that all datasets are in high agreement in the western end of the bay where the primary project infrastructure is proposed to be constructed, though some small merging artefacts are evident. Agreement diverges towards the E, suggesting greater uncertainty in these regions.

[3] Other formulations exist within MIKE, but this was the formulation employed here.

In evaluating the two versions of the high-resolution datasets provided by LS, O2Me found the first version performed better in the deeper areas [4], and the second performed better in the shallow waters of Regnard Bay. For use in modelling, O2Me merged these datasets taking the shallow areas from version 2 and the deeper areas from version 1. The delineation was made along the line of intersection of the two datasets.

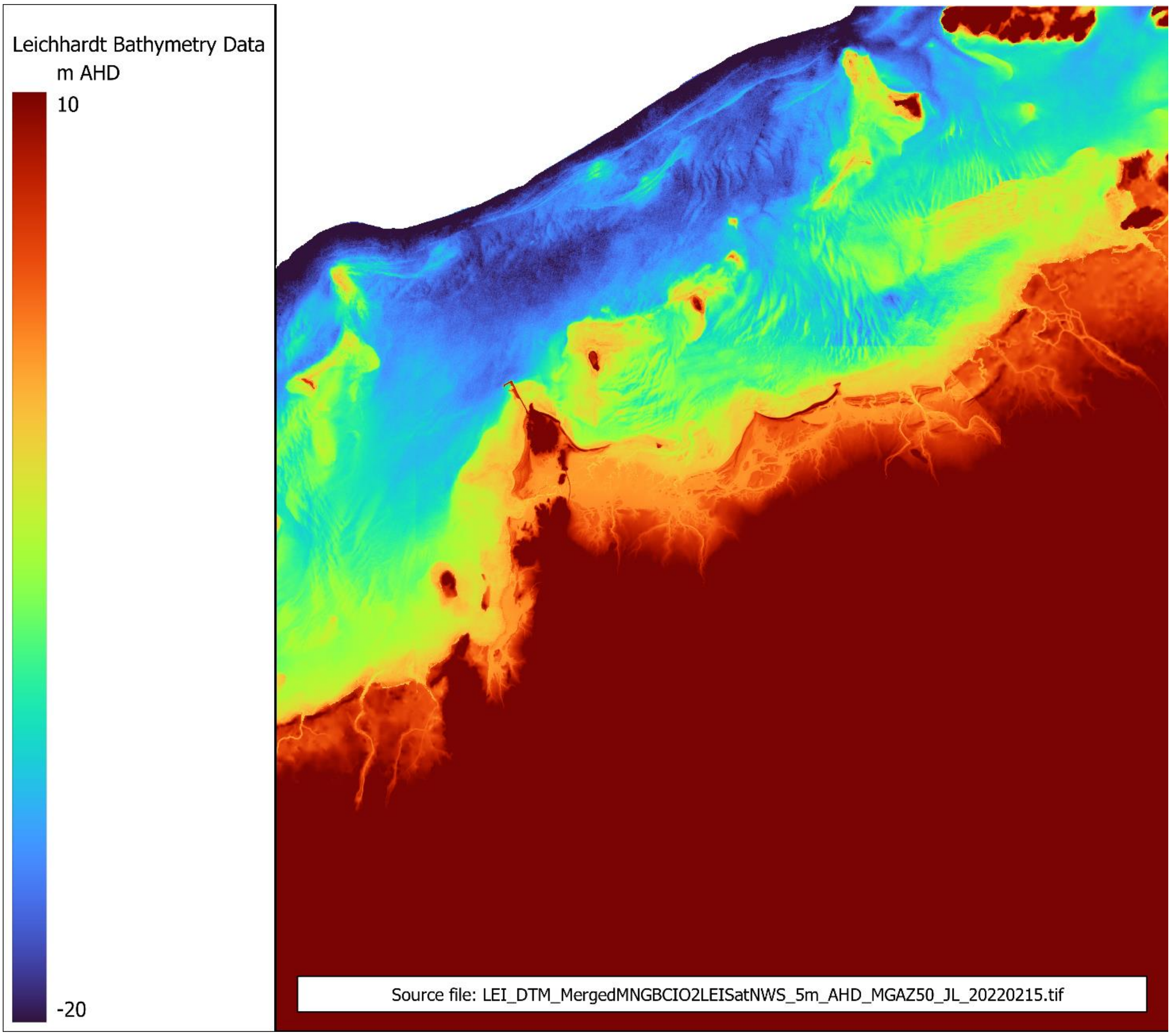


Figure 13: Compiled bathymetry provided by LS.

[4] Performance evaluated via preliminary comparison of model results to measured currents and waves at OCP20 and NCP05 (refer to O2Me, 2022c).

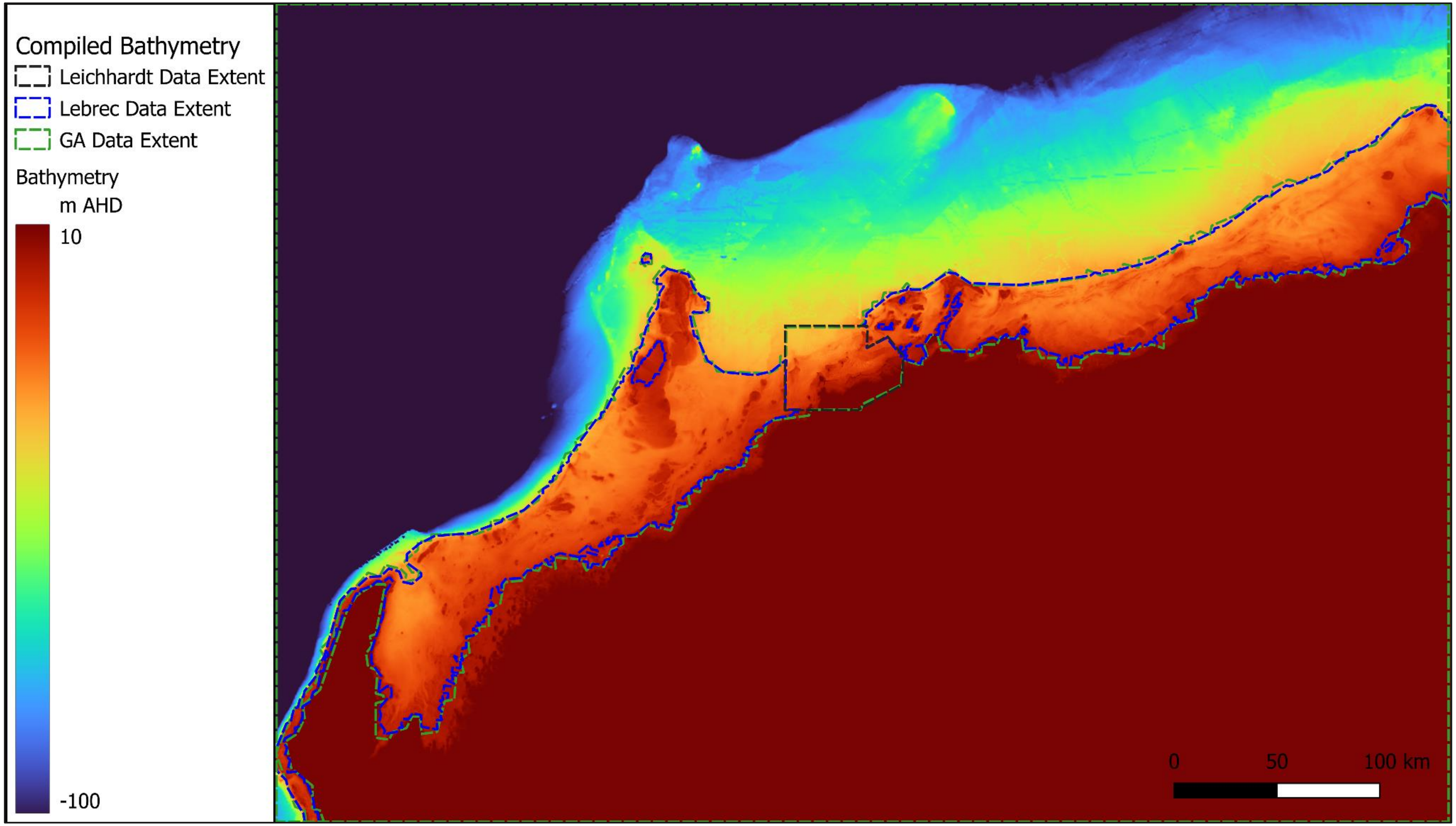

Figure 14: Compiled bathymetry datasets for model use.

## 3.2. Numerical Meshes – Extent and Spatial Resolution

Two numerical meshes were used in this study:

1. The Pilbara model; and
2. The Local Regnard Bay model.

The two meshes were used to model key hydrodynamic conditions in the Regnard Bay area, and combined are referred to as the 'base hydrodynamic model'.

### Pilbara model

The Pilbara model domain extends from North West Cape to approximately 85 km E of Karratha and has a single open boundary (Figure 15). Placement of this boundary was one of the key considerations in model optimisation. The domain was discretised with triangular elements only, ranging from 7 km offshore along the open boundary to 50 m inshore ([5]). The offshore resolution was chosen to match that of a larger regional model developed by O2Me spanning the entire NWS. O2Me did not use this comprehensively larger NWS model in the final simulations of the present study but retained the high-offshore resolution notwithstanding. The inshore resolution was chosen to (1) provide a minimum resolution for Regnard Bay, (2) minimise resolution mismatch when nesting the final models, and (3) to permit low-resolution pilot tests of localised transport studies, which ultimately advised the setup of high-resolution transport studies in the project area.

The Pilbara model consisted of ten (10) sigma layers and solved hydrostatic barotropic pressure. Though the barotropic assumption neglects some circulation in the deepest waters near the open boundary, this study is concerned principally with circulation inshore of the 20 m isobath where the influence of the deep-water flow features is small, and hence was deemed appropriate. The extent of the model domain does not resolve shelf waves originating past Port Hedland – though their influence in the shallow regions of Regnard Bay is dwarfed by the dominant tidally driven currents (O2Me 2022d). Other challenges exist with accurate modelling of shelf waves, such as availability of appropriate forcing data. The final choice of boundaries was involved a trade-off between resolution of these processes, and the dominant tidal process. The choice was made with consideration of the available forcing data, project requirements, and the cost-benefit of resolving additional (secondary) processes.

The model domain has been adapted specifically for the ESSP by the inclusion of a significant area in the project vicinity that is above HAT (red area in the bottom panel of Figure 15). The resolution in this area is around 25 m, which allows for inundation by tides and surge for preliminary investigation of these processes, but the resolution is insufficient for accurate resolution of processes within the creeks (note that a high resolution nested grid was implemented separately to model the creek hydrodynamics, as described in O2Me 2022g).

[5] The model resolution was refined nearshore in the dredge plume and brine dispersion modelling applications, refer to O2Me 2022b and 2022e.

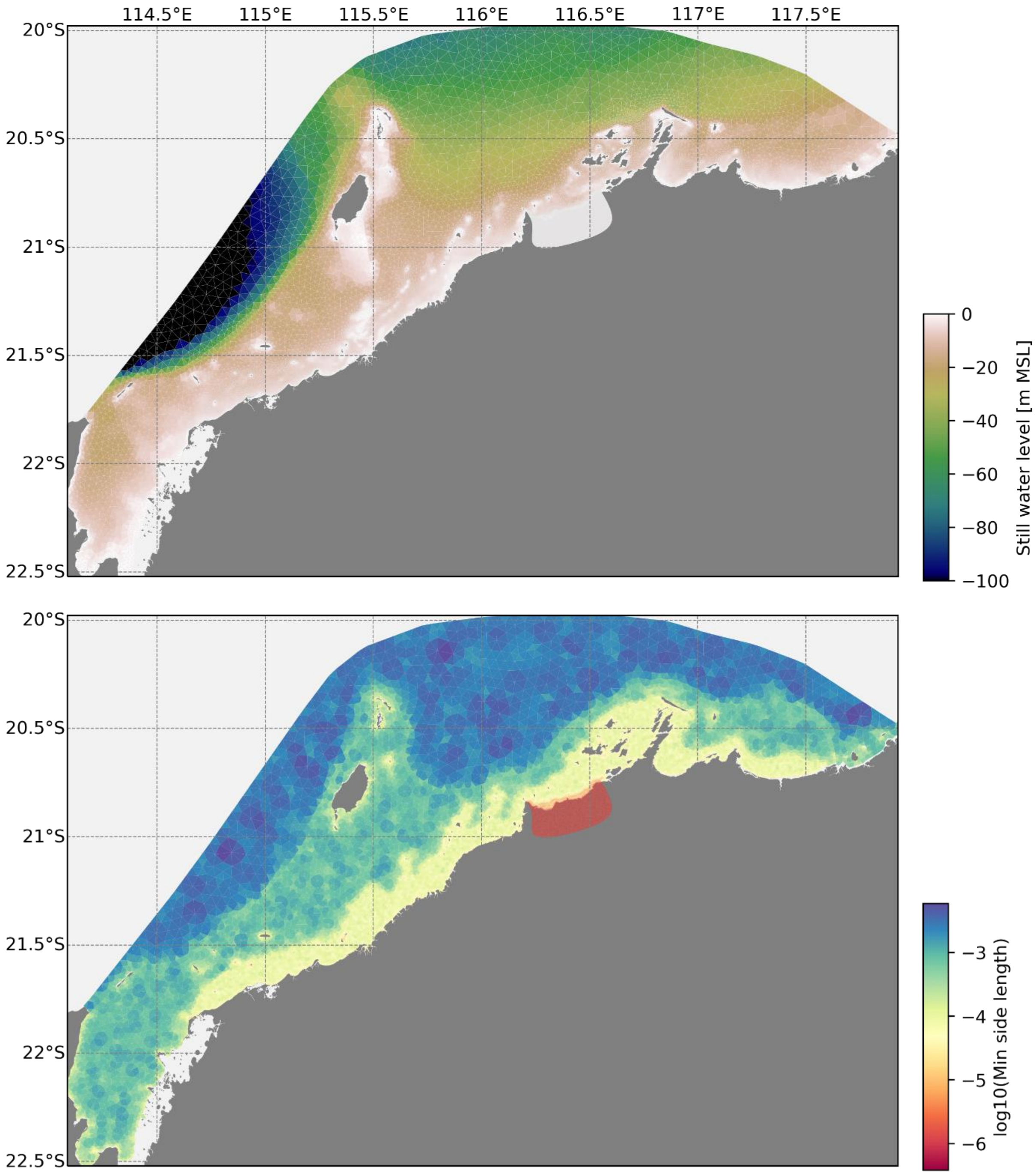


Figure 15: Pilbara model extent and resolution. Top Panel: Still-water level. Bottom Panel: the numerical grid coloured by the logarithmic smallest side length (in degrees).

## Local Regnard Bay model

As per the Pilbara model, used to investigate nearshore processes.

