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DEVELOPING BETTER PREDICTIONS FOR EXTREME WATER LEVELS

FINAL DATA REPORT

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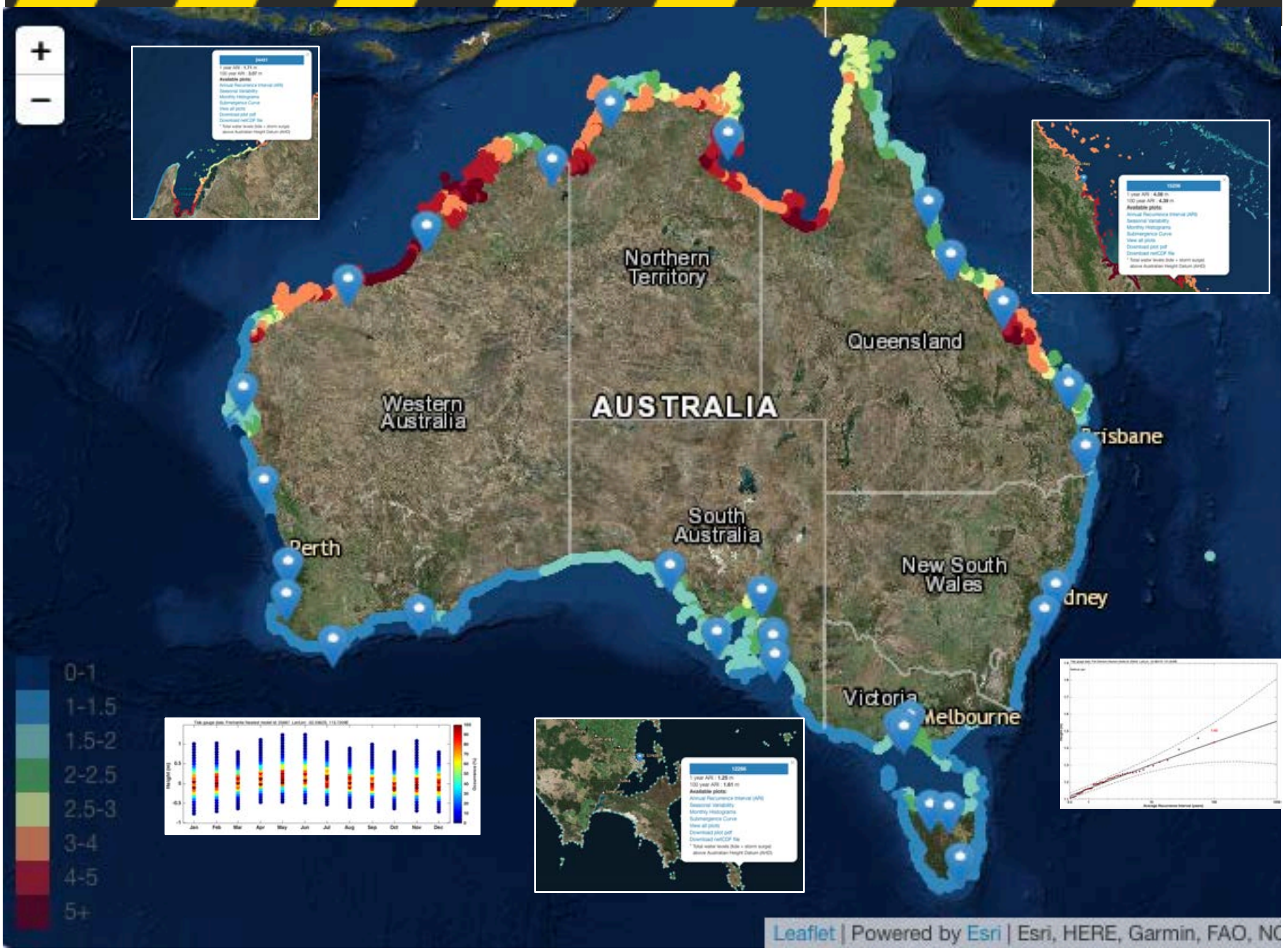
The University of Western Australia
Bushfire and Natural Hazards CRC



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Cover: Australian extreme sea levels website screenshot showing predicted present day 100 year Average Recurrence Interval water levels.

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ABSTRACT

EXTREME SEA LEVELS FOR THE AUSTRALIAN COAST

Charitha Pattiaratchi, Yasha Hetzel, Ivica Janekovic. *Oceans Graduate School and UWA Oceans Institude, The University of Western Australia, WA.*

The major hazard in coastal regions is inundation through extreme water levels generated in the ocean through different mechanisms such as storm surges and tsunamis or through a combination of effects such as a relatively small storm surge coinciding with high astronomical tides. With rising in sea level, given water levels will be exceeded more and more frequently as progressively less severe storm conditions are required to achieve that water level.

Therefore, it is critical that the exceedance probabilities of extreme water levels are accurately evaluated to inform flood and erosion risk-based management and for future planning. To address this concern, this study estimated present day extreme sea level exceedance probabilities due to storm surges, tides and mean sea level around the whole coastline of Australia through the application of a numerical model.

The SCHISM hydrodynamic model, forced by TPXO tides and JRA55 atmospheric reanalysis (wind and air pressure), was successfully applied to produce a 59 year sealevel hindcast (1958-2016) for the entire Australian region. The outputs provide uninterrupted hourly sea level records at <1 km resolution around the Australian coast. Improvements compared to the previous Haigh et al. [1] dataset included: extending the hindcast by six years including several record storm surge events, higher spatial resolution, improved meteorological forcing, and 3-D hydrodynamic model implementation. Other physical processes, missing from earlier studies, were also examined in detail including: effects of surface gravity waves, continental shelf waves, and meteorological tsunamis.

Extreme value analysis has been applied to the sea level data to predict Average Recurrence Intervals (ARI) at ~1km spacing around the entire Australian coastline including islands. These statistics and relevant plots and time series data have been made available to the public via an interactive web tool (www.ozsealevelx.org), providing a consistent, accessible, up-to-date dataset for use by coastal planners and emergency managers.

END USER STATEMENT

Miriam Middelmann-Fernandes, *Geoscience Australia, Canberra*

This project continues to work towards delivering high quality science to improve our ability to model extreme water levels around the coastline. Given the concentration of the Australian population and infrastructure in coastal areas, this understanding is key to managing the risk from inundation. An improved understanding of the likelihood and severity of extreme water level heights along the coast as a national dataset remains a high priority issue across jurisdictions. This project has just completed its major milestone, which has delivered 59 year model runs for the Australian coastline. End users are eagerly anticipating access to the data through a new web based tool that has been developed by the project.

INTRODUCTION

The major hazard in coastal regions is inundation through extreme water levels generated in the ocean through different mechanisms such as storm surges and tsunamis or through a combination of effects such as a relatively small storm surge coinciding with high astronomical tides [2]. The impacts of seismic tsunamis (generated through underwater earthquakes) have been highlighted by the recent mega-tsunamis in the Indian Ocean (2004) and Pacific Ocean (2011). These events were accompanied by large loss of life and extreme damage to coastal infrastructure. Similarly, the effects of storm surges have had significant affects such as those due to major storms: *Sandy* in New York City [3], *Haiyan* in the Philippines [4], and Hurricanes Harvey, Irma, and Maria in the Caribbean during 2017 [5].

Throughout history, coastal residents have had to adapt to periodic coastal flooding. However, as a society we have become increasingly vulnerable to extreme water level events as our cities and our patterns of coastal development become more intricate, populated and interdependent. In addition to this, there is now a real and growing concern about rising sea levels. Over the last 150 years, global sea levels have on average risen by about 25 cm [6] and it is predicted that this rise will continue over the 21st century (and beyond) at an accelerated rate [7]. With rises in sea level, given water levels will be exceeded more and more frequently as progressively less severe storm conditions are required to achieve that water level [8]. In some coastal regions, extreme water levels could be amplified further by changes in storminess, such as more intense tropical cyclones, although there are still significant uncertainties regarding possible future changes in tropical and extra-tropical storm activity [9].

Therefore it is important that the exceedance probabilities of extreme water levels are accurately evaluated to inform flood and erosion risk-based management and for future planning—particularly for Australia where a majority of the population and infrastructure exist at the coast. Motivated by this need, this project built upon previous studies [1, 8] with the aim of producing more accurate estimates of present day extreme sea level exceedance probabilities due to storm surges, tides and mean sea level around Australia.

The SCHISM hydrodynamic model, forced by TPXO tides and JRA55 atmospheric reanalysis (wind and air pressure), was successfully applied to produce a 59 year sealevel hindcast (1958-2016) for the entire Australian region. The outputs provide uninterrupted hourly sea level records at <1 km resolution around the Australian coast. Improvements compared to previous the Haigh et al. [1] dataset included: extending the hindcast by six years including several record storm surge events, higher spatial resolution, improved meteorological forcing, and 3-D hydrodynamic model implementation. Other physical processes, missing from earlier studies that were also examined in detail included: effects of surface gravity waves, continental shelf waves, and meteorological tsunamis.

Analysis of the sea level data included application of Extreme Value Theory to predict Average Recurrence Intervals (ARI) at ~1km spacing around the entire Australian coastline including islands. These statistics and relevant plots and time series data have been made available to the public via an interactive web tool, providing a consistent, accessible, up-to-date dataset for use by coastal planners and emergency managers.

This report provides an overview of the methodology, including model setup, validation, extreme value analysis, and describes the final data available to the end-users and public.