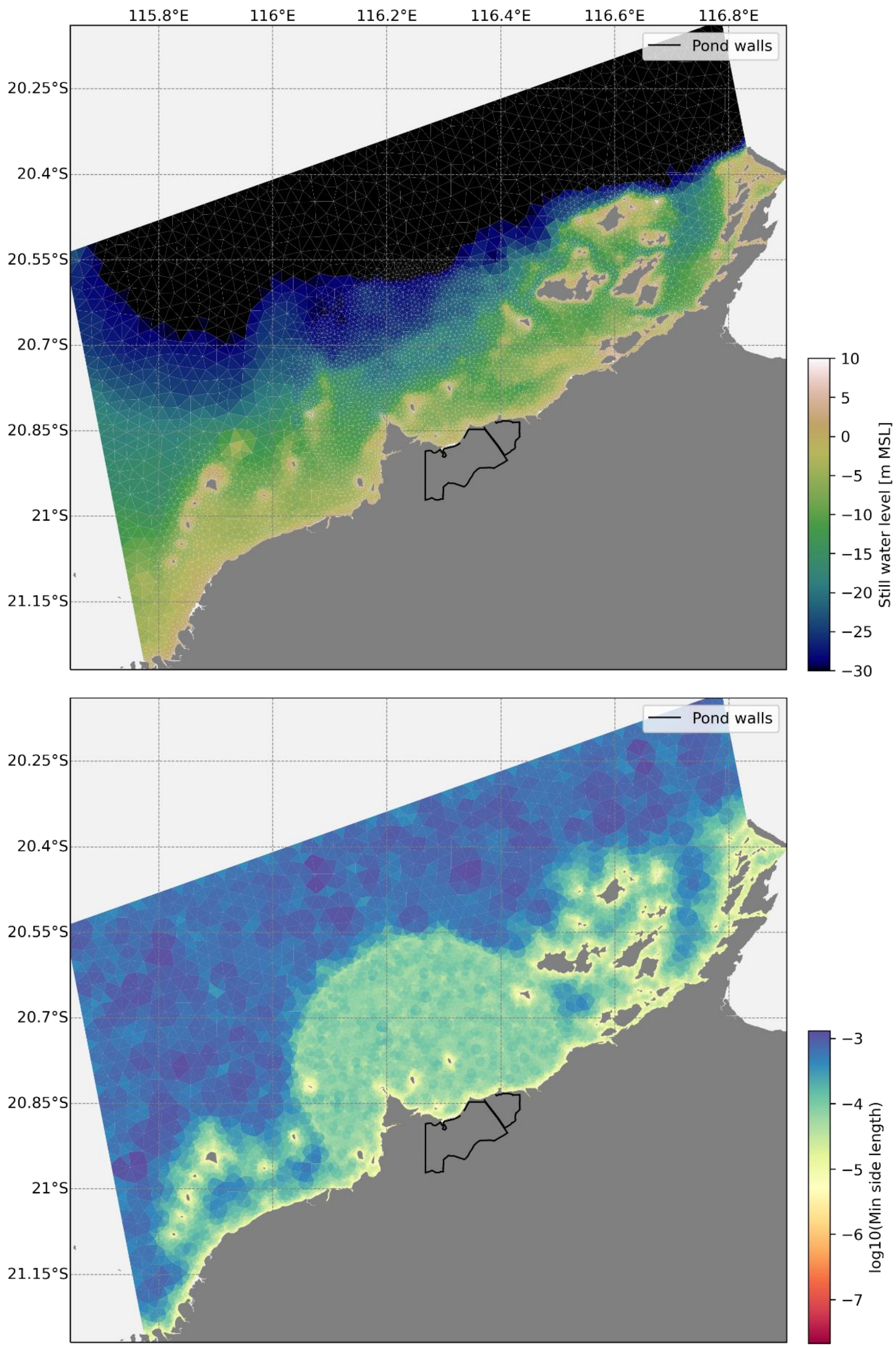


Figure 16: Local Regnard Bay model extent and resolution. Top Panel: Still-water level. Bottom Panel: the numerical grid coloured by the logarithmic smallest side length (in degrees).

# 4. Regnard Bay Validation Exercise

Regnard Bay validation exercise was run for both a wet and dry season period (see Section 4.1). These same periods were used to inform environmental impact assessment. The *Pilbara model* (see Section 3.2) was the outer (largest) domain used, with open boundary conditions and atmospheric forcing taken directly from global models (see Section 4.2.1). The *local Regnard Bay model* was nested within the *Pilbara model.* Water levels and currents were extracted from the *Pilbara model,* though wind and wave forcing were derived from observations (see Section 4.2.2).

## 4.1. Simulation Periods

The two periods simulated to generate boundary-conditions for finer resolution environmental studies were:

1. One four-month dry season simulation from 2020-06-01 to 2020-09-24 [115 days]; and
2. One four-month wet season simulation from 2020-12-01 to 2021-03-26 [115 days].

The 2020-2021 period was chosen due to the availability of high-quality validation data within Regnard Bay. This was not an extreme year for interannual variability by either of the ENSO or IOD indices [Section 2], and so is a valid choice to meet the objective of the base hydrodynamic model.

## 4.2. Forcing

### 4.2.1. Adapted Pilbara model

The open boundary was forced by water-levels reconstructed from the harmonic constituents output by the TPXO ([6]) Indian Ocean 1/12$^{th}$-degree regional model. The outputs include only diurnal and semidiurnal constituents (Table 5), and so the domain must be sufficiently large to account for non-linear interactions. Coefficients for lunar nodal modulation were calculated for the start of the simulation, which is reasonable for simulation durations of this scale. Spatial interpolation of the TPXO outputs onto the boundary points was performed by a weighted nearest neighbour interpolation. For each boundary node the three nearest TPXO grid points were used, weighted by the inverse of the distance between TPXO output location and the boundary node location.

Reasonable resolution of the prevailing wind-driven low-frequency currents (Section 2) in this inner-shelf site can be achieved without nesting within a data assimilated regional or global numerical model (e.g. HYCOM or Bluelink). Despite corrections for barometric pressure and spatiotemporal wind stress applied at the boundaries, surge under very large storms may be under resolved with a domain of this size. Nesting may improve this, though quality wind-fields are not always readily available for very large storms (Steve Buchan pers. comm.). As this study is not concerned with extremes (Section 1.1), the present methodology was adopted. Regional and baroclinic currents in the deeper areas of the domain will not be resolved, though

[6] TPXO is a series of fully-global models of ocean tides that best fit the Laplace Tidal Equations and altimetry data. For further details, please refer to https://www.tpxo.net/global.

interactions between these currents and surface tides is secondary to the circulation on the inner-shelf, and so the approximation is valid for the present purposes.

Table 5: Amplitudes of TPXO tidal water levels for each constituent at selected points along the model boundary.

| Const | [-21.502] [114.338] | [-21.098] [115.593] | [-20.536] [115.046] | [-20.21] [116.256] |
|---|---|---|---|---|
| **M2:** | 0.41 | 0.77 | 0.53 | 0.91 |
| **S2:** | 0.22 | 0.44 | 0.28 | 0.52 |
| **N2:** | 0.078 | 0.15 | 0.098 | 0.17 |
| **K2:** | 0.061 | 0.12 | 0.08 | 0.15 |
| **K1:** | 0.19 | 0.22 | 0.2 | 0.22 |
| **O1:** | 0.13 | 0.14 | 0.13 | 0.14 |
| **P1:** | 0.059 | 0.067 | 0.062 | 0.068 |
| **Q1:** | 0.03 | 0.032 | 0.03 | 0.033 |

The Pilbara model was forced with winds and atmospheric pressure from ECMWF ERA5 0.25 degree hourly hindcast. A sample comparison to publicly available observations at the Bureau of Meteorology (BOM) Karratha Airport station is shown in Figure 17. BOM data were averaged to the same hourly interval of the ERA5 data. ERA5 resolves the prevailing seasonal winds accurately and the land-sea breeze modulation however often under-resolves the magnitude of the peaks. Resolution of synoptic-scale modulation is also improved against earlier generations, though remains imperfect, and is often not adequate for modelling tropical storms in this region (S. Buchan pers. comm.). The ability to accurately simulate low-frequency currents controlled by either local wind stress, wind setup or pressure setup will be affected by the skill of these large-scale weather products.

No waves were forced on the Pilbara model domain.

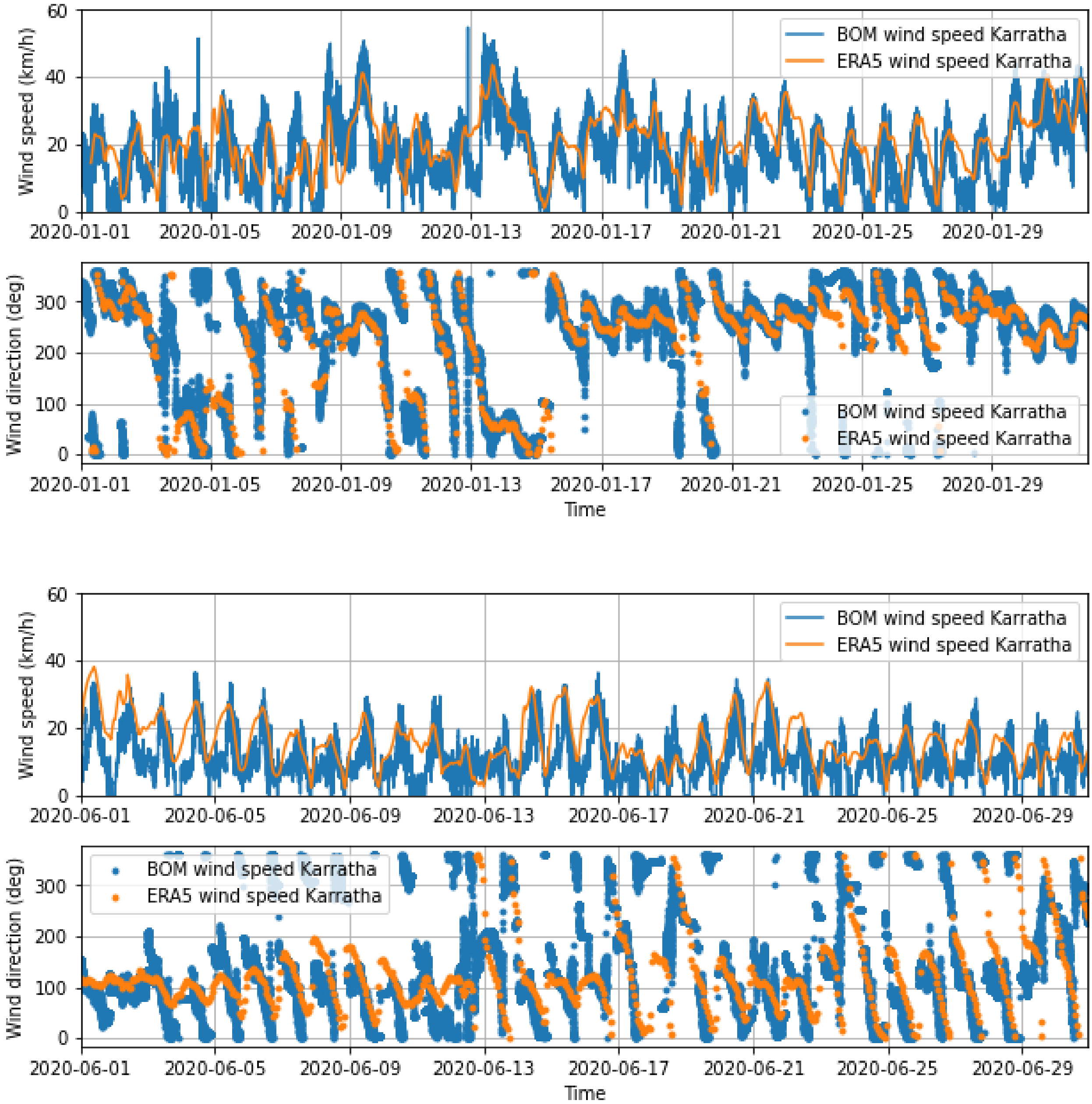


Figure 17: Comparison of wind observations at BOM Karratha Airport station and ERA5 at the nearest output point. Top two panels: January 2020. Bottom two panels: June 2020. Note that the selected time periods serve as examples only.

### 4.2.2. Local Regnard Bay model

The open boundaries of the local Regnard Bay model were forced with water levels and fluxes derived from the Pilbara model. Surface stress was spatially uniform, taken from observations at the BOM Karratha Airport weather station ID 4083 ([7]). The sensitivity of the wave results to wind forcing was investigated by applying a

[7] BOM Karratha Airport winds were compared to winds measured at Pilbara Ports Authority's Dampier Fairway station corrected to 10 m height during the internal review phase of this document. Fairway station winds were typically <10% higher than those measured at Karratha airport, however the two datasets correlated well (Pearson's correlation coefficient of 0.74 and 0.66, and slope of best fit line passing through [0,0] of 0.91, and

scaling factor to the wind field ranging from 0.9 to 1.4 in calibration. Best model agreement to measured waves was obtained for a scaling factor of 1 (i.e. no correction to measured winds from BOM Karratha Airport station).

Wave boundary conditions were applied at the northern boundary. These were derived from observations at OCP20, with significant wave-height of the swell component adjusted by a linear correction factor. As the environment was found to be dissipative in early model tests, the factor was selected by iterative calibration against the OCP20 data. Only one calibration site was used due to satisfactory validations at the remaining sites with this approach. Using more calibration sites and one validation site may allow fine tuning of the variability along the northern boundary but this was not pursued given the satisfactory validations achieved with the original approach.

Gaps in OCP20 observations were supplemented by waves from ERA5 offshore of Barrow Island. No calibration was performed for these gaps as there was no instrument at the calibration site, however the gap constitutes only a very small portion of the overall modelled record.

## 4.3. Validation

### 4.3.1. Primary validation data

Data available for this model are given in Table 6. The primary sites for hydrodynamic validation of water-levels and current velocities are OCP20, NCP05, UNS05 and ERA05. For an appraisal of the data see O2Me (2022d). The detailed QC in O2Me (2022d) updates and supersedes the basic QC presented in O2Me (2022c).

Table 6: Metadata for available validation data sets.

| Location | Latitude (°) | Longitude (°) | Nominal Depth (m) | Date Range | Parameters Measured* |
|---|---|---|---|---|---|
| OCP20 | -20.6693 | 116.27239 | -23.5 | 26/08/2020 > 08/10/2021 | Current Speed/Direction<br>Total/Sea/Swell Hs<br>Total/Sea/Swell Direction<br>Total/Sea/Swell Period |
| ERA05 | -20.8065 | 116.41400 | -4.9 | 14/07/2020 > 09/10/2021 | Current Speed/Direction<br>Total/Sea/Swell Hs<br>Total/Sea/Swell Direction<br>Total/Sea/Swell Period |
| UNS05 | -20.8309 | 116.30000 | -4.8 | 15/07/2021 > 09/10/2021 | Current Speed/Direction<br>Total/Sea/Swell Hs<br>Total/Sea/Swell Direction<br>Total/Sea/Swell Period |
| NCP05 | -20.8237 | 116.22292 | -7.5 | 14/07/2020 > 09/10/2021 | Current Speed/Direction<br>Total/Sea/Swell Hs<br>Total/Sea/Swell Direction<br>Total/Sea/Swell Period |

0.83 for the wet and dry seasons, respectively). Correlation- and QQ-plots showed that the underlying trends were in reasonable agreement (O2Me 2022h). Wind directions were equivalent..

### 4.3.2. Quantification of model Skill

The validity of the model was quantified through a set of skill scores, namely:

- model bias:

$$Bias = \frac{1}{n}\sum_{i=1}^{n}[M_i - O_i],$$

- root mean squared error:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}[M_i - O_i]^2\right]^{\frac{1}{2}},$$

- Murphy (1988) skill score:

$$SS^M = 1 - \frac{\sum_{i=1}^{n}[M_i - O_i]^2}{\sum_{i=1}^{n}[O_i - \bar{O}]^2},$$

- the Wilmott (1981) Index of Agreement:

$$IOA^W = 1 - \frac{\sum_{i=1}^{n}[M_i - O_i]^2}{\sum_{i=1}^{n}\left[[M_i - \bar{O}] + [O_i - \bar{O}]\right]^2}$$

In these formulae 'n' is the number of observations, $M$ and $O$ represent modelled and observed values, respectively, the subscript $i$ indicates the $i^{th}$ point in the record, and the overbar denotes the arithmetic mean. As each of these equations require that $Mi$ and $Oi$ are contemporaneous, the observed data are transformed by means of linear interpolation in time. As per Sun and Branson (2018), O2Me present $SS^M$ for waves and currents, and $IOA^W$ for wave heights. For comparison with other recent hydrodynamics modelling studies for Environmental Impact Assessment (EIA) purposes in WA, O2Me also present $IOA^W$ for currents.

Prior to quantification of model skill for wave height, observed data were adjusted to account for the noise floor present in acoustic wave measurements, where the noise floor was estimated as the lowest variance observed over a 12-month observation period.

### 4.3.3. Selected validation periods

Water level and current validation are present for three principal periods:

- One tidally dominated period (herein the TD period) where atmospheric effects are minimal [15-Aug-2021 to 19-Aug-2021], and;
- Two periods with moderate along-shore drift:
  - NW drift over 4-12 Mar 2021, and
  - SW drift over 01/08/2021-09/08/2021.

The three periods selected cover the dominant forcing mechanisms necessary to demonstrate model skill for environmental impact assessment. The validation is focused primarily on the TD period, as this period represents the dominant forcing at the site (see Section 4.4.1). In the interest of brevity, only drift current validations (progressive vector diagrams) are presented for the drift periods (see Section 4.4.2). O2Me note that the model was not designed for accurate resolution of tropical storms, but do present a qualitative validation only (see Appendix A).

Spectral wave validations are presented for the full simulation periods as the timescales of wave events of interest are longer than for currents, therefore long-period validations can be presented without loss of resolution (Section 4.5).

## 4.4. Validation results: surface elevation and currents

### 4.4.1. Tide dominated period

This section focuses on the results of the TD period, noting that the model agreement is similar during periods with moderate atmospheric forcing, as it will be shown when presenting drift currents in Section 4.4.2. Reproduction of water level was skilful (Murphy SS > 0.98, |bias| < 0.01 m/s) at all sites (OCP20, NCP05, ERA05 and UNS05, Figure 18). The E-W currents at OCP20 were slightly rotated in the model compared to the observations [8], which manifests as a slight apparent phase lag in the along-shore velocity (Figure 19). Rotations of this nature are reasonable given the uncertainty in the regional bathymetry and are within the potential limits for error of the compass calibration on the observed data.

O2Me rotated currents onto the principal and minor components of the tidal flow to remove the influence of the slight apparent phase lag described above. The principal component is referred to as *Along-shore* direction, and the minor component as the *Cross-shore* direction, noting that the definition is statistical and not based on the local shoreline morphology. The along-shore currents at OCP20 were reproduced skilfully though there was a slight systematic underestimate of the along-shore tidal variance (RMSE approx. 0.04 $ms^{-1}$; Figure 19), which is commensurate with the uncertainty in the local depth. Non-linearities (asymmetries) in the cross-shore currents were resolved qualitatively, though the modelled tidal ellipse was narrower, resulting in an under-representation of cross-shore currents in the narrowing of the ellipse. The cross-shore currents at this site are related to the exchange of water between Barrow Island and the mainland, meaning large areas of high-quality bathymetry are required. The Lebrec et al. (2021) satellite derived dataset covers these areas in high spatial resolution for the first time to the public, though uncertainties in shallow areas are known.

The model skilfully resolves tidal currents at NCP05 (nearest to the ESSP) including the general asymmetry in the tidal currents (Figure 20 & Figure 21), though there are weak high-frequency non-linear effects in the observed data at high tide and towards the end of the ebb that are not resolved (Figure 20 & Figure 21). Such effects are driven by the complex bathymetry of tidal channels and require precise and comprehensive channel bathymetry to resolve ([9]). High-resolution surveys of the channel do not cover its full extent, and so local artefacts are expected. This effect is anticipated to be highly local, and with limited implications for broader environmental studies in the Cape Preston area.

[8] Layers affected by side lobe interference near the water surface were removed from the measurements prior to comparison with model results from the same portion of the water column. All comparisons consist of vector-averaged velocities.

[9] The thalweg between Cape Preston and Southwest Regnard Island is referred to as the 'channel' in the bathymetry.

The model also skilfully resolves tidal currents at UNS05 (Figure 22) but slightly underestimated maximum current speeds at ERA05 (Figure 23). The most likely candidate for this discrepancy is the greater uncertainty in bathymetry towards the E of Regnard Bay (Section 3.1).

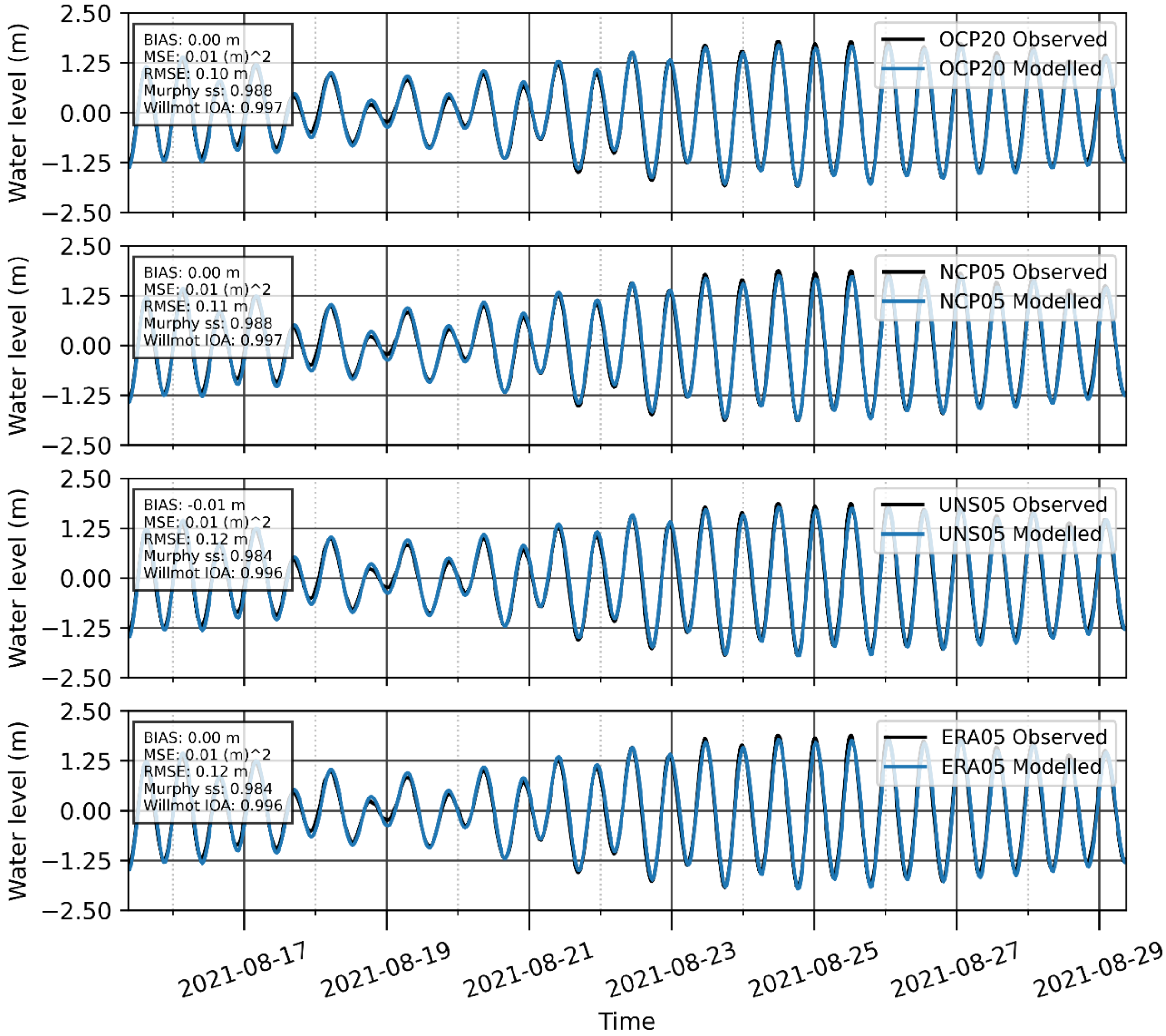


Figure 18: Observed vs modelled water levels at key sites during a tide dominated period – 15-Aug-2021 to 29-Aug-2021.

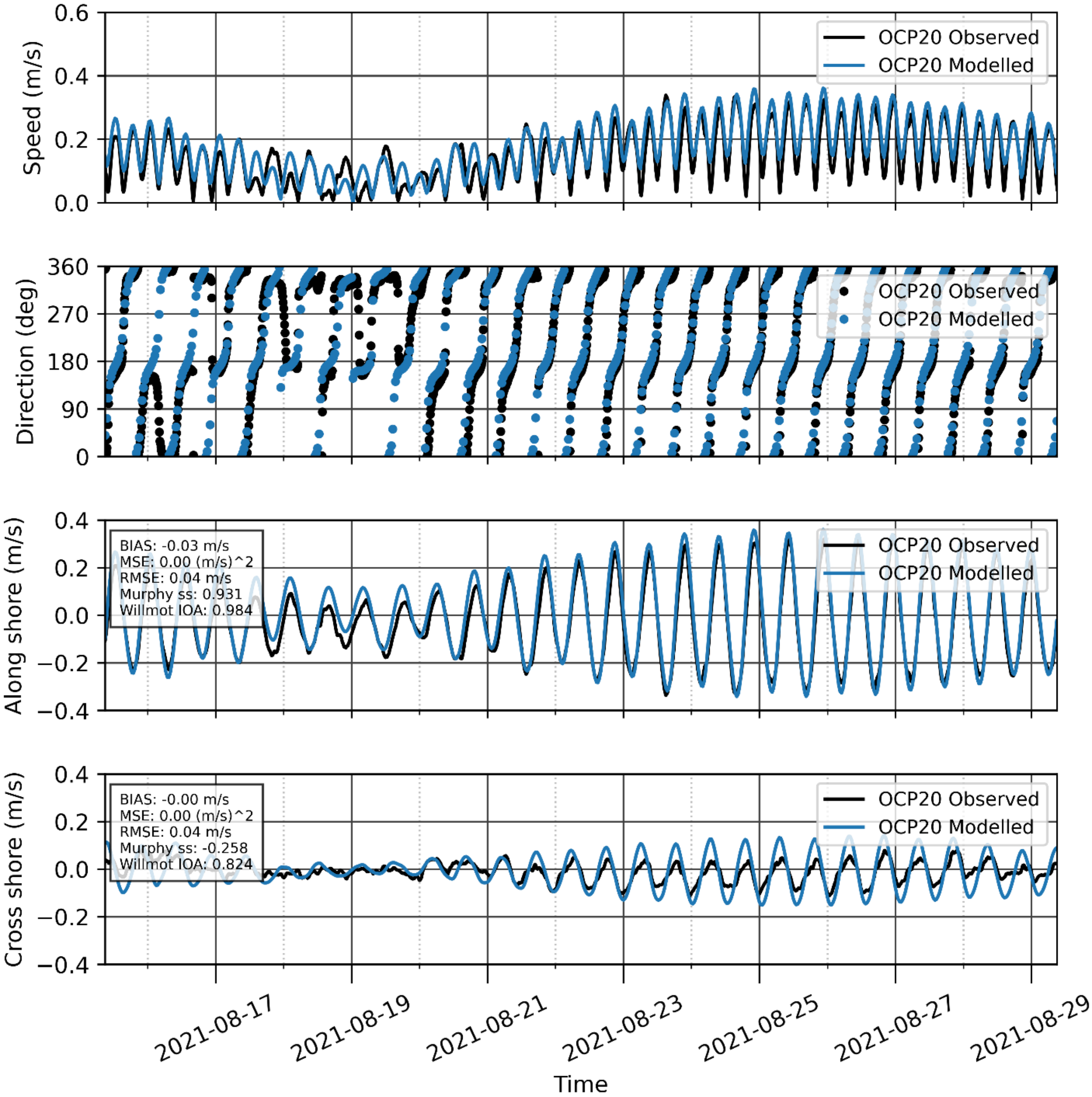


Figure 19: Observed vs modelled currents at OCP20 during a tide dominated period – 15-Aug-2021 to 29-Aug-2021.

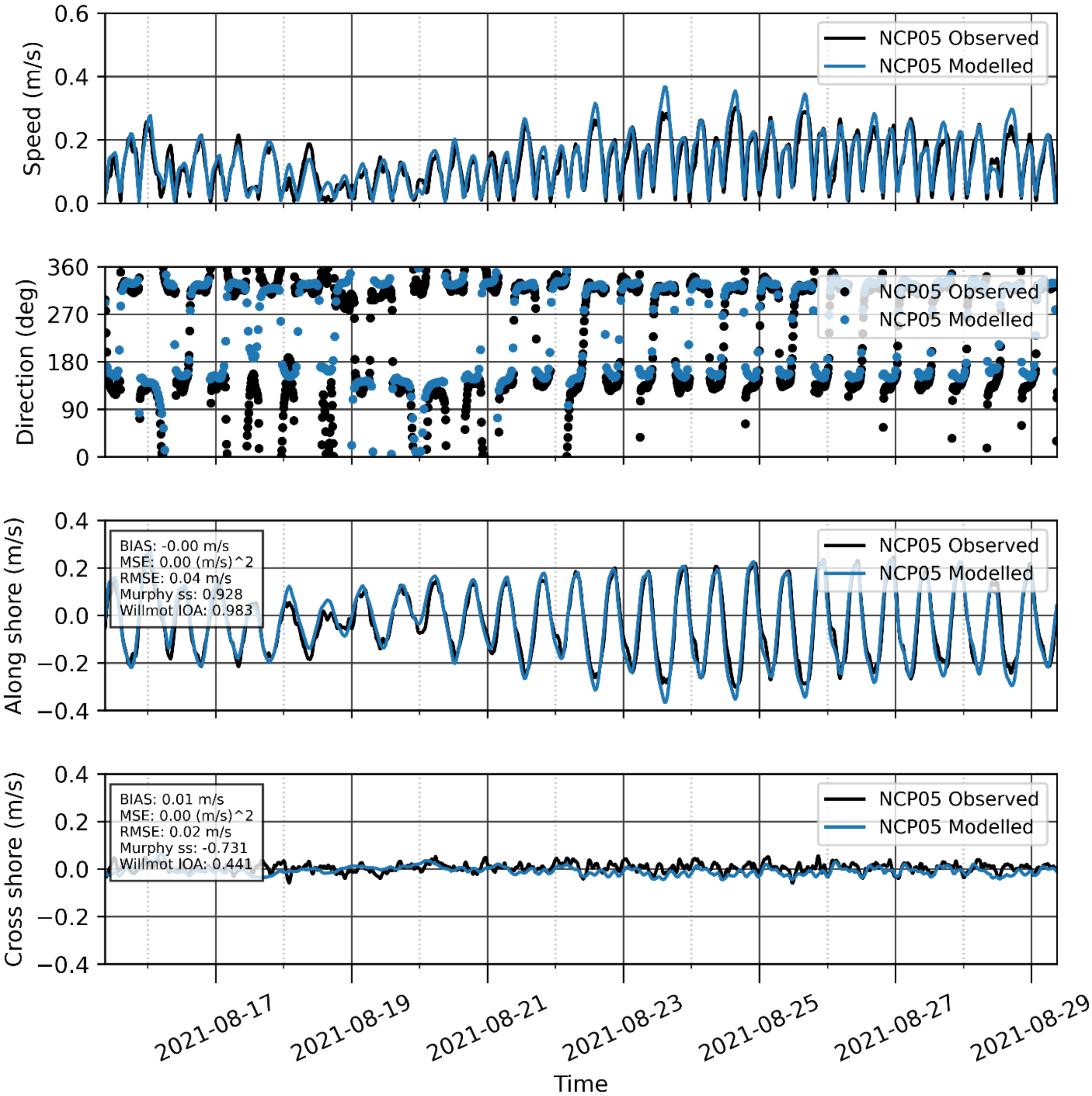


Figure 20: Observed vs modelled currents at NCP05 during a tide dominated period – 15-Aug-2021 to 29-Aug-2021.