METHODOLOGY

MODEL SETUP

Model Description

We used the full 3D finite element hydrodynamic modeling system SCHISM [10, 11] has successfully simulated circulation and storm surges in a broad range of coastal environments [12-15]. Other applications of the model include tsunami inundation [16] oil spill [17], and ecological studies [18]. The model uses a semi-implicit finite element Eulerian-Lagrangian algorithm to solve the Navier-Stokes momentum equations and naturally incorporates wetting and drying of tidal flats. The numerical algorithm is stable, computationally efficient and does not suffer from numerical stability constraints (e.g. the Courant-Friedrich-Lewy (CFL) condition) that restrict the maximum allowable timestep, as is an issue in many other ocean modeling codes (e.g. ROMS, POM, ADCIRC) [10]. The benefits of using SCHISM for cross scale modeling are described in detail in [11]. An earlier version of SCHISM (previously named SELFE) was evaluated to have equal skill (both coupled/ uncoupled) compared to leading unstructured coastal hydrodynamic models (e.g., ADCIRC, FVCOM) for simulating water levels for a tropical cyclone in the Gulf of Mexico, and outperformed the official National Weather Service operational storm surge forecast SLOSH model that has a structured framework [19]. The SCHISM model was run in 3D mode, allowing for improved representation of vertical current structure, tide-current interactions, and improved storm surge predictions. The model was run with both tidal and atmospheric forcing resulting in 59-year hourly time series of total water levels over the entire domain.

Unstructured model grid

The total model domain included all oceanic waters surrounding Australia, spanning between 93.6°E to 171.5°E and -49.7°S to -7°S with a curved outer boundary (Figure 1). The horizontal spatial resolution of the unstructured triangular mesh grid increased from ~10 km in the open ocean to between 100 and 800m at the coast. The model utilized the hybrid vertical coordinate system LSC^2 [20] that allowed the number of vertical levels to vary with depth, ranging in our grid from 18 (shallow) to 76 (deep). This is helpful for regions that include sharp depth gradients as it minimizes bathymetric smoothing requirements. Bathymetry data were merged from various sources, with priority given to data with higher spatial resolution and/or reliability including: General Bathymetric Chart of the Oceans (GEBCO), Geoscience Australia 250m [21], NSW State Wide Wave Model Bathymetry Mesh 100m, 3DGBR 100m for Queensland [22] and 5m LIDAR in southwest WA.

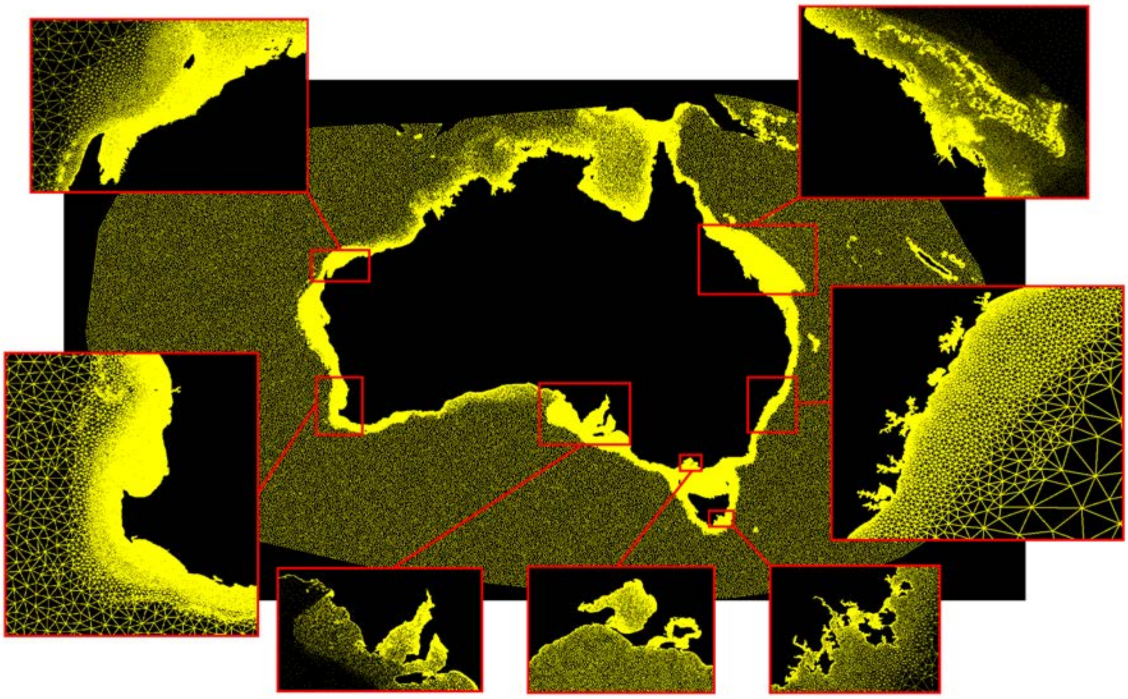

FIGURE 1. SCHISM NUMERICAL MODEL DOMAIN WITH SUBSETS ILLUSTRATING HIGHER RESOLUTION AT THE COAST. SPATIAL RESOLUTION AT THE COAST RANGED FROM 100 TO 800 METRES AND DECREASED OFFSHORE.

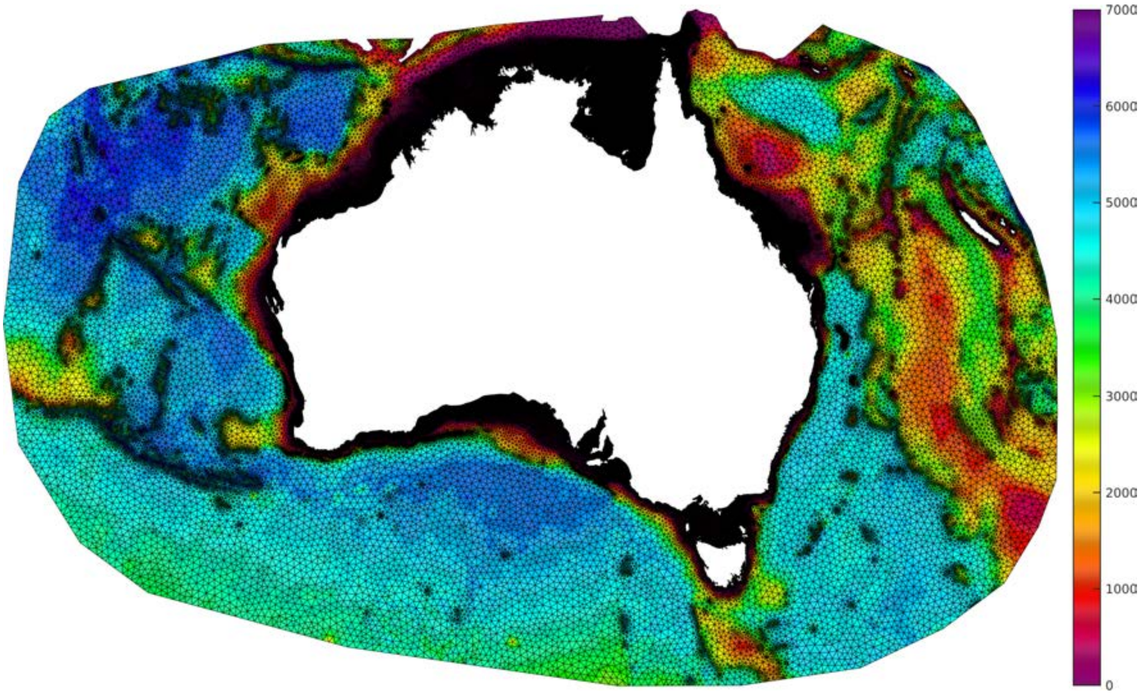

FIGURE 2. SCHISM UNSTRUCTURED MODEL MESH WITH COLOURS INDICATING DEPTH IN METRES.

Forcing

Atmosphere: Extratropical storms

The recently released Japanese Reanalysis JRA-55 reanalysis atmospheric model [23-27] provided wind and mean sea level (MSL) pressure fields at 0.5 degree resolution at 3-hour intervals. JRA-55 data were obtained from the NCAR Research Data Archive [24] dataset (1958-present) accurately reproduces broad scale synoptic and climate variability [27]. Additionally, the JRA-55 model appears to be among the best at capturing the structure of storms transitioning from tropical to extratropical [25] and assimilates tropical cyclone track data to ensure that simulated tropical cyclones follow accurate trajectories. Using a global reanalysis model to force our model ensured that the methodology and lessons learnt through our experiment could be easily transferrable to other regions and events over the past ~60 years.

Atmosphere: Tropical cyclones

Tropical cyclone intensities in reanalysis models [25] are universally underestimated and as a result the long-term model runs for Australia provided low estimates of the extreme sea levels at longer ARIs in tropical regions. To account for this limitation, the final analysis merged extreme sea level exceedence probabilities derived in previous work focused on tropical cyclones [8] with the SCHISM model results used for the rest of Australia. The Haigh et. al [8] model was forced with wind and pressure fields from a stochastic tropical cyclone model that synthetically extended the tropical cyclone record to 10,000 years. The stochasitic model provided sea level for tropical cyclone extremes whilst the SCHISM 59-year simulations included tidal and longer term (seasonal, interannual, ENSO) variability. Combining the two datasets in this way allowed for best estimate of extreme values all around Australia.

Tides

The eight primary harmonic tidal constituents (M2,S2,K2,N2,K1,O1,P1,Q1) from the 1/30 degree TPXO08 Atlas *[28]* (http://volkov.oce.orst.edu/tides/tpxo8_atlas.html) were assigned to the outer boundaries of the model grid, and sea levels were calculated by SCHISM. Direct gravitationally forced tides, or tidal potential, were also calculated internally within the SCHISM model.