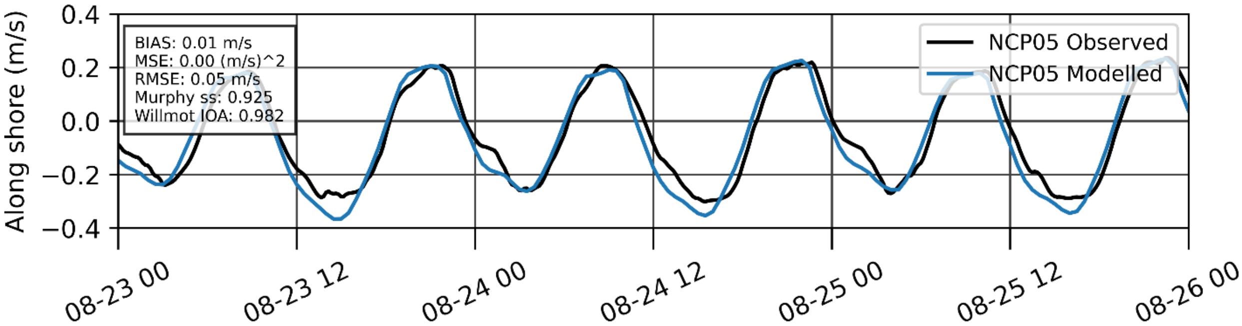


Figure 21: As in Figure 21c but for 23-Aug-2021 to 26-Aug-2021 only.

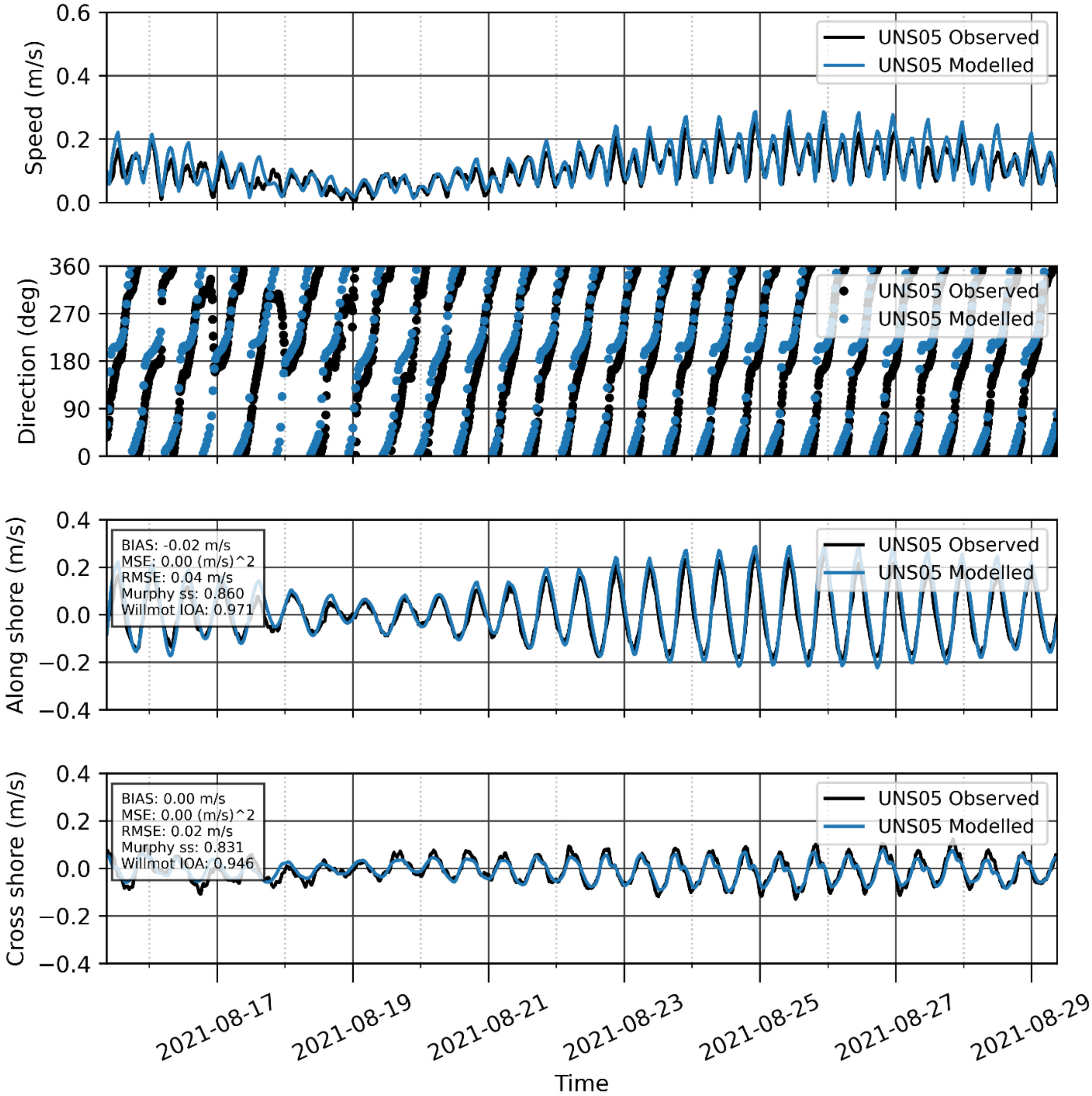


Figure 22: Observed vs modelled currents at UNS05 during a tide dominated period – 15-Aug-2021 to 29-Aug-2021.

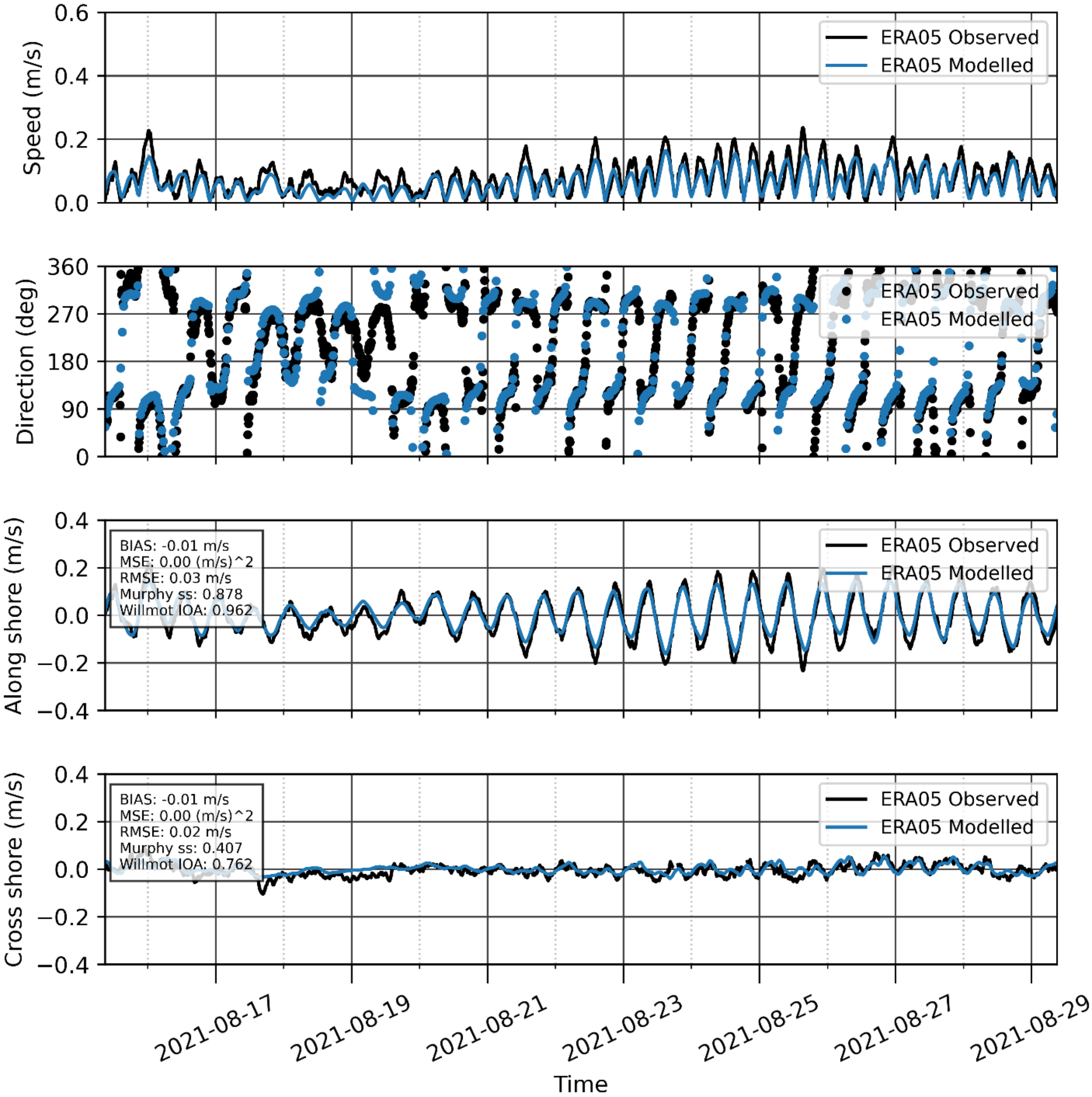


Figure 23: Observed vs modelled currents at ERA05 during a tide dominated period – 15-Aug-2021 to 29-Aug-2021.

### 4.4.2. Low frequency drift current validation

As demonstrated in Sun and Branson (2018), representation of the low-frequency drift currents in this region is much more challenging than tidal currents. Resolution of these currents rely on accurate wind-fields and steric gradients, which are harder to obtain than tidal forcing. Following Sun and Branson (2018), a sample progressive vector diagram (PVD) for near-surface currents at the offshore site for two 9-day periods are presented in Figure 24 and Figure 25. The first period (04-03-2021 to 12-03-2021) was characterised by persistent westerly winds, and the PVD showed considerable agreement throughout (Figure 24). The second period (1-08-2021 to 9-08-2021) was characterised by persistent easterlies, though winds were more variable in the beginning of the period (Figure 25). The PVD diverges in the early days where the winds were variable, but agreement improves when winds stabilise to a moderate strength easterly (Figure 25).

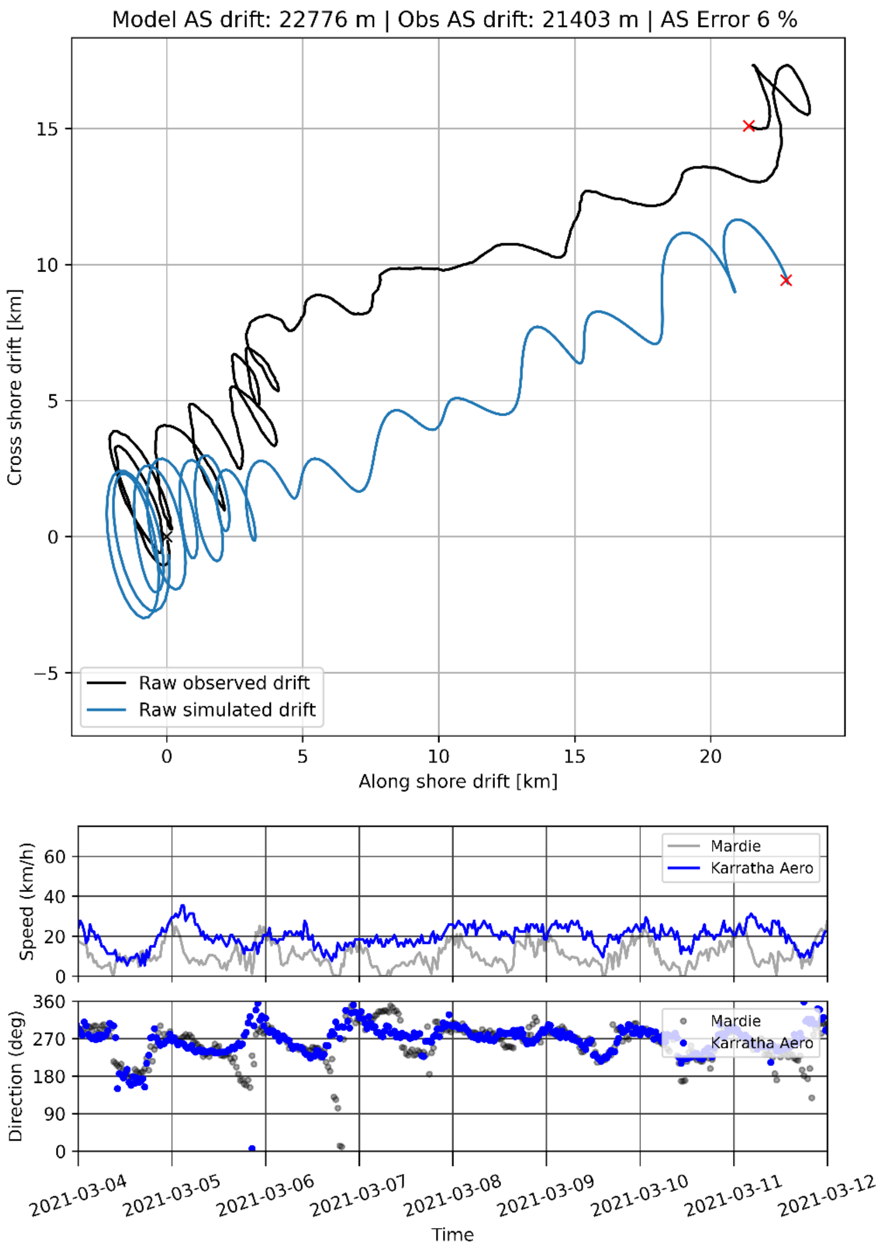


Figure 24: Top panel: Progressive vector diagram for OCP20 during a period with sustained westerlies (04/03/2021-12/03/2021); Bottom panel: winds from BOM's Karratha Airport and Mardie stations during the period of the PVD.