Waves

Waves were not included in the 59-year simulations due to computational constraints. Wave effects were investigated for a number of specific events around the Australian coast and these results are presented in Hetzel et al. [29].

Multi decadal simulations (1958-2016)

Model simulations, in parallelised mode, were performed on the supercomputer Magnus at Pawsey Supercomputing Centre (https://www.pawsey.org.au) using between ~200-700 computational cores. Overlapping yearly simulations were completed with time series of sea level saved at hourly intervals for the entire domain and every 10-minutes at tide gauge locations. Hourly data were archived in yearly netCDF files.

Post processing

Due to the very large size of the total dataset, 31,479 data points were extracted from raw model output for post-processing. The data consisted of 59-year sea level time series for 31,479 locations evenly spaced at 2 km intervals along the entire coastline of Australia including islands.

In order to account for steric sea level effects (due to temperature and salinity) and long-term mean sea level (MSL) variability originating outside the model domain, the SCHISM model output were adjusted to match monthly (and longer) gridded AVISO satellite altimeter data. The 'DT all-sat-merged Global Ocean Gridded SSALTO/DUACS Sea Surface Height L4 product' (http://marine.copernicus.eu) contained sea level anomalies relative to a 20-year mean and covered the period from 1993-2016 at ¼ degree resolution. Sea level from the nearest representative AVISO grid point was extracted for each SCHISM coastal data point and monthly mean values and seasonal climatology were computed and then interpolated to hourly time steps. Correspondingly, SCHISM sea level variability at periods longer than 1 month was removed and replaced with the AVISO MSL signal, thus aligning the model seasonal and interannual variability (e.g. ENSO) with observations. For the period prior to the satellite era, the seasonal climatology was incorporated into the model data, but not the longer-term component. Overall, the method was found be a physically accurate way to improve model skill, particularly in areas with large seasonal variability (e.g. Gulf of Carpenteria, Western Australia, South Australia).

These total sea level data were then validated against tide gauge observations and archived for each coastal data point as individual netCDF files available through the website.

MODEL VALIDATION

Harmonic tidal analysis was undertaken on predicted and observed hourly water levels at 28 tide gauge sites around Australia (Figure 3) using the MATLAB T-tide toolbox [30]. This allowed for the separation of the total sea level into tide and residual components that were then evaluated against tide gauge observations (Table 1), over the entire 59 year period, as well as for specific events at additional tide gauge sites. Accuracy of the predicted sea levels compared to observations was assessed by calculating "model skill" [*Wilmott*, 1981; *Warner et al.*, 2005] for total sea level (skill>0.9), tide (skill>0.9) ,and non-tidal residuals. Root mean square error was also assessed for individual components (tide, surge) and total water levels and was normalised against spring tidal range, mean surge range, and maximum total water level range (Table 1). The main tidal constituent amplitude and phases were also compared and found to be reasonable [Figure 4].

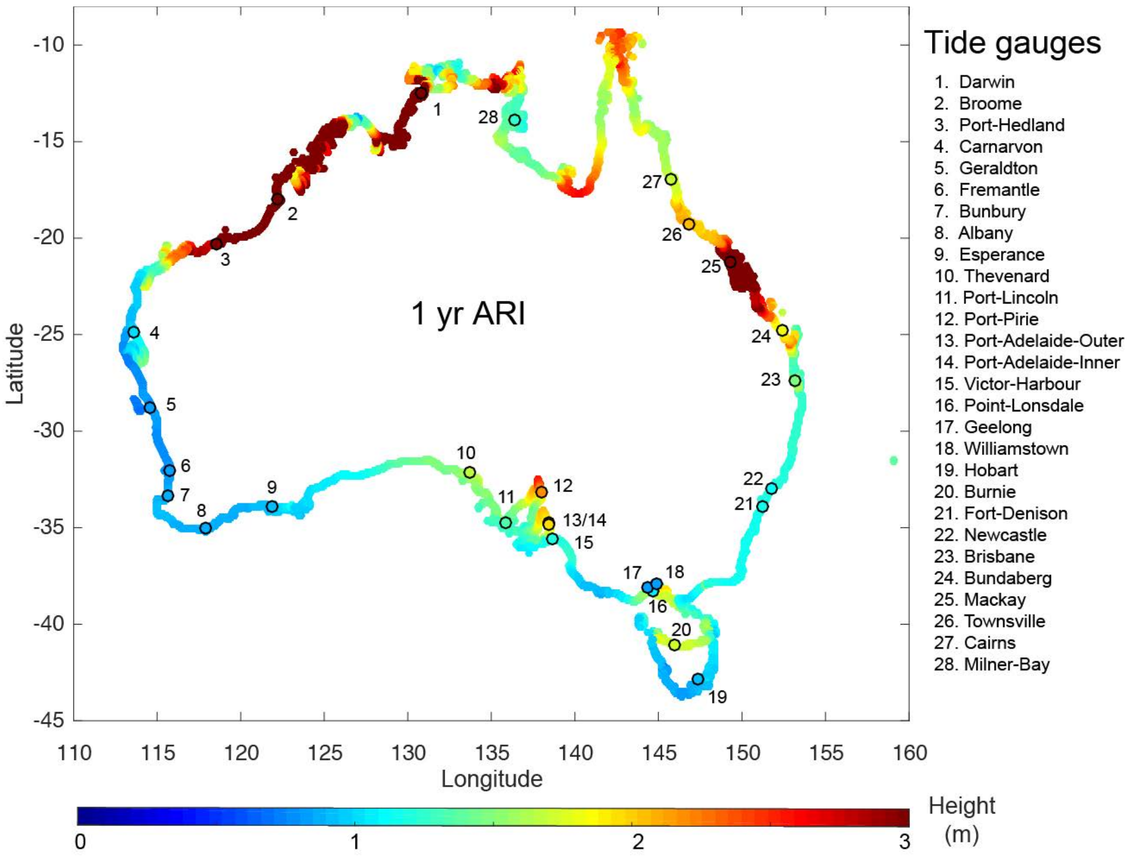

FIGURE 3. LOCATION OF TIDE GAUGE SITES USED FOR VALIDATION OF SCHISM STORM SURGE MODEL OVERLATED ON PREDICTED 1 YEAR AVERAGE RECURRENCE INTERVAL AS AN INDICATOR FOR TIDAL RANGE AROUND AUSTRALIA.

		Observed		Model Skill			RMSE (m)			Normalised RMSE (%)			Standard deviation error (m)		
ID	Site	Spring tidal range	Mean surge range	Tide	Surge	Total	Tide	Surge	Total	Tide	Surge	Total	Tide	Surge	Total
1	**Darwin**	6.39	0.79	0.98	0.67	**0.98**	0.46	0.12	**0.47**	0.10	0.17	**0.09**	-0.10	0.03	**-0.10**
2	**Broome**	8.75	1.05	0.99	0.65	**0.99**	0.35	0.15	**0.38**	0.06	0.23	**0.05**	-0.08	-0.02	**-0.08**
3	**Port-Hedland**	6.13	0.95	0.99	0.69	**0.98**	0.34	0.12	**0.36**	0.09	0.16	**0.07**	-0.01	0.00	**-0.01**
4	**Carnarvon**	1.26	0.70	0.98	0.85	**0.97**	0.09	0.08	**0.12**	0.12	0.12	**0.09**	0.05	0.03	**0.05**
5	**Geraldton**	0.76	0.67	0.98	0.91	**0.96**	0.05	0.07	**0.09**	0.11	0.11	**0.09**	0.00	0.03	**0.02**
6	**Fremantle**	0.69	0.67	0.98	0.88	**0.95**	0.05	0.08	**0.09**	0.10	0.12	**0.10**	-0.01	0.04	**0.01**
7	**Bunbury**	0.74	0.78	0.98	0.88	**0.95**	0.05	0.08	**0.10**	0.10	0.11	**0.10**	-0.01	0.05	**0.02**
8	**Albany**	0.88	0.53	0.99	0.84	**0.96**	0.04	0.08	**0.09**	0.07	0.16	**0.09**	0.00	0.04	**0.02**
9	**Esperance**	0.85	0.63	0.99	0.87	**0.97**	0.04	0.08	**0.09**	0.06	0.13	**0.09**	-0.01	0.04	**0.01**
10	**Thevenard**	1.66	1.20	0.98	0.92	**0.97**	0.10	0.10	**0.14**	0.10	0.09	**0.08**	0.01	0.02	**0.02**
11	**Port-Lincoln**	1.34	0.89	0.97	0.89	**0.96**	0.11	0.09	**0.14**	0.14	0.10	**0.10**	0.03	0.05	**0.05**
12	**Port-Pirie**	2.61	1.54	0.96	0.87	**0.95**	0.23	0.14	**0.27**	0.16	0.09	**0.11**	0.12	0.06	**0.13**
13	**Port-Adelaide-Outer**	2.23	1.17	0.94	0.90	**0.94**	0.23	0.11	**0.25**	0.23	0.09	**0.12**	0.17	0.05	**0.17**
14	**Port-Adelaide-Inner**	2.35	1.23	0.91	0.91	**0.91**	0.28	0.11	**0.30**	0.28	0.09	**0.14**	0.21	0.06	**0.22**
15	**Victor-Harbour**	0.99	0.92	0.98	0.89	**0.96**	0.06	0.10	**0.11**	0.09	0.11	**0.09**	-0.02	0.05	**0.01**
16	**Point-Lonsdale**	1.37	0.66	0.97	0.89	0.96	0.15	0.08	0.17	0.13	0.12	0.13	-0.10	0.02	-0.09
17	**Geelong**	0.81	0.62	0.96	0.88	**0.95**	0.09	0.08	**0.12**	0.14	0.12	**0.13**	-0.05	0.02	**-0.03**
18	**Williamstown**	0.71	0.65	0.96	0.89	**0.94**	0.09	0.08	**0.12**	0.15	0.12	**0.13**	-0.05	0.03	**-0.03**
19	**Hobart**	1.14	0.57	0.99	0.87	**0.97**	0.05	0.08	**0.09**	0.08	0.13	**0.08**	0.00	0.03	**0.01**
20	**Burnie**	3.02	0.78	0.96	0.81	**0.96**	0.28	0.09	**0.30**	0.16	0.11	**0.12**	0.20	0.03	**0.20**
21	**Fort-Denison**	1.62	0.43	1.00	0.77	**0.99**	0.05	0.07	**0.09**	0.05	0.18	**0.06**	0.00	0.01	**0.00**
22	**Newcastle**	1.58	0.50	0.99	0.74	**0.99**	0.07	0.08	**0.10**	0.06	0.16	**0.07**	-0.02	0.02	**-0.02**
23	**Brisbane**	2.16	0.50	0.98	0.62	**0.98**	0.15	0.09	**0.17**	0.10	0.18	**0.09**	0.01	0.03	**0.01**
24	**Bundaberg**	2.78	0.71	0.98	0.55	**0.98**	0.18	0.10	**0.20**	0.10	0.17	**0.09**	0.03	0.05	**0.04**
25	**Mackay**	5.41	0.76	0.94	0.74	**0.93**	0.69	0.13	**0.70**	0.18	0.18	**0.16**	-0.10	0.01	**-0.09**
26	**Townsville**	2.93	0.75	0.99	0.78	**0.99**	0.11	0.09	**0.14**	0.06	0.14	**0.05**	-0.03	0.03	**-0.02**
27	**Cairns**	2.46	0.51	0.99	0.68	**0.99**	0.10	0.08	**0.13**	0.07	0.17	**0.06**	0.04	0.04	**0.05**

TABLE 1. MEAN MODEL VALIDATION STATISTICS FOR 27 TIDE GAUGE SITES AROUND AUSTRALIA FOR 1958-2016 HOURLY WATER LEVELS. SPRING TIDAL RANGE WAS CALCULATED AS 95TH PERCENTILE OF PREDICTED TIDE RANGE AND USED TO NORMALISE TIDE ROOT MEAN SQUARE ERROR (RMSE). MEAN SURGE RANGE (PEAKS-TROUGHS), AND 95TH PERCENTILE OF OBSERVED TOTAL RANGE (PEAKS-TROUGHS) WERE USED TO NORMALISE SURGE AND TOTAL WATER LEVELS RESPECTIVELY. MODEL SKILL WAS CALCULATED FOLLOWING WILLMOT (1981) [31]. STATISTICS WERE CALCULATED ONLY WHERE >70% GOOD TIDE DATA WERE AVAILABLE.

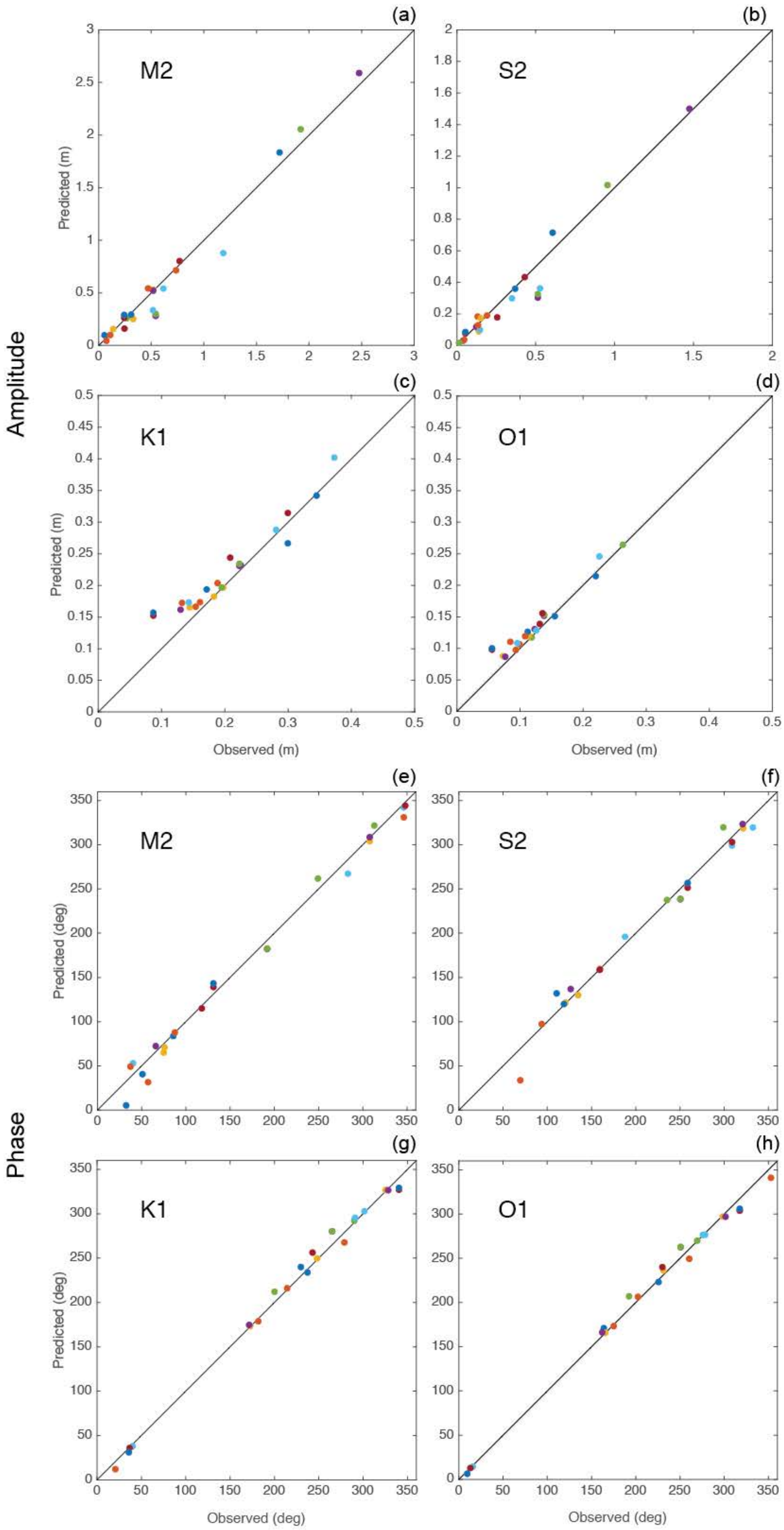

FIGURE 4. OBSERVED VS. PREDICTED AMPLITUDE (A-D) AND PHASE (E-F) OF THE FOUR MAIN TIDAL CONSTITUENTS AT 28 TIDE GAUGE SITES OBTAINED THOUGH HARMONIC ANALYSIS OF PREDICTED AND OBSERVED TOTAL WATER LEVELS.

A subset of the data from around the continent is shown here to illustrate the model results. Main outputs are total sea levels that include tides, storm surges, and longer term sea level variability (Figure 5). The dramatic range in tides is evident when comparing outputs from different regions either as time series (Figure 5) or as a map of 1 year ARI Figure 3). Sea level extremes, therefore, are relative to the each site, with the coincidence of tide and storm surge often critical. Tidal analyses of the total water level data allowed for the separation into tidal and non-tidal residuals. The non-tidal residuals (e.g. Figure 6) enable the identification of individual storm surge events, i.e. higher periods of water levels caused by high winds and reduced air pressure.

For example, Thevenard, South Australia (Figure 6) showed a high frequency of storm surge events over the entire simulated period, visible as spikes of ~1 m amplitude in the non-tidal residual time series. The highest amplitude storm surge occurred in September 2016 (Figure 7a green circle) but did not coincide with high spring tides, making the total water level slightly less extreme than the event during May 2016 (Figure 1b red circle) when high tides and high surge combined to cause record sea levels.

The final year of the simulation (2016) proved to be exceptionally stormy with high and storm surges over the south half of the continent, including notable damaging storms in NSW and South Australia. Whilst the accuracy of the model at individual sites and for individual storms varied varied due to many factors, in general, both the total water levels (Figure 8) and non-tidal residuals (Figure 9) were well represented when compared to tide gauge data.

The complete dataset of simulated sea levels available through the website will allow for the identification of vulnerable areas, specific conditions causing extreme sea levels, and probabilities of those levels being exceeded at all areas around the coastline.