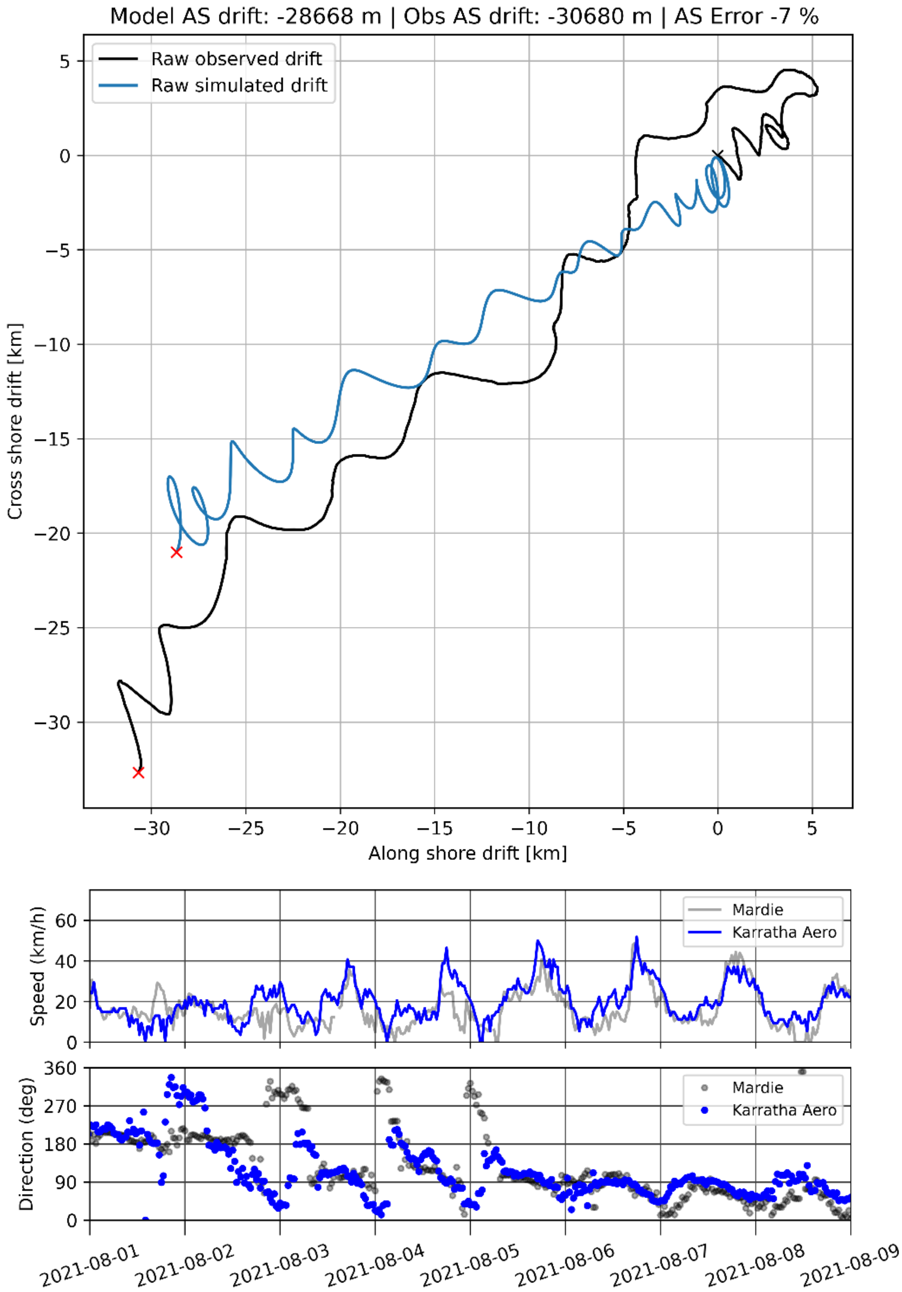


Figure 25: Top panel: Progressive vector diagram for OCP20 during a period with moderate easterlies (01/08/2021-09/08/2021); Bottom panel: winds from BOM's Karratha Airport and Mardie stations during the period of the PVD.

Direct comparison of periods of ADCP-measured and modelled wind effects is challenging during weak and variable winds, as wind-driven effects are often strongest in the upper 10% of the water column which the field instrument does not detect. Comparison is also challenging during storm winds, as wind-fields are often not well resolved in the global models adopted to force the model, and observed winds lack the spatial coverage to drive regional scale models.

## 4.5. Validation results: spectral waves

Emphasis was placed on the validation of spectral waves for the entire validation simulations, as the validation was targeting the overall magnitude of the events rather than individual (isolated) diurnal peaks.

### 4.5.1. Wet season

Significant wave-heights at the calibration site OCP20 were reproduced skilfully (Figure 26). Wave period and direction were also resolved well at this site, though an artifact in peak period is observed where peak periods are near the 8 second sea-swell cut-off used to specify boundary conditions in the model. This is common in the presence of old-seas arising from tropical storms passing to the NW of the site – e.g. Tropical Low 12U and the Tropical Cyclone Marian period. The same artifact was not encountered under Tropical Low 08U that made land fall 400 km to the E.

Sea and swell propagation into the NCP05 (Figure 27), UNS05 (Figure 28), and ERA05 (Figure 29) sites were also reproduced skilfully, with little-to-no bias. A notable exception is the wave-heights at NCP05 during TL-08U (late January). Offshore conditions were dominated by westerly wind-waves that were slightly underpredicted by the model as they refract around Cape Preston.

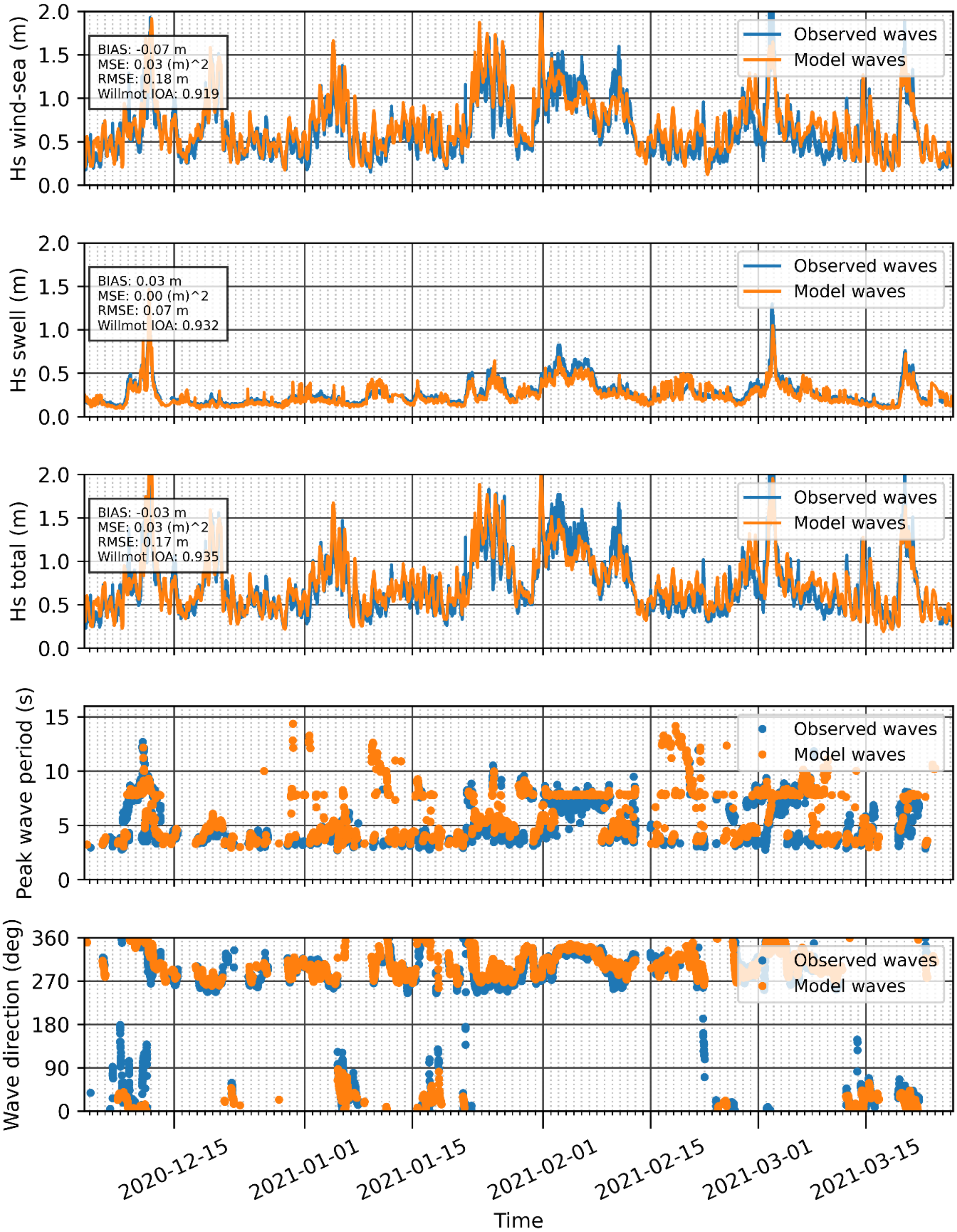


Figure 26: Wave simulation validation at site OCP20 for the entire wet season simulation.

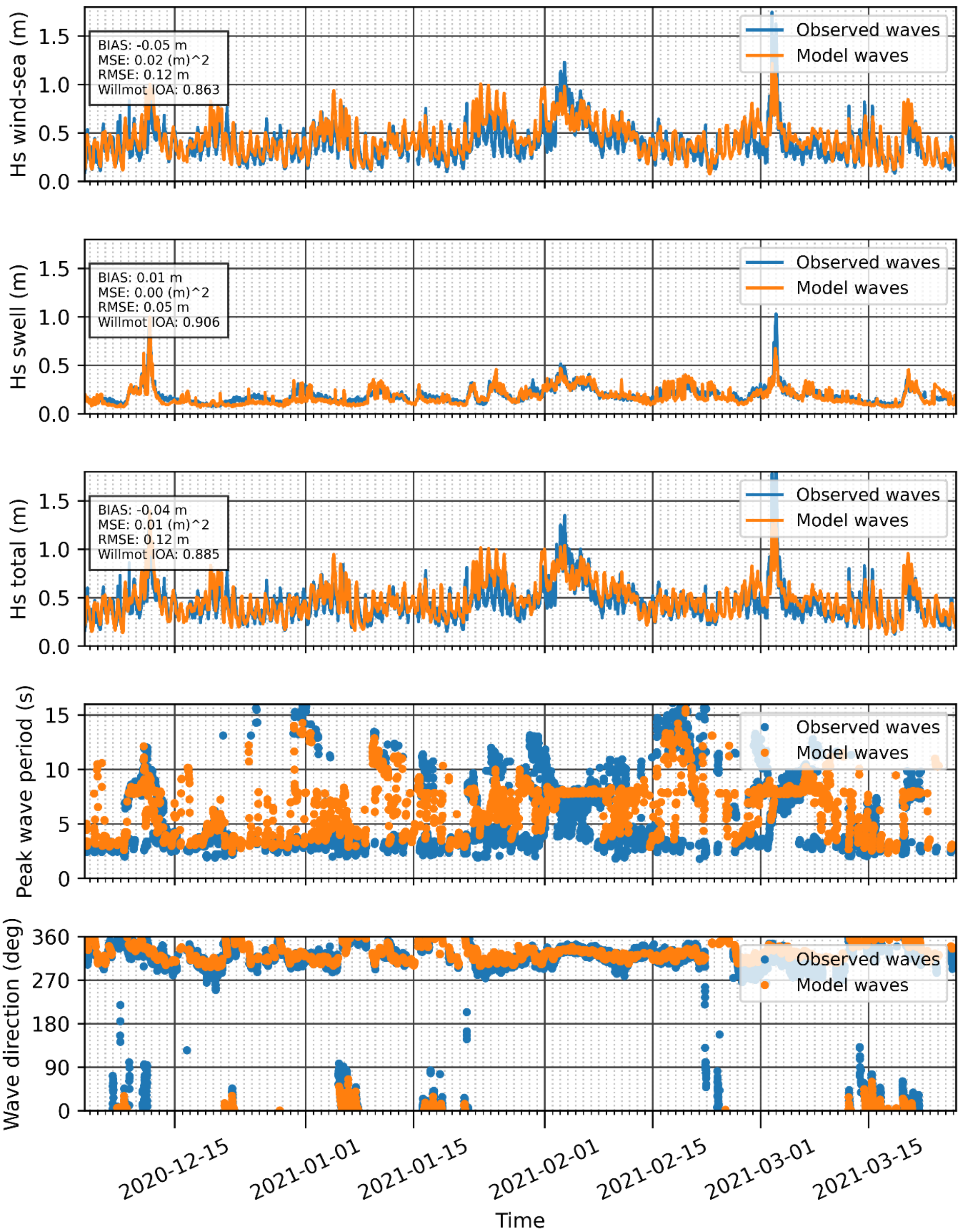


Figure 27: Wave simulation validation at site NCP05 for the entire wet season simulation.