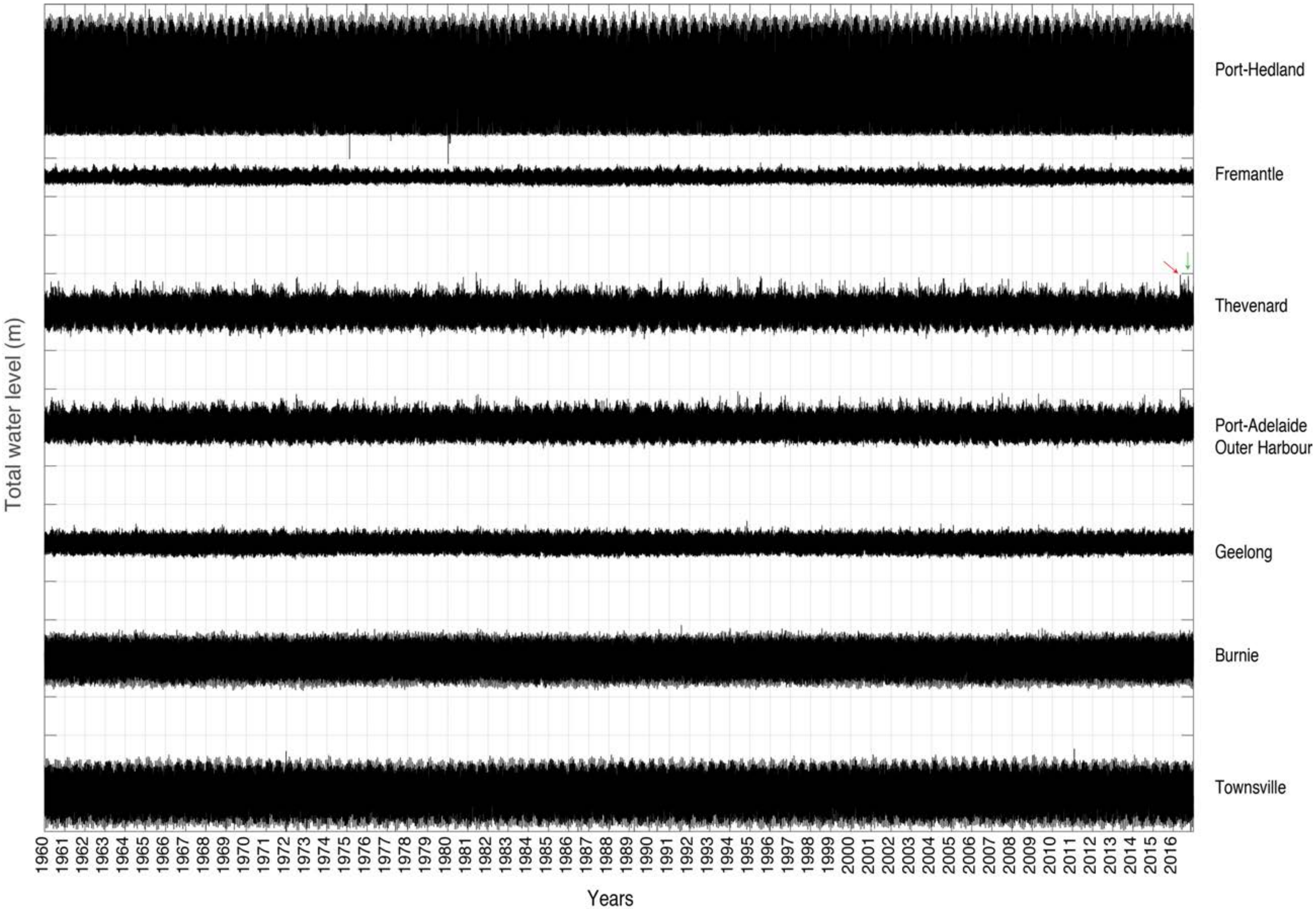

FIGURE 5. SIMULATED TOTAL WATER LEVELS, STARTING IN FREMANTLE, WA AND MOVING ANTICLOCKWISE AROUND THE COAST. DATA PLOTTED WITH ARBITRARY OFFSET AND TICK MARKS AT 1 M INTERVALS ON THE Y-AXIS. EVENTS AT THEVENARD, SA INDICATED WITH RED/GREEN ARROWS.

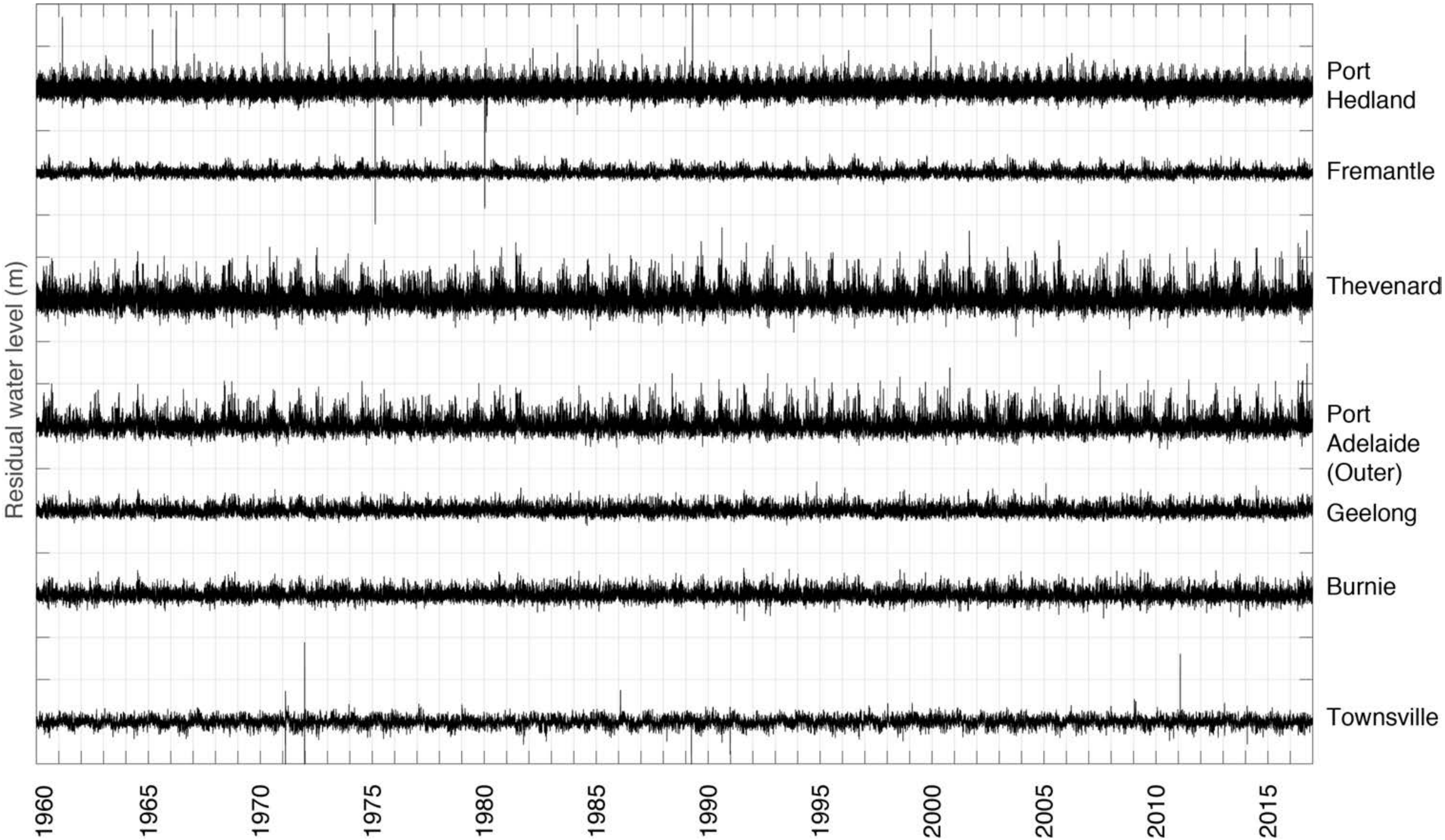

FIGURE 6. PREDICTED NON-TIDAL RESIDUAL SEA LEVELS AT A SELECTION OF SITES, STARTING IN PORT HEDLAND, WA AND MOVING ANTICLOCKWISE AROUND THE COAST. DATA ARE PLOTED WITH AN ARBITRARY OFFSET AND TICK MARKS AT 1 M INTERVALS ON THE Y-AXIS.