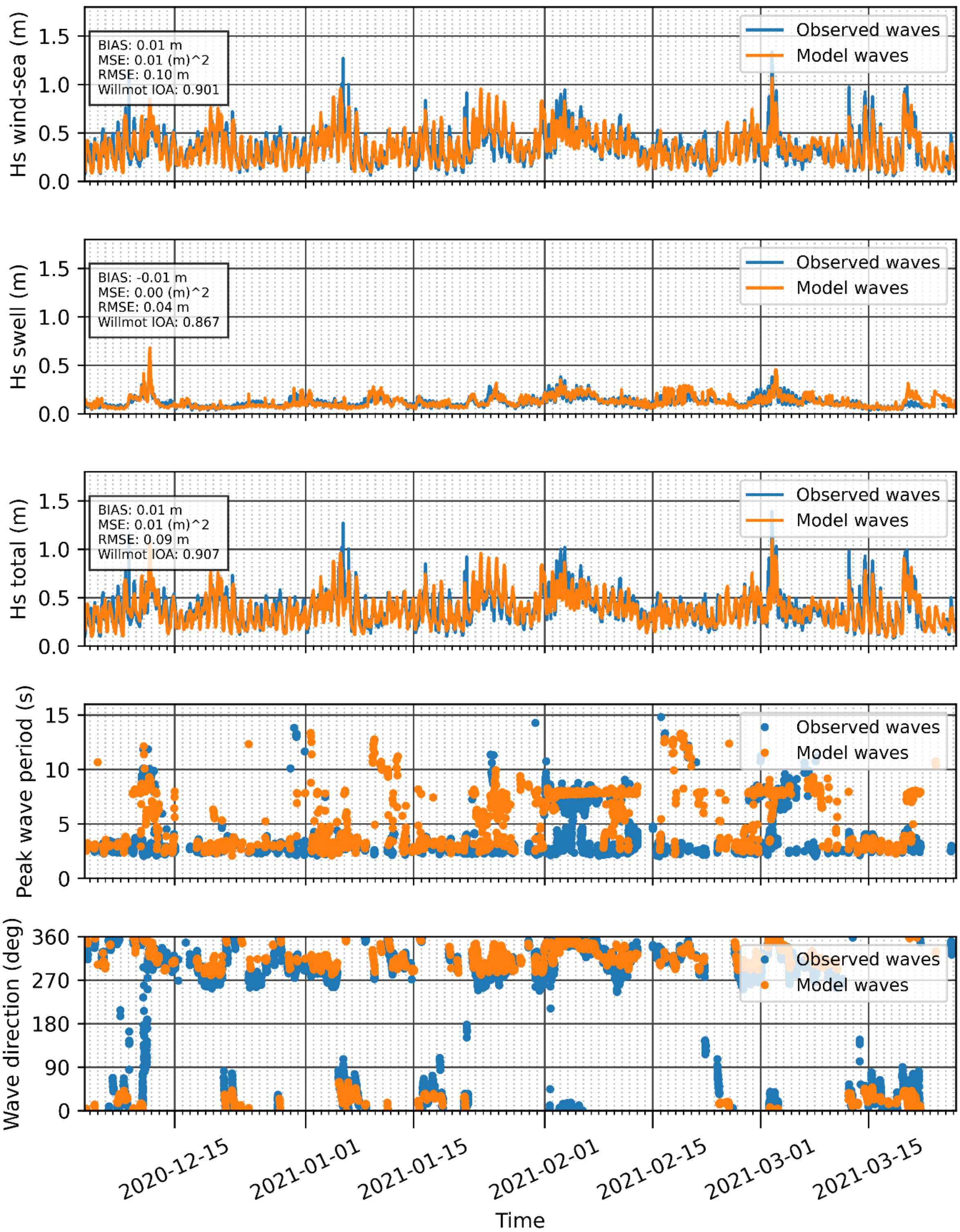


Figure 28: Wave simulation validation at site UNS05 for the entire wet season simulation.

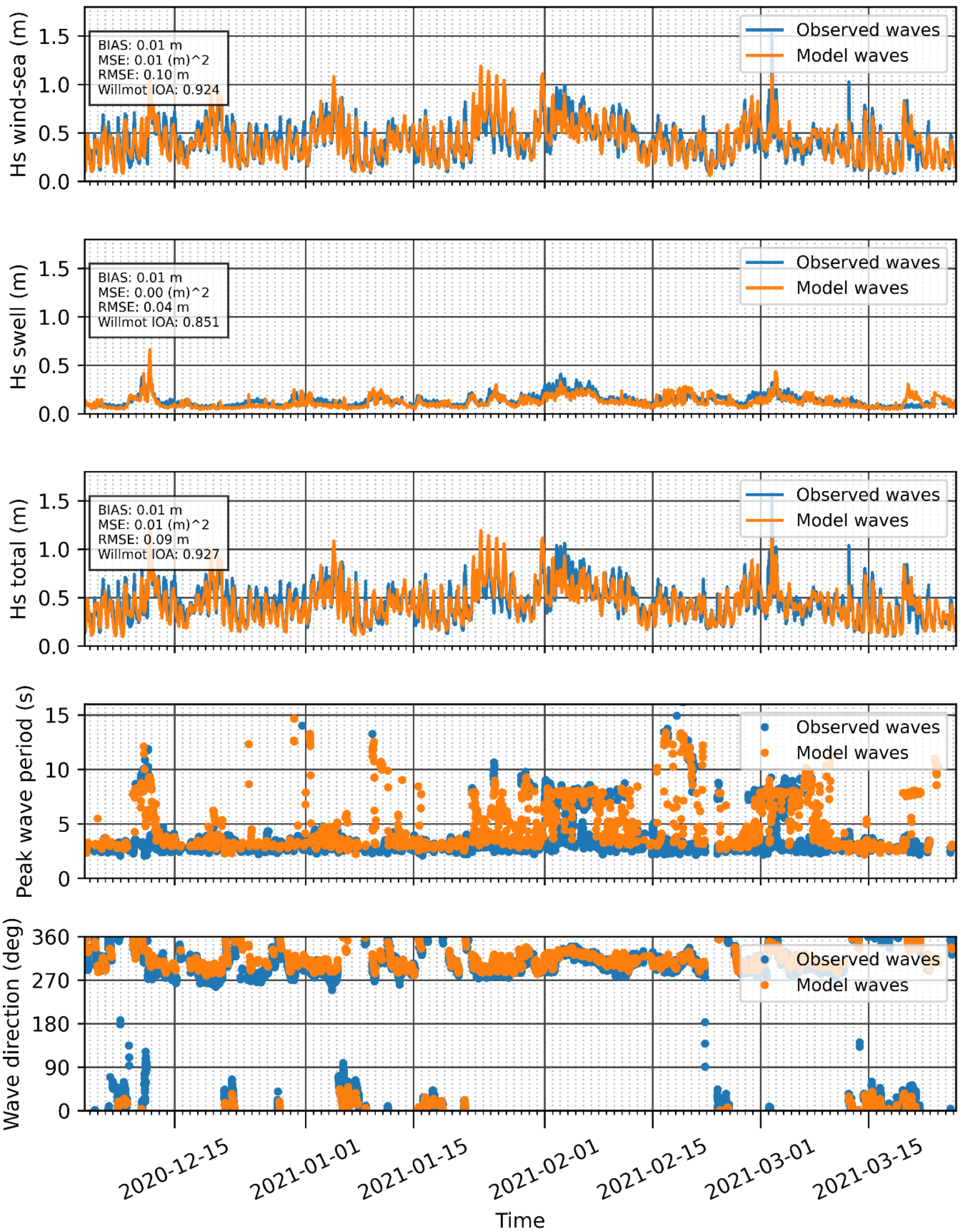


Figure 29: Wave simulation validation at site ERA05 for the entire wet season simulation.

### 4.5.2. Dry season

Again, significant wave-heights at the calibration site OCP-20 were reproduced skilfully (Figure 30). Validation of wave period during the dry season is confounded by the frequent occurrence of low wave energy periods. However, the amplitude of sea and swell waves propagating into the UNS05 (Figure 31), and ERA05 (Figure 32) sites were again reproduced skilfully, with little to no bias. There was, however, a 10–35° deviation in wave direction at the UNS05 and ERA05 sites that was not seen in the wet season validation. The impact of this deviation on environmental studies near Cape Preston itself are anticipated to be minor, though further investigation and refinement may be required for engineering studies in the vicinity of the pond walls, though this is beyond the present objective.

Note that the NCP05 AWAC sustained heavy data losses during this period (>80%), and so the validation for this site is not presented here. This is not a major limitation to the assessment given the satisfactory validation at other sites.

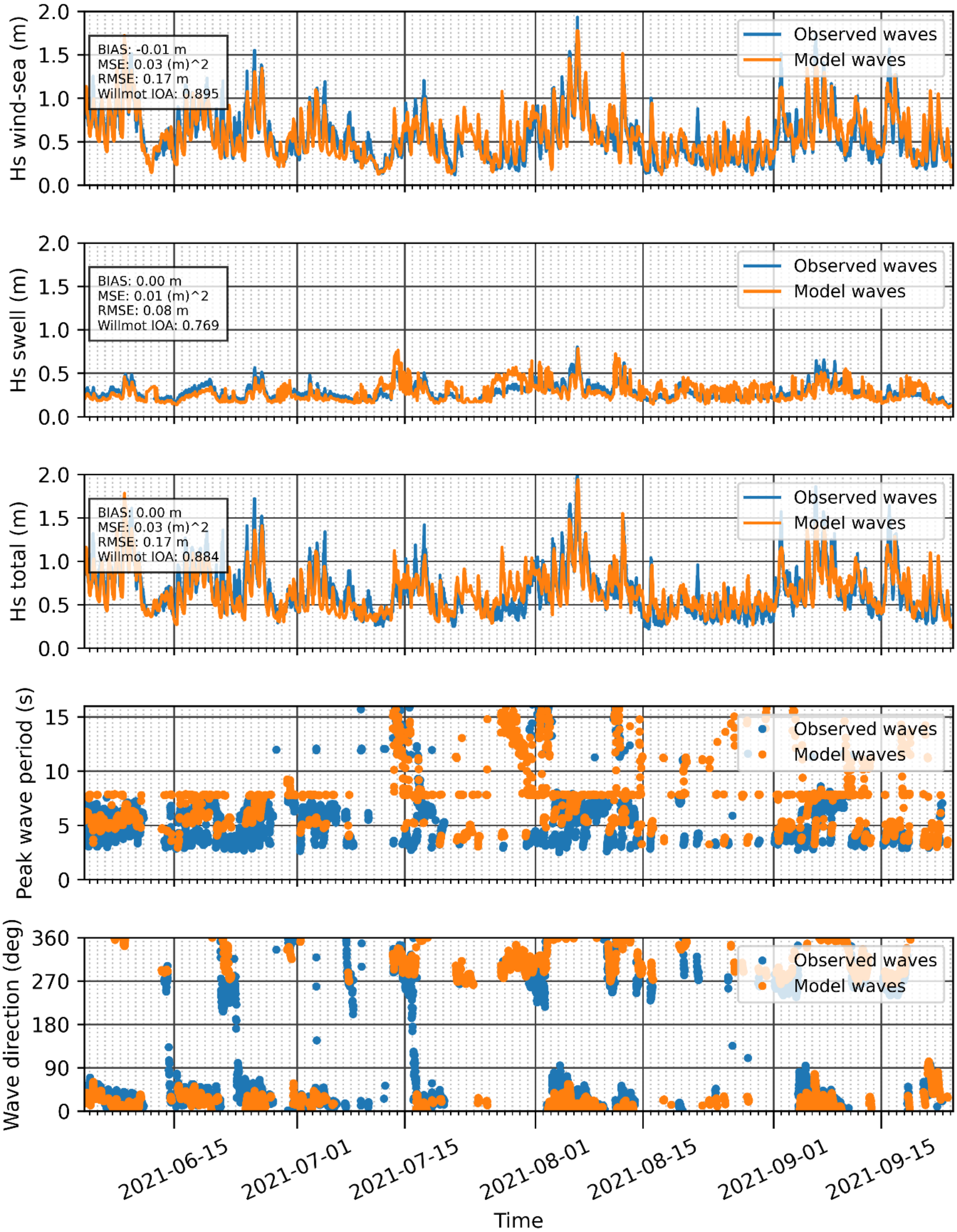


Figure 30: Wave simulation validation at site OCP20 for the entire dry season simulation.

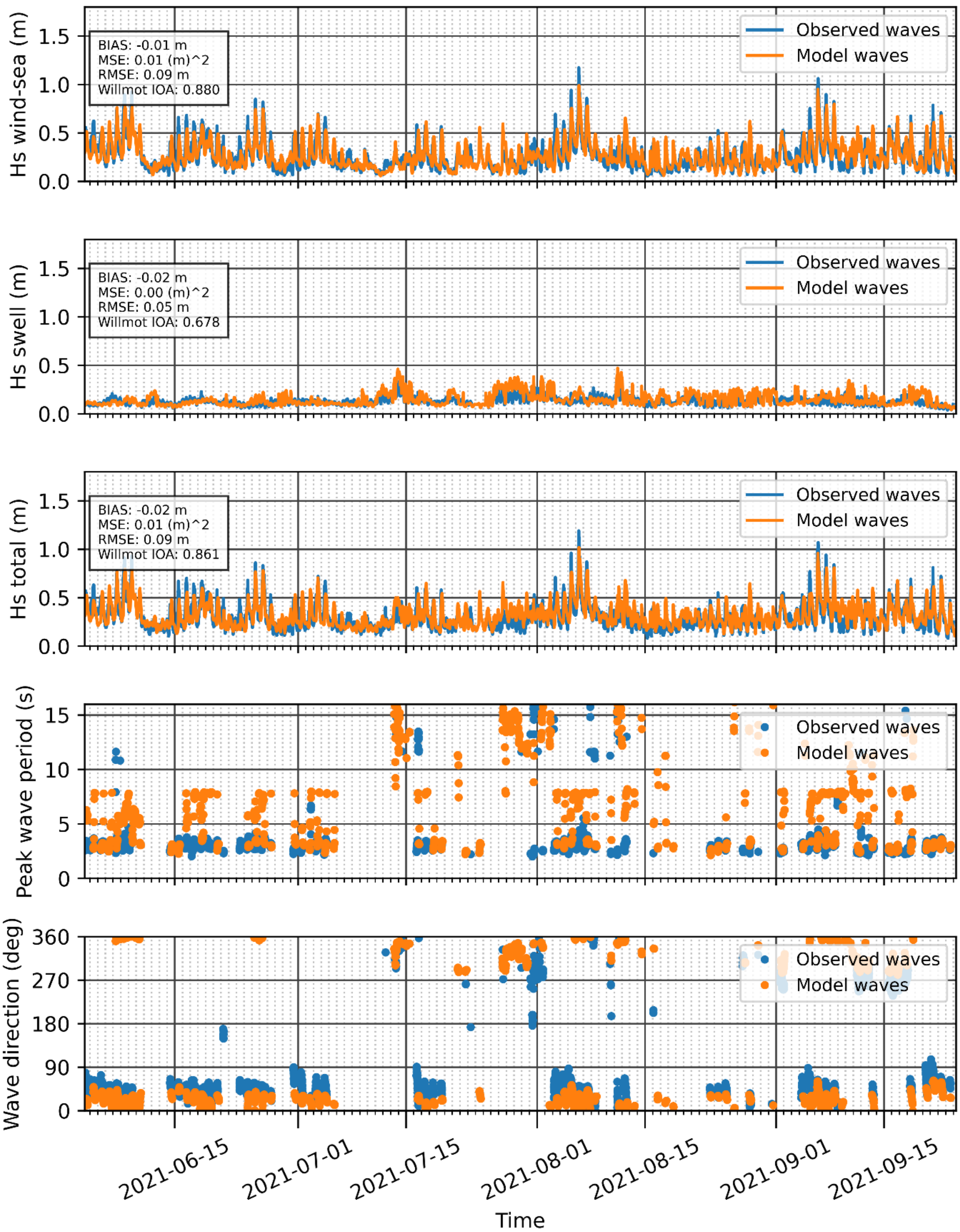


Figure 31: Wave simulation validation at site UNS05 for the entire dry season simulation.