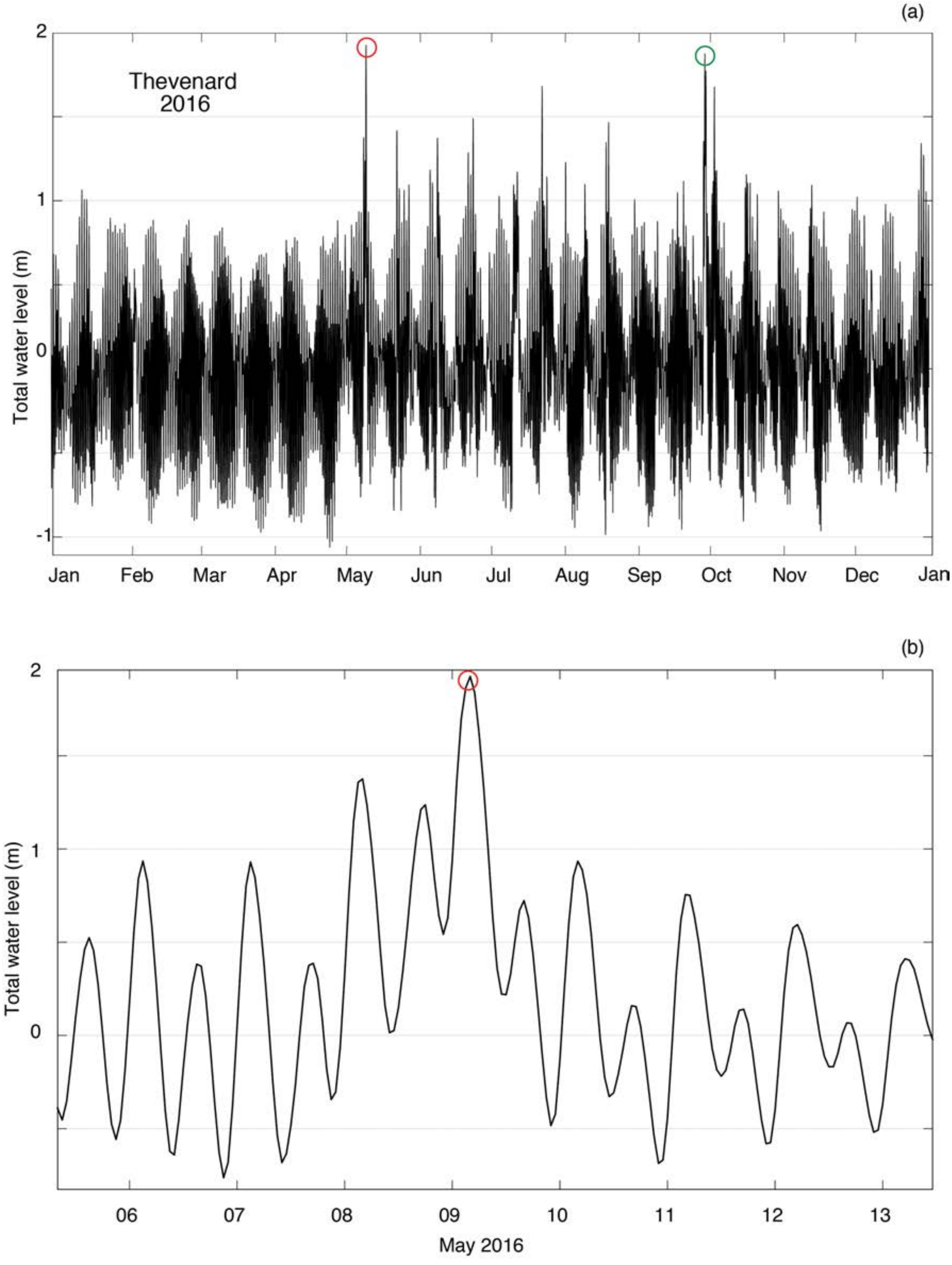

FIGURE 7. PREDICTED TOTAL WATER LEVELS AT THEVENARD, SA FOR ALL OF 2016 (A) AND FOR THE HIGHEST RECORDED SEA LEVEL EVENT ON 9 MAY 2016 (B), CAUSED BY LARGE STORM SURGE COINCIDING WITH HIGH SPRING TIDES. THEVENARD EXPERIENCED A HIGH FREQUENCY OF STORM SURGES DURING 2016 THAT WERE SUCCESSFULLY REPRODUCED BY THE HYDRODYNAMIC MODEL

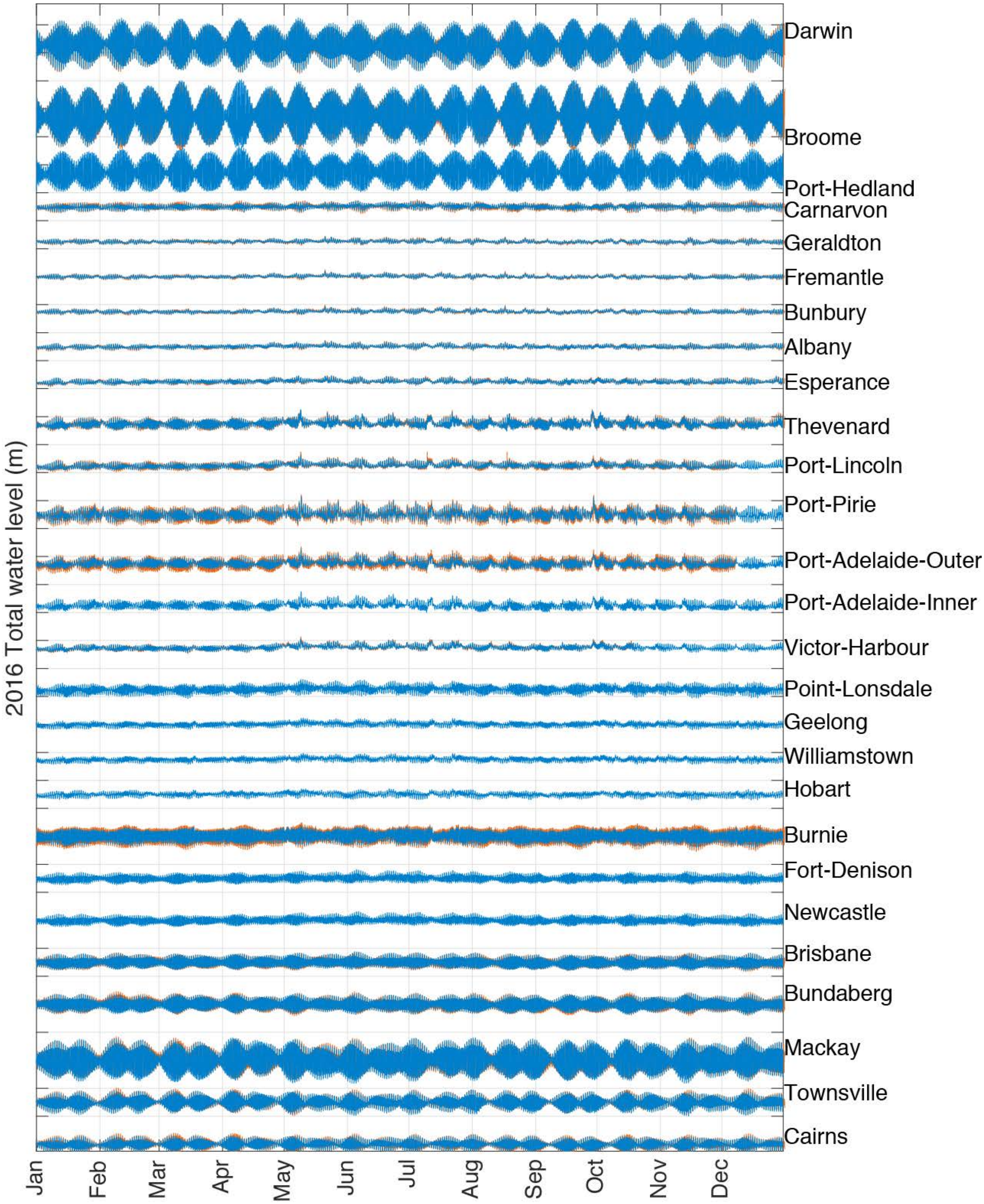

FIGURE 8. PREDICTED (BLUE) AND OBSERVED (ORANGE) TOTAL SEA LEVELS FOR 2016 PLOTTED WITH ARBITRARY OFFSET STARTING AT DARWIN AND MOVING ANTICLOCKWISE AROUND THE COAST. DATA ARE PLOTED WITH AN ARBITRARY OFFSET AND TICK MARKS AT 4 M INTERVALS ON THE Y-AXIS. THE EXTREME TIDAL RANGE VARIABILITY AROUND THE COAST CAN BE SEEN CLEARLY IN THE PLOT.

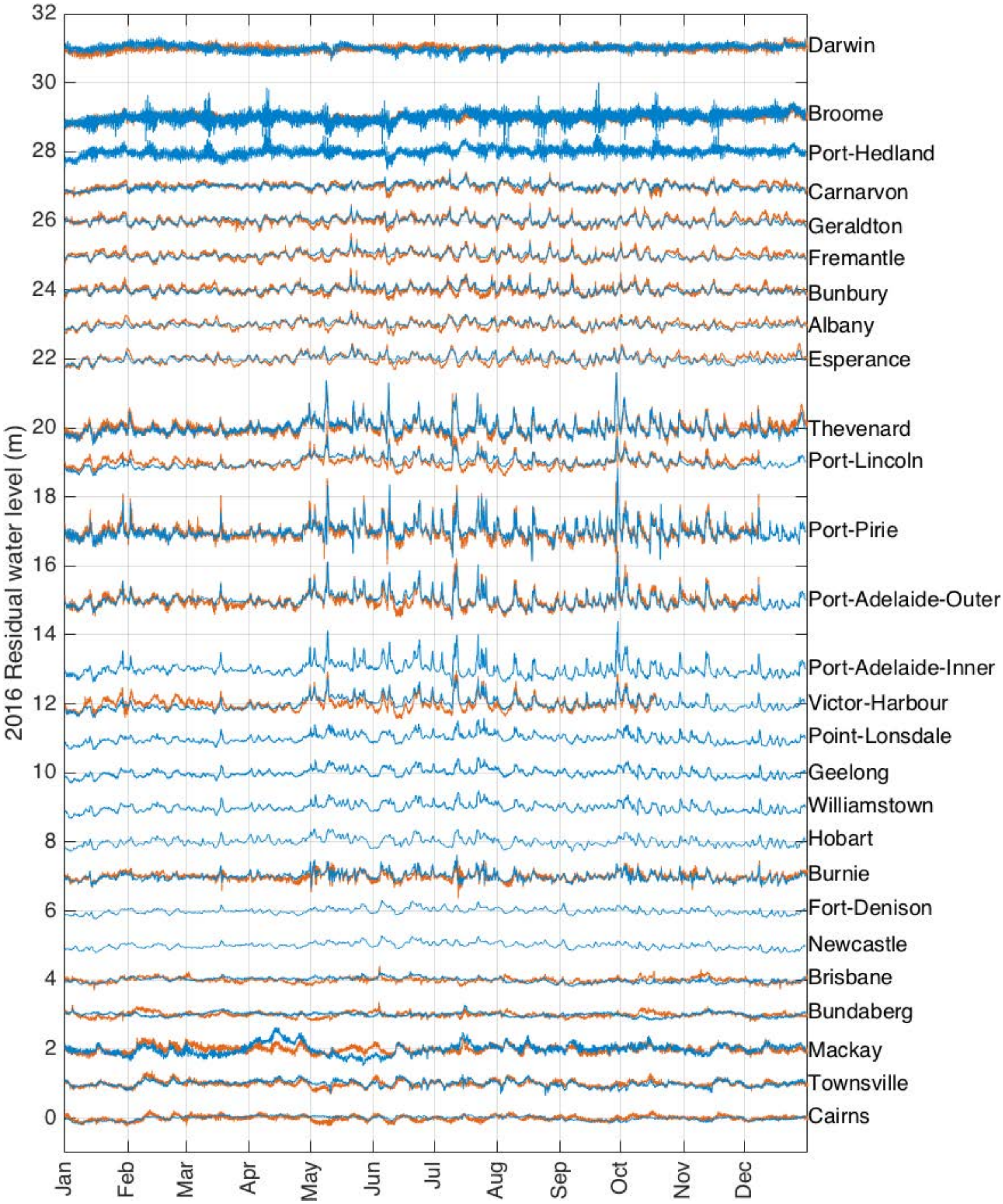

FIGURE 9. PREDICTED (BLUE) AND OBSERVED (ORANGE) NON-TIDAL RESIDUAL SEA LEVELS (STORM SURGE) FOR 2016 PLOTTED WITH ARBITRARY OFFSET STARTING AT DARWIN AND MOVING ANTICLOCKWISE AROUND THE COAST. DATA ARE PLOTED WITH AN ARBITRARY OFFSET. 2016 WAS ONE OF THE STORMIEST YEARS ON RECORD FOR SOUTH AUSTRALIA, THE HIGH AMPLITUDE AND FREQUECY OF STORM SURGES BETWEEN THEVENARD AND VICTOR HARBOUR. NOISE IN THE SIGNAL FOR NORTHERN AUSTRALIAN SITES RESULTS FROM CHALLENGES IN HARMONIC TIDAL ANALYSIS DUE TO EITHER INCOMPLETE TIDA GAUGE DATA OR MODEL DATA POINTS THAT WERE SHALLOWER THAN LOWEST WATER LEVELS AND IS NOT INDICATIVE OF INACURACIES IN PREDICTIONS OF HIGHEST WATER LEVELS.

EXTREME VALUE ANALYSIS

Extreme value theory is a statistical method that allows for the calculation of the probability of the occurrence of extreme events. The generalized extreme value (GEV) distribution is commonly applied to model the maxima of random variables, across many disciplines including extreme sea levels in order to determine the probability of sea levels occurring. These probabilities commonly presented as Average Recurrence Intervals (ARI) or return periods, are an estimate of the average interval of time between events of a certain magnitude. For example, the 100 year ARI (or return period) sea level means that on average that level will be exceeded once every hundred years. Or, more clearly, that level has a 1/100 (or 1%) chance of occurring *each year*. A common misconception is that that level can only occur once over that time period, but in reality there is a small probability that it could happen at any time, even if it has recently occurred.

Over recent decades a number of statistical methods have emerged to estimate probabilities of extreme sea levels, each with various benefits and limitations, and with no one method universally accepted [32]. The main procedure involves several steps: 1) detrending the input water levels; 2) reducing the high frequency dataset to a representative subset; 3) fitting the subset to an extreme value distribution so that extreme sea levels can be determined beyond the length of the dataset; 4) testing the appropriateness of fit against an empirical distribution [32].

When applying a particular method over a large area such as Australia it is important that the results are not sensitive to parameters, such as varying numbers of data points, or thresholds (step 2). For this study we compared several direct methods, including the Annual Maximum (AMM), r-largest, and Peaks over Threshold (POT) following Coles [33] and Arns et al.[32]. Whilst there were some benefits from using the POT method (selects subset based on whether they exceed a given threshold, such as 99.7 percentile level) over the AMM (a single value for each year), it was not possible to choose a single threshold for all sites and thus the method could not be applied consistently for all coastal grid points. In general, the differences between the two methods were within minimal, since the length of the time series (59 years) was sufficient for the AMM to produce reliable results—therefore the AMM was used for the extreme value analysis.

Total predicted hourly sea levels (tide + storm surge), at 31479 coastal locations, were detrended and annual maximum water levels were extracted used for extreme value analysis. The classical Annual Maximum method with a Generalised Extreme Value (GEV) distribution [33] was used to determine Average Recurrence Intervals (ARI) all around the coast using MATLAB functions contained in the statistics toolbox. The same analysis was applied to tide gauge data at 28 sites Figure 3; Table 2).

To ensure consistency with observations predicted levels were adjusted so that the 1-year return period levels matched those of the measured estimates, calculated using the same methods, at each tide gauge site similar to Haigh et al [2010]. The adjustment was linearly interpolated along the coast between tide gauge sites, taking into account local dynamics. This allowed the predicted water levels (relative to model mean sea level (MSL)), to align with observations relative to AHD. Around mainland Australia, AHD was defined using MSL records between 1966 and 1968 at 30 sites and hence differs slightly from present day MSL.

A comparison between model and tide gauge 1 and 100 year ARI values indicated a reasonable agreement at the tide gauge validation sites (Table 2; Figure 10.). Differences were generally attributed to specific storm systems (e.g. tropical cyclones, cutoff lows, East Coast Lows) that were underestimated in the atmospheric reanalysis used to force the SCHISM storm surge model. Other secondary factors included that the tide gauge data contained gaps or did not cover the complete time period of the model. The tide gauge ARIs have also been made available alongside the model ARIs on the website, allowing the user to account for any under/over estimations of the predicted levels in regions of interest.

Tropical cyclone intensities in reanalysis models [25] are universally underestimated and as a result the long-term model runs for Australia provided low estimates of the extreme sea levels at longer ARIs in tropical regions. To account for this limitation, the final analysis merged extreme sea level exceedence probabilities derived in previous work focused on tropical cyclones [8] with the SCHISM model results used for the rest of Australia. The Haigh et.al [8] model was forced with wind and pressure fields from a stochastic tropical cyclone model that synthetically extended the tropical cyclone record to 10,000 years. The stochasitic model provided sea level for tropical cyclone extremes whilst the SCHISM 59-year simulations included tidal and long term (seasonal, interannual, ENSO) variability. The final extreme sea level products contained ARI levels that were the higher value at each coastal data point. The regions where the synthetic tropical cyclone data provided ARIs was mostly limited to ARIs >100 years within the northern regions of Western Australia and Northern Territory, whilst values in the rest of Australia were derived directly from the SCHISM model. The difference between the two datasets can be seen in the ARI curve plots, where the synthetically derived values are plotted as triangles when they exceed the SCHISM ARI values (Figure 11). Combining the two datasets in this way allowed for best estimate of extreme values all around Australia (Figures 10, 12-18).

Tide Gauge ID	Site	Longitude	Latitude	# observation years available (1958-2016)	Observed 1 yr ARI	Observed 100 yr ARI	Model 100 yr ARI
1	Darwin	130.8461	-12.4716	49	3.69	4.03	**3.91**
2	Broome	122.2183	-18.0008	37	4.57	5.19	**5.33**
3	Port-Hedland	118.5831	-20.3001	41	3.38	3.97	**4.41**
4	Carnarvon	113.6182	-24.9038	37	1.00	1.77	**1.61**
5	Geraldton	114.5818	-28.7788	49	0.80	1.15	**1.02**
6	Fremantle	115.7209	-32.0562	55	0.81	1.17	**1.00**
7	Bunbury	115.6444	-33.2995	49	0.88	1.53	**1.20**
8	Albany	117.8889	-35.0333	47	0.85	1.02	**1.03**
9	Esperance	121.8854	-33.8664	49	0.93	1.13	**1.08**
10	Thevenard	133.6622	-32.1407	49	1.66	2.05	**2.13**
11	Port-Lincoln	135.8692	-34.717	49	1.33	1.78	**1.66**
12	Port-Pirie	138.0101	-33.1368	55	2.20	2.82	**2.96**
13	Port-Adelaide-Outer	138.4927	-34.7658	55	1.87	2.44	**2.44**
14	Port-Adelaide-Inner	138.4787	-34.862	45	1.95	2.58	**N/A***
15	Victor-Harbour	138.6442	-35.5724	47	1.18	1.59	**1.51**
16	Point-Lonsdale	144.6607	-38.288	51	1.05	1.31	**1.30**
17	Geelong	144.3965	-38.1253	38	0.82	1.05	**1.09**
18	Williamstown	144.9165	-37.8694	49	0.81	1.04	**1.09**
19	Hobart	147.3385	-42.8806	42	0.93	1.38	**1.18**
20	Burnie	145.9149	-41.0472	37	1.73	1.99	**2.00**
21	Fort-Denison	151.2536	-33.8607	55	1.16	1.43	**1.34**
22	Newcastle	151.7891	-32.9346	49	1.12	1.34	**1.36**
23	Brisbane	153.1667	-27.3666	42	1.50	1.72	**1.63**
24	Bundaberg	152.3946	-24.7433	46	1.82	2.44	**2.14**
25	Mackay	149.287	-21.2818	41	3.39	3.88	**3.84**
26	Townsville	146.834	-19.2525	54	2.06	2.54	**2.47**
27	Cairns	145.7839	-16.9162	41	1.69	2.06	**1.88**
28	Milner-Bay	136.4158	-13.86	17	1.26	N/A	**3.76**

TABLE 2. AVERAGE RECURRENCE INTERVALS (ARI) FOR TOTAL WATER LEVELS (M AHD) CALCULATED FROM HOURLY TIDE GAUGE DATA AND MODEL OUTPUTS USING ANNUAL MAXIMUM GENERALISED EXTREME VALUE (GEV) METHODS AT 28 SITES AROUND AUSTRALIA. NUMBER OF YEARS USED FOR TIDE GAUGE DATA (>70% GOOD DATA) OVER THE 1958-2016 PERIOD. THE COMPLETE 59 YEARS WERE USED FOR MODEL CALCULATIONS. * REPRESENTATIVE MODEL GRID CELL NOT AVAILABLE FOR PORT ADELAIDE INNER HARBOUR.