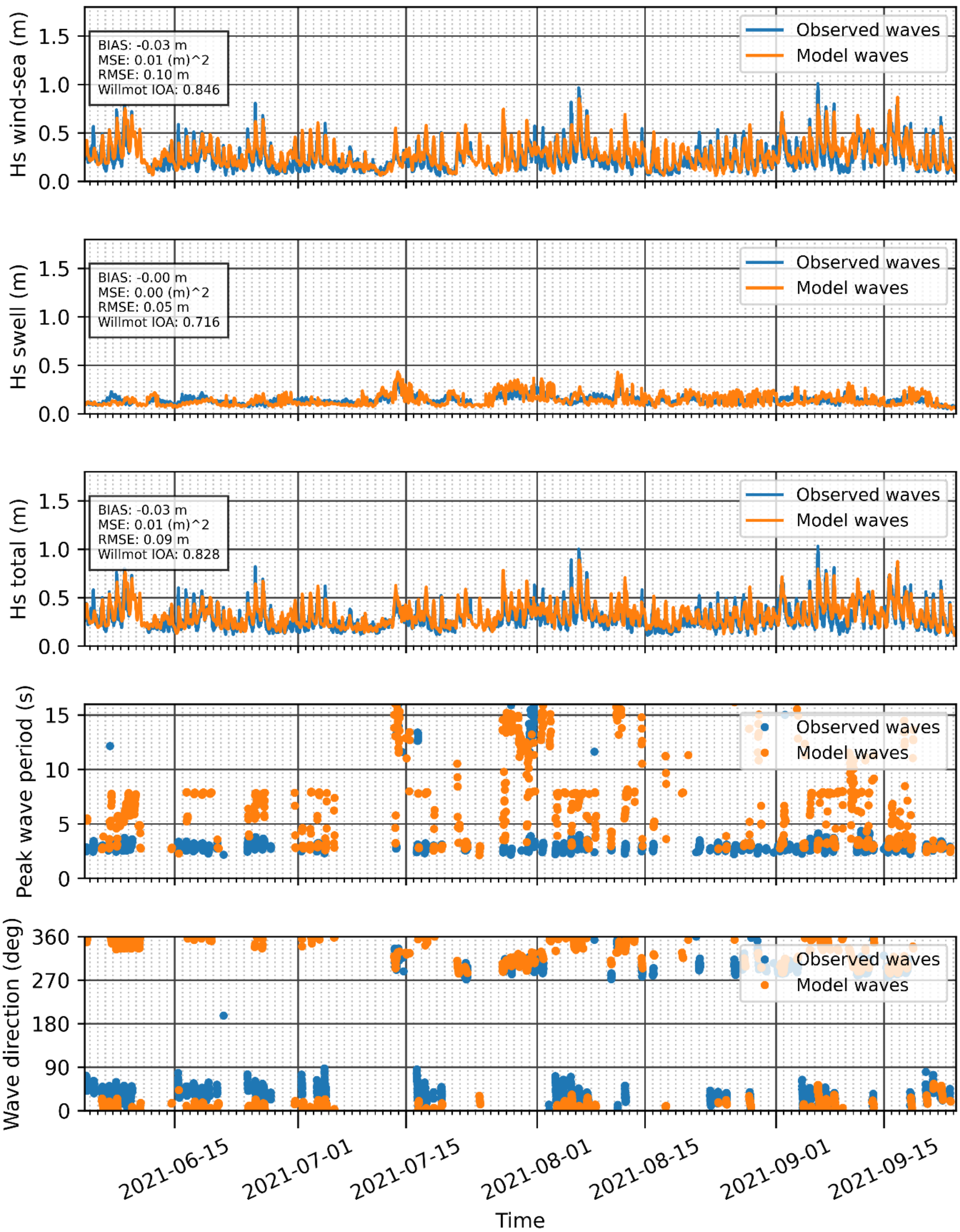


Figure 32: Wave simulation validation at site ERA05 for the entire dry season simulation.

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# 5. Summary and Conclusion

This document presents a base hydrodynamics and spectral wave model of Regnard Bay, designed to support the environmental impact assessment of the ESSP. The model consists of 2 domains: The larger domain extending from North West Cape to ~85km E of Karratha, forced principally with global model output, and a smaller domain of Regnard Bay nested within this larger model, though wind and wave forcing were derived from observations.

Validation was performed (1) offshore of Cape Preston, (2) at two sites within Regnard Bay, and (3) within the tidal channel connecting the project area to the open ocean (nominally near the thalweg between Cape Preston and Southwest Regnard Island, at site NCP05). The following was observed in the model validation:

- The model skilfully resolves the dominant tidal water levels;
- The model skilfully resolves the dominant tidal currents;
- The model resolves the shallow water tidal constituents that lead to asymmetries in the along-shore coastal tidal currents W and E of Barrow Island;
- The model qualitatively resolves the major asymmetries in tidal currents in the vicinity of the ESSP (the NCP05 observation site), though there are some complex topographically-driven processes that are not resolved; and
- The model qualitatively captures the water level setup and the associated currents under strong tropical storms (TL-08U), though tends to under-resolve the magnitude of storm-driven currents (see Appendix A).

Overall, the model is evaluated as being fit for the purpose of deriving boundary conditions for environmental studies in the Cape Preston region. This judgement is based on the physical processes resolved, the model skill and the domain size. Improvements to boundary conditions, improved atmospheric forcing, and/or a larger domain may be required if more accurate resolution of storm events is sought -e.g. for engineering studies.

# 6. Third-Party Review

Third-party reviews offer invaluable insight from an unbiased perspective. In July 2022, O2Me commissioned Dr Ray Steedman to conduct an independent review of this base hydrodynamic report and nested modelling approach.

## 6.1. About the Reviewer

Dr Steedman is a metocean and environmental business consultant with over 40 years' experience providing advanced science, geophysical fluid dynamics, environmental and technology services and products to resource and defence industries, engineering and environmental service companies and government agencies. Dr Steedman's previous employment appointments include principal environmental consultant with leading national and international engineering and environmental service companies. He has also held executive and non-executive directorships for both private and listed national and international services companies. Dr Steedman acted as non-executive and executive chairman of Australian and WA statutory agencies and sat on numerous government scientific policy and advisory committees.

## 6.2. Findings by the Reviewer

Dr Steedman arrived at the following conclusions after reviewing earlier versions of O2Me's Base Hydrodynamic Model ([10]) and Dredge Plume Modelling ([11]) reports for LS's ESSP:

- the method of the O2M Hydrodynamic Model provides a reasonably reliable estimate of the Regnard Bay coastal circulation and turbulent diffusion (friction) processes;
- the O2M Hydrodynamic Model is suitable to force open boundary conditions of local scale nested numerical physical and dispersion models, within Regnard Bay to the E of Cape Preston;
- the nested specialised dredge plume turbidity and bitterns dispersion, and tidal inundation dissipation models, will be adequate to support the marine environmental impact assessment of Leichhardt Salt's Proposal; and
- the proposed system of numerical hydrodynamic and dispersive models will facilitate the environmental approval of Leichhardt Salt's Proposal.

Dr Steedman's independent review is provided in Appendix B. His recommendations were considered in the preparation of version of the report.

[10] O2METOCEAN Base Hydrodynamic Model Eramurra Solar Salt Project - REPORT NUMBER: 20MET-0016-07 / R210323; dated 6 July 2022.

[11] O2METOCEAN Eramurra Dredge Plume Modelling - REPORT NUMBER: 20MET-0016-09 / R210324, dated 24 June 2022.

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# Appendix A. Example storm validation - TL08U

Validation of the hydrodynamic module during Tropical Low 08 U (TL08 U; Section ), for which the model under-resolved the ocean's response.

## Appendix A.1. TL08 U

TL08U formed in the Timor Sea and made landfall approximately 400 km E of Regnard Bay at on 22-January 2021. While it did not reach as far W as Cape Preston (Figure 33), it drove rapid changes in wind direction as it approached, and had a sustained effect of strong westerly winds for days after crossing the coast (Figure 34, Figure 35). Strong southwesterlies were sustained until the 24th of January, well after the low had passed.

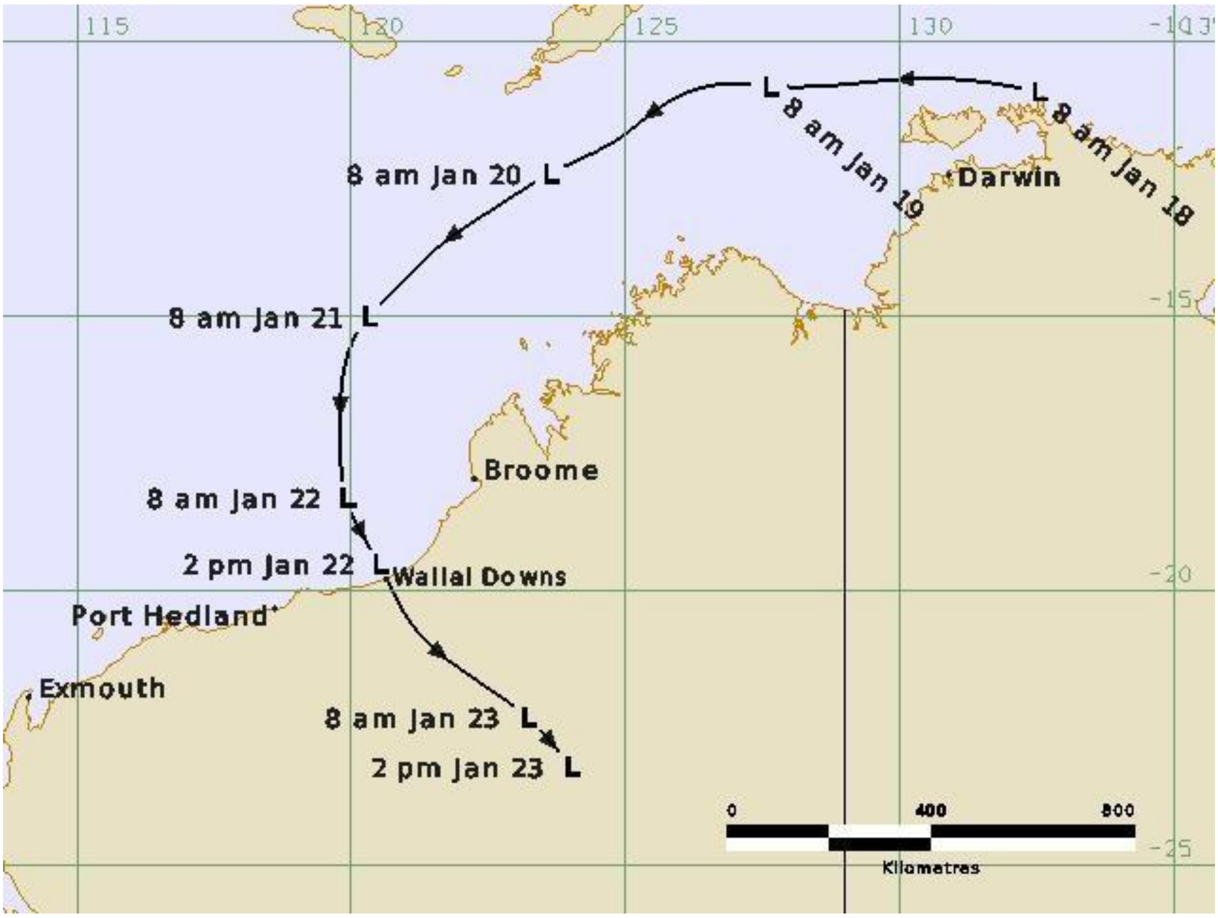


Figure 33: Tropical Low 08U track (Source: BOM). Note times here are AEDT, while elsewhere the report uses AWST.

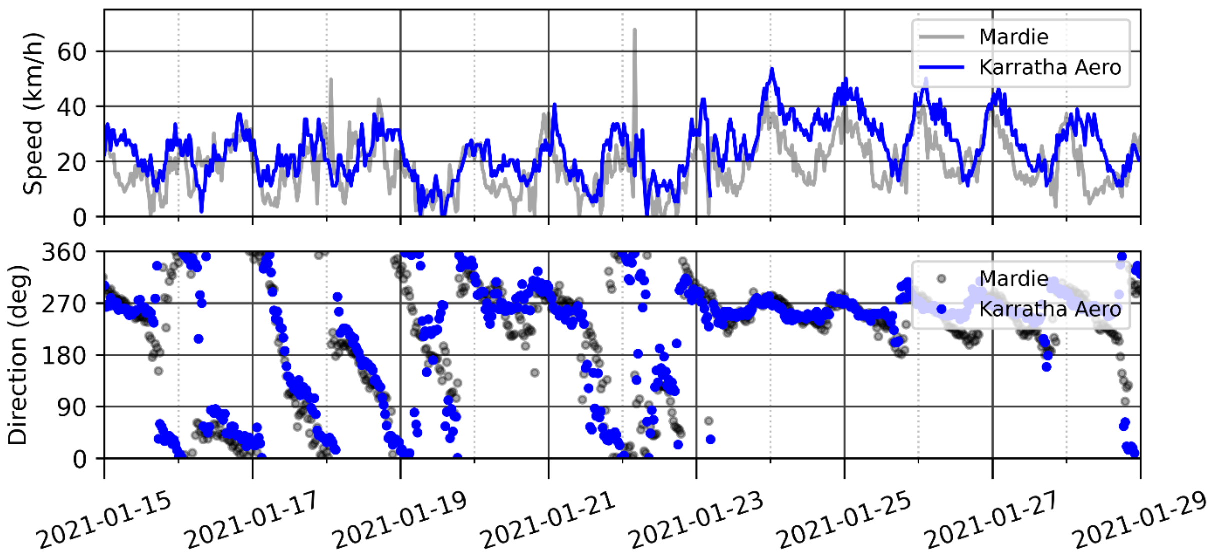


Figure 34: Wind recorded at BOM's Karratha Airport and Mardie stations over 15/01/2021-29/01/2021 where TL08U was active.

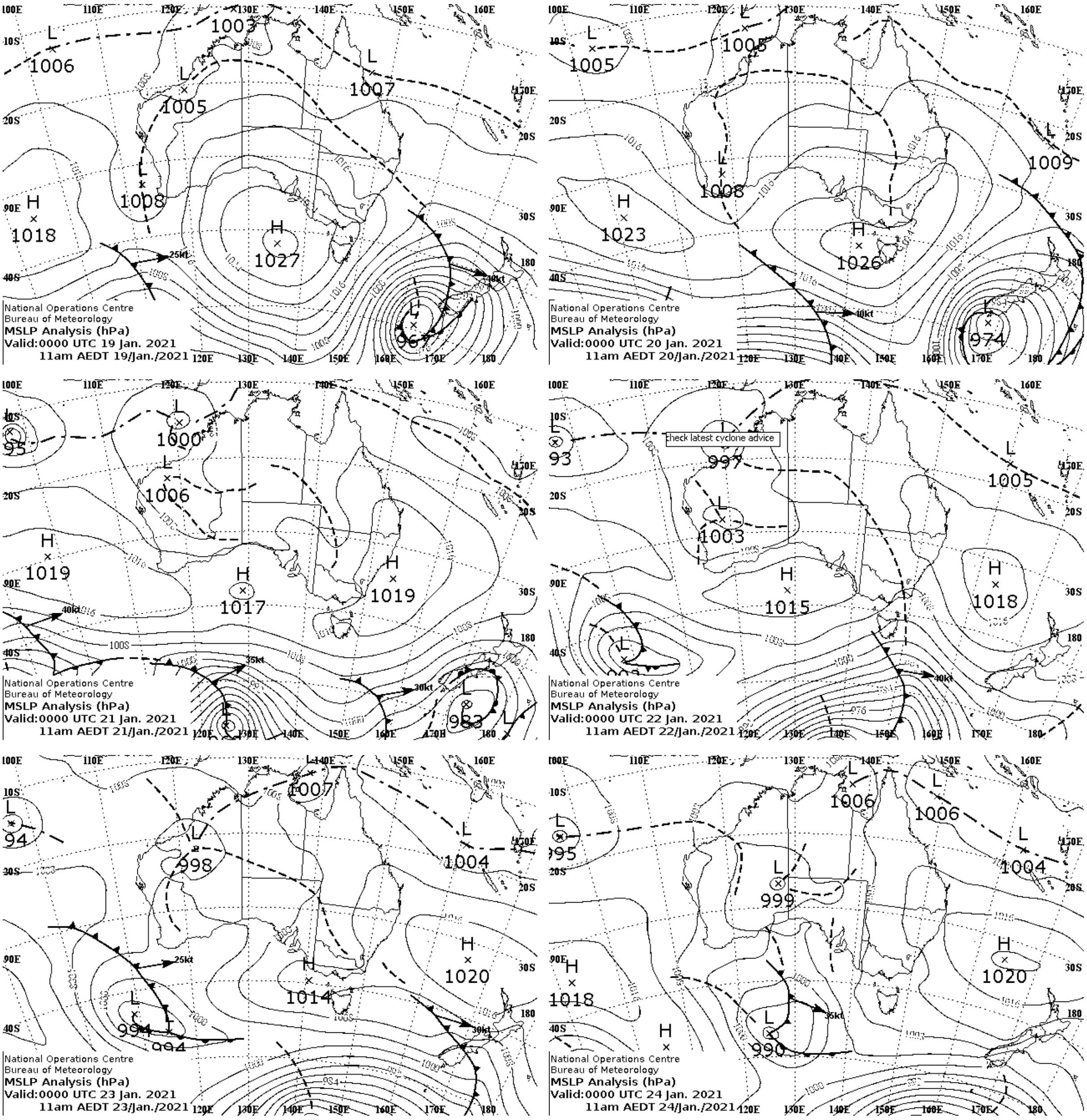


Figure 35: Period 2 mean sea level pressure charts where TL08U was active (Source: BOM). Note times here are AEDT, while elsewhere the report uses local AWST.

## Appendix A.2. Sample current validation

For brevity, validations at OCP20 only are shown. The system drove a small water level setup prior to reaching landfall, and a small set-down after landfall (Figure 36). The model resolved these only qualitatively, under-resolving their magnitude. Similarly, the westward drift currents prior to landfall, and eastward drift after landfall were resolved only qualitatively, with the model underestimating the strength in both cases (Figure 37).

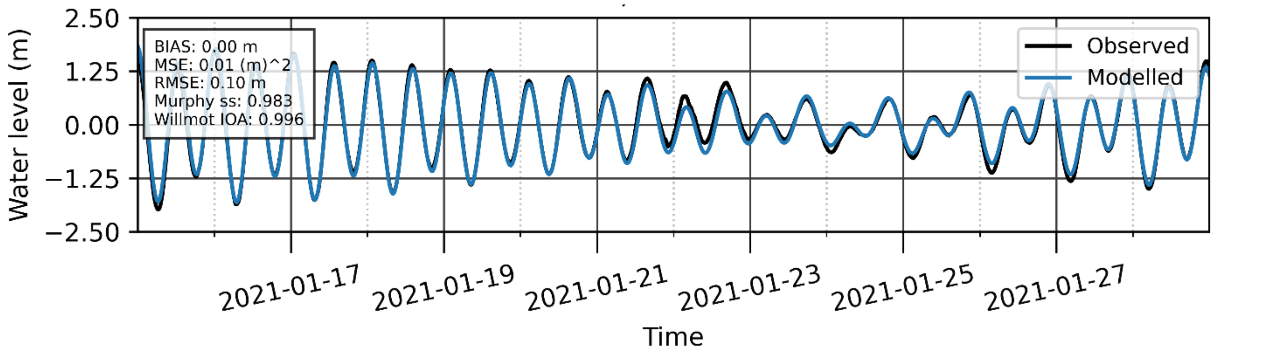


Figure 36: Observed vs modelled water levels at key sites during Period 1- 27 February to 15 March 2021 and Period 2- 15 January to 29 January 2021.

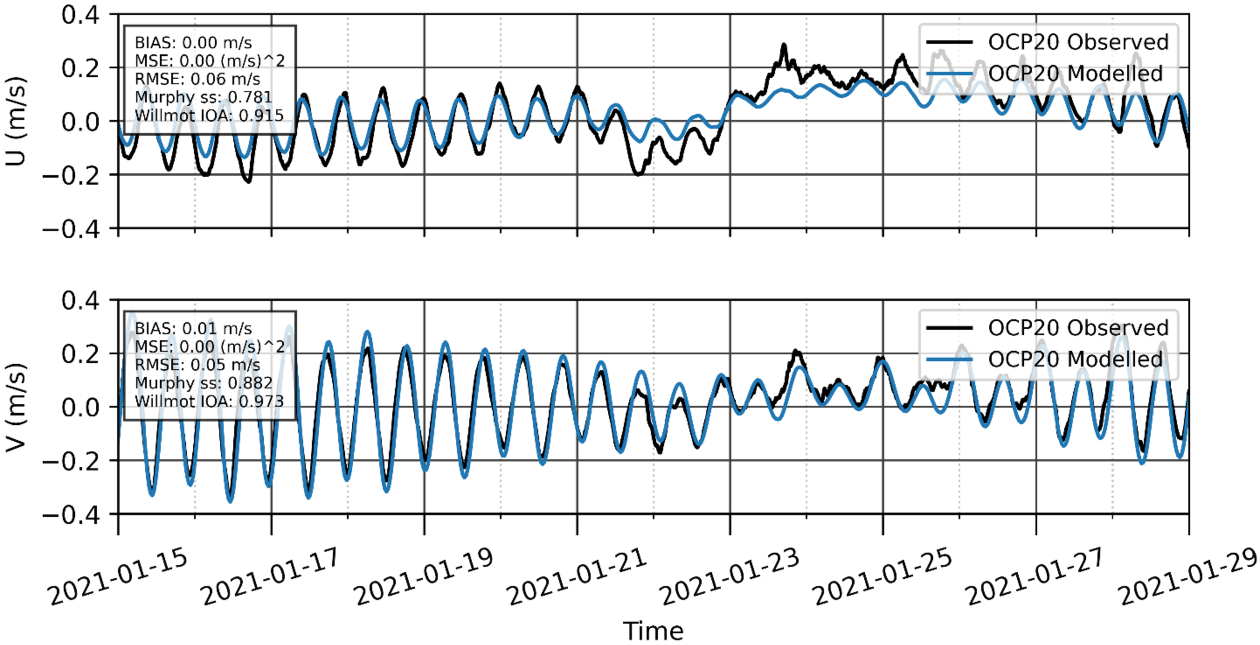


Figure 37: Observed vs modelled currents at OCP20 during Period 2, where TL 08U was active (15/01/2021-29/01/2021).

## Appendix A.3. Conclusion

This model was designed to resolve the dominant tidal and seasonal along-shore wind drift on the inner Pilbara Shelf, for the purposes of informing a range of coastal environmental studies. The model has been demonstrated (not in this appendix) to resolve these processes adequately. The model was not designed to resolve tropical storms, and this appendix demonstrates that the model does so only qualitatively – both water level setup and along-shore currents were under resolved. To improve this resolution the model would likely require:

- Local reanalysis wind fields at high spatial resolution;
- Improvements to bathymetry, particularly S of Barrow Island;
- Alternate nesting schemes; and
- Finer vertical resolution.

As the present scope is concerned with prevailing flow patterns to inform environmental studies only, the present approach is considered appropriate.

## Appendix B. A review O2METOCEAN Base Hydrodynamic Model of Cape Preston East, Leichhardt Salt Pty Ltd, (proposed) Eramurra Solar Salt Project.

*- discussed -*
Memorandum 093

Email transmission
Email: sebastian.morillo@o2metocean.com.au

14 July 2022

To: Sebastián Morillo
Technical Director (Metocean) / Principal Metocean Engineer
O2METOCEAN
From: Ray Steedman
Subject: A review O2METOCEAN Base Hydrodynamic Model of Cape Preston East
Leichhardt Salt Pty Ltd, (proposed) Eramurra Solar Salt Project.

## Review

The following is my review O2METOCEAN Base Hydrodynamic Model of Cape Preston East, developed by O2M for environmental and engineering purposes, on behalf of Leichhardt Salt Pty Ltd, proposed Eramurra Solar Salt Project.

O2METOCEAN (O2M) have applied a numerical Hydrodynamic Model to the Regnard Bay to Cape Preston East coastal area, Pilbara, North Western Australia.

It is planned to use a numerical O2M Hydrodynamic Model for environmental assessment purposes in regard to the proposed Eramurra Solar Salt Project (the Proposal)[1].

Numerical modelling of dredge plumes, bitterns discharge and tidal inundation has progressed to a point where spatial distribution estimates of water column parameters such as water flow and sea levels provide new insight into the coastal biophysical receiving environment.

O2M Hydrodynamic Model simulates water level and circulation current parameter maps, graphs and other results, which enhance the understanding of both normal and extreme processes that underly environmental impact assessment and engineering decision making.

Central to applied hydrodynamic modelling of Cape Preston region are the following:

- necessary and sufficient measurements to calibrate and validate the model
- a reliable mesoscale and local hydrodynamic and spectral wave models of Northwest Cape to Legendre Island
- a reliable relocatable local scale hydrodynamic model nested within the mesoscale model
- specialised dispersion or dissipation models, such as: dredge plume; bitterns discharge; and tidal inundation model applicable to available

[1] O2METOCEAN Base Hydrodynamic Model Eramurra Solar Salt Project - REPORT NUMBER: 20MET-0016-07 / R210323; dated 6 July 2022.

- specialised model runs forced by the local hydrodynamic model runs applicable to Regnard Bay environmental or other assessment procedures.

## Purpose

The purpose of this memorandum is to provide O2M an opinion on the questions:

- *Is the regional scale numerical O2M Hydrodynamic Model suitable to force open boundary conditions of local scale nested numerical physical and dispersion models, within Regnard Bay to the East of Cape Preston regional coastal area?*
- *Will the nested specialised environmental dredge plume turbidity and bitterns dispersion, and tidal inundation dissipation models be adequate to support the marine environmental impact assessment of Leichhardt Salt's Proposal; and*
- *Will the proposed system of numerical hydrodynamic and dispersive models "facilitate the environmental approval of the ESSP"?*

## Conclusions

In the absence of detailed site-specific measurements in the Regnard Bay to Cape Preston coast line, bathymetry numerical modelling by the method of the O2M Hydrodynamic Model provides a reasonably reliable estimate of the Regnard Bay coastal circulation and turbulent diffusion (friction) processes

Having considered the Proposal site location, other relevant information, and the O2M regional and nested model draft reports[1,2] I have formed the following opinion that:

- the O2M Hydrodynamic Model is suitable to force open boundary conditions of local scale nested numerical physical and dispersion models, within Regnard Bay to the East of Cape
- the nested specialised dredge plume turbidity and bitterns dispersion, and tidal inundation dissipation models, will be adequate to support the marine environmental impact assessment of Leichhardt Salt's Proposal
- the proposed system of numerical hydrodynamic and dispersive models will facilitate the environmental approval of Leichhardt Salt's Proposal

## Recommendations

Several physical processes need further consideration:

- North-South coastal steric height difference, or Holloway current, or Indonesian Through Flow contributes to continuous annual average regional low velocity flow parallel to the coast. The continuous flow generally reduces the retention time of adverse water quality events in a given near shore area.

  A simple estimate of the steric height flow should be made from existing current meter and wind data by a method developed by Csanady and Scott.

[2] O2METOCEAN Eramurra Dredge Plume Modelling - REPORT NUMBER: 20MET-0016-09 / R210324, dated 24 June 2022.

- it is likely that the seasonal and storm change in local water quality is controlled in part by the thermohaline circulation. Release of bitterns as a seabed gravity flow along the seabed drainage pattern is likely to influence the thermohaline circulation.

  A desk review should be undertaken to check there is no adverse environment effect to the benthic water quality and habitat values; and

- in time, address weaknesses in the model as identified in the O2M report.

## Assessment method

There relevant physical oceanographic measurements, analyses and numerical model studies, which describes the dominant physical coastal oceanographic processes in, or about, the coastal area of Regnard Bay to Cape Preston East, spanned by O2M's regional Hydrodynamic Model.

Measurement, analyses and mathematical (numerical) modelling of the coastal ocean circulation has advance to the point where reasonably reliable water level and circulation estimate can be established in data poor area about the Proposal.

The assessment will consider and compare other studies with those of O2M Hydrodynamic Model. If there are strong similarities of measurement, theories and results it be considered that O2M Hydrodynamic Model are reliable for the current purposes described[1,2].

## Assessment

Aspects considered during the assessment:

- O2M used DHI's MIKE FM suite of models and coupling of hydrodynamic surface wind wave and swell models. The application of DHI Mike FM is sensible and practical.
- agreement between the overlap of each of three historical bathymetric data sets in the area of interest about the Proposal. Noted the disagreement between bathymetric data sets, and between new water level measurements and historical bathymetrical water level.
- extent and triangular numerical mesh spacing of O2M regional model a single optimised open boundary offshore. The inshore resolution was chosen to provide a minimum resolution for Regnard Bay, and to permit tests of localised transport studies.
- Regnard Bay nested local model water levels and currents were compared to the in situ water column measurements made during both a wet and dry season periods.
- O2M regional model was forced by open data from TPXO model tidal water levels and historical BoM surface meteorological data. Then the barotropic mode of the regional model forced the local circulation model about the Proposal.
- five in situ measurement sites were used to validate of water-levels and current velocities
- under normal conditions the nested local model simulated the wet and dry season and in particular skilfully resolved tidal currents and water levels close to the Proposal area of interest. The general asymmetry in the tidal currents was successfully delineated.
- under storm conditions of TC Marian the model storm events about the Proposal area. Water level surge and alongshore currents for TC Marian were simulated but magnitude of the model currents were lower than those measured *in situ*.

## Discussion

Offshore and coastal meteorological and oceanographic measurements and physical processes of the North West Shelf show that there several types of coastal ocean circulation mechanisms which occur in Northwest Cape to Legendre Island region.

At any instance during the runtime, the model may be forced by either one or both of the periodic, or near random, normal or storm conditions.

O2M model is in principle capable of simulating the known dominant physical oceanographic processes. There are at least seven physical processes important to environmental engineering and assessment.

The report results show that the model(s) simulate normal and storm:

- shallow water effects
- enhanced astronomical tidal motion
- coast lines; and
- sea level variations.

Given the available data and scope of O2M study, the following physical process have not been addressed:

- stratification in shallow water
- thermohaline circulation; and
- terrestrial influences.

O2M have, within a limited scope of work and time frame, have organised and produced an effective hydrodynamic model of Cape Preston region which include:

- accurate high resolution bathymetric survey and water level data
- open access to government or industry agency metocean measurement, satellite and global model data,
- undertaken necessary and sufficient site-specific oceanographic measurements to calibrate and validate the model
- made sensible assumptions
- obtained a reasonable balance between too much and insufficient detail
- experienced professional judgement
- recognition of the limitations of the present system of models and data/information

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