EXTREME VALUES

The extreme values derived from the numerical model are provided below and are available at 2 km resolution around Australia through the website.

AVERAGE RECURRENCE INTERVALS AROUND AUSTRALIA

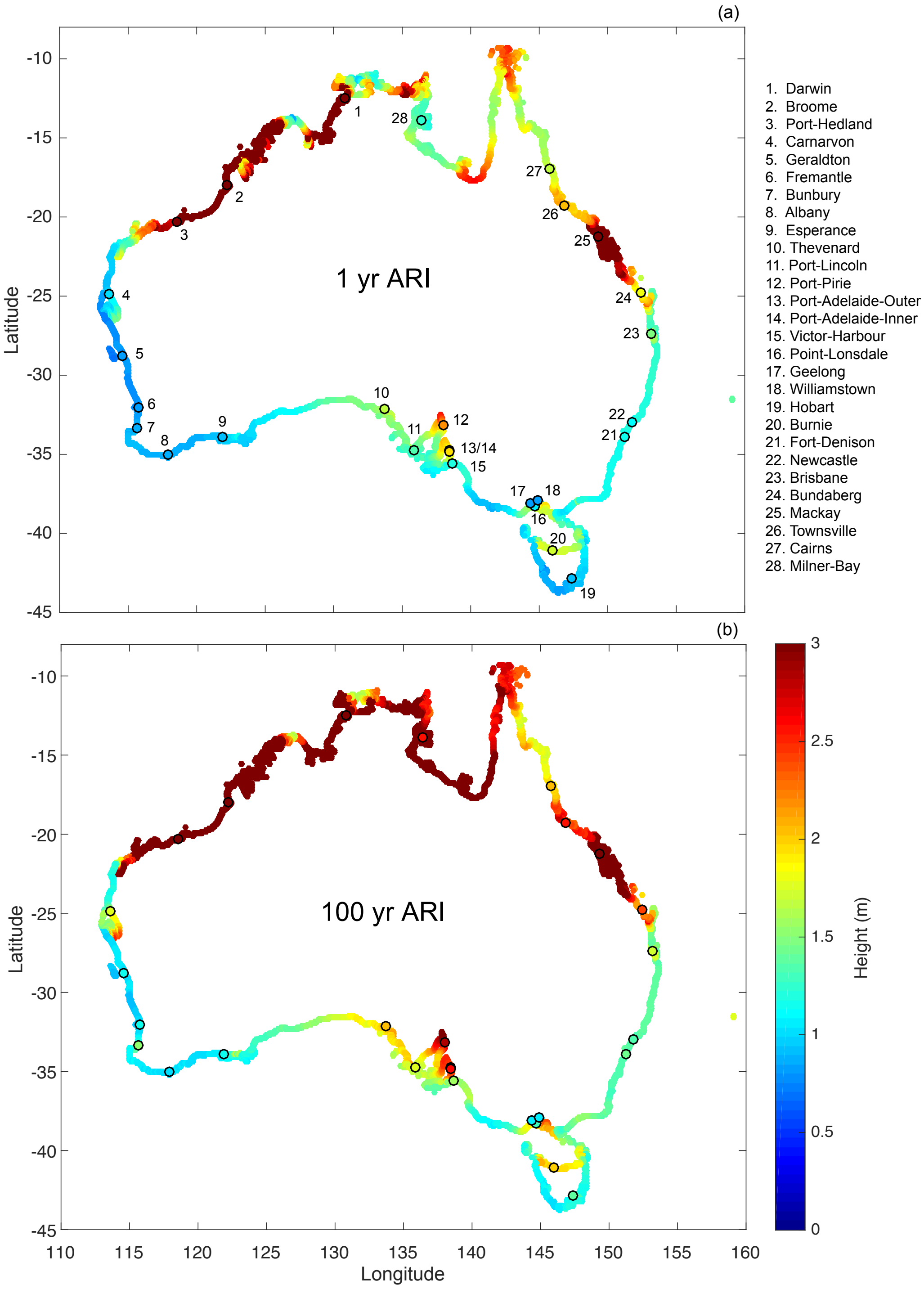

FIGURE 10. ESTIMATES OF 1YEAR AND 100 YEAR TOTAL SEA LEVEL ARI AROUND THE AUSTRALIAN COASTLINE DERIVED FROM THE NUMERICAL MODEL (COLOURED DOTS) AND TIDE GAUGE OBSERVATIONS (BLACK BORDERED CIRCLES).

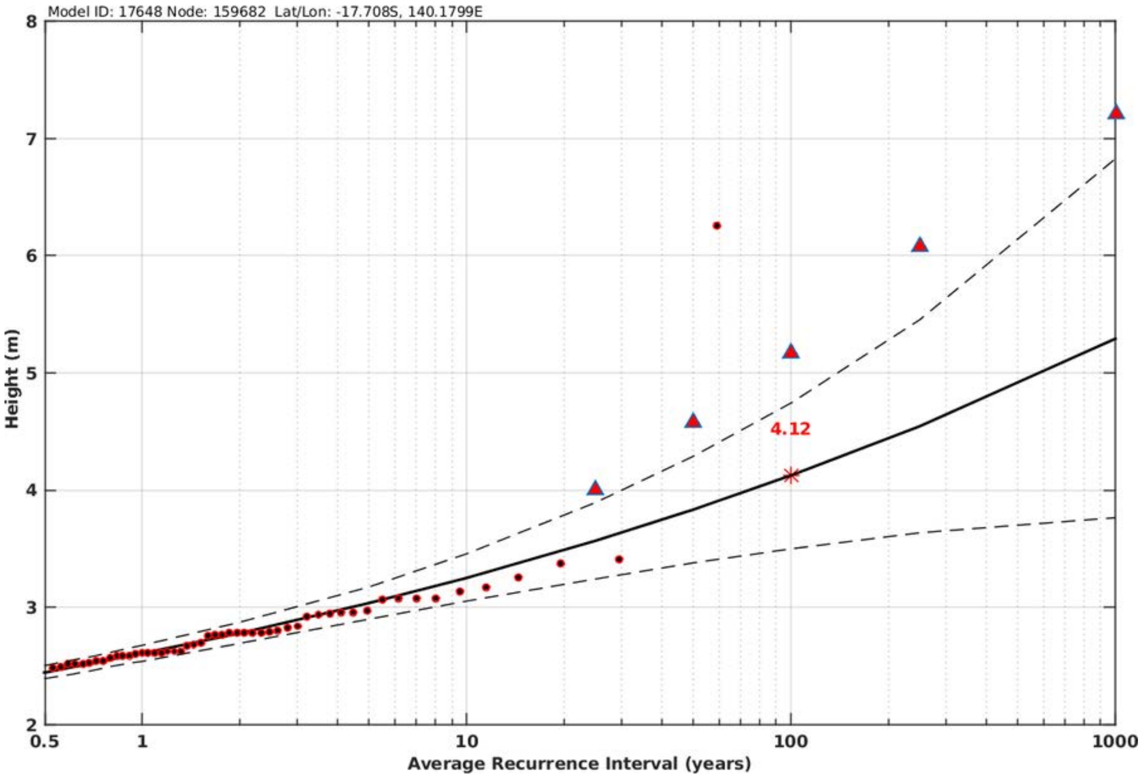

FIGURE 11. AVERAGE RECURRENCE INTERVAL (ARI) CURVE DERIVED FROM THE SCHISM MODEL FOR A SITE NEAR KARUMBA IN THE GULF OF CARPENTERIA. THE HEIGHT OF SEA LEVEL (Y-AXIS) IS SHOWN RELATIVE TO GIVEN ARI IN YEARS (X-AXIS). THE THE BLACK DOTS REPRESENT MODEL SEA LEVEL ANNUAL MAXIMUMS AND THE RED TRIANGLES INDICATE ARI VALUES CONTAINED IN THE SYNTHETIC TROPICAL SYCLONE HAIGH ET AL. 2014 DATASET WHERE THEY EXCEED THE BLACK CURVE

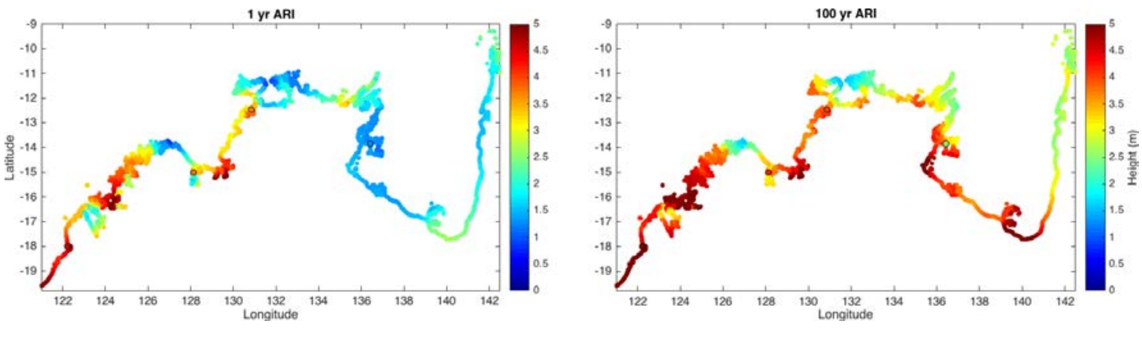

FIGURE 12. ESTIMATES OF 1YEAR AND 100 YEAR TOTAL SEA LEVEL ARI FOR NORTHERN AUSTRALIA DERIVED FROM THE NUMERICAL MODEL (COLOURED DOTS) AND TIDE GAUGE OBSERVATIONS (BLACK BORDERED CIRCLES).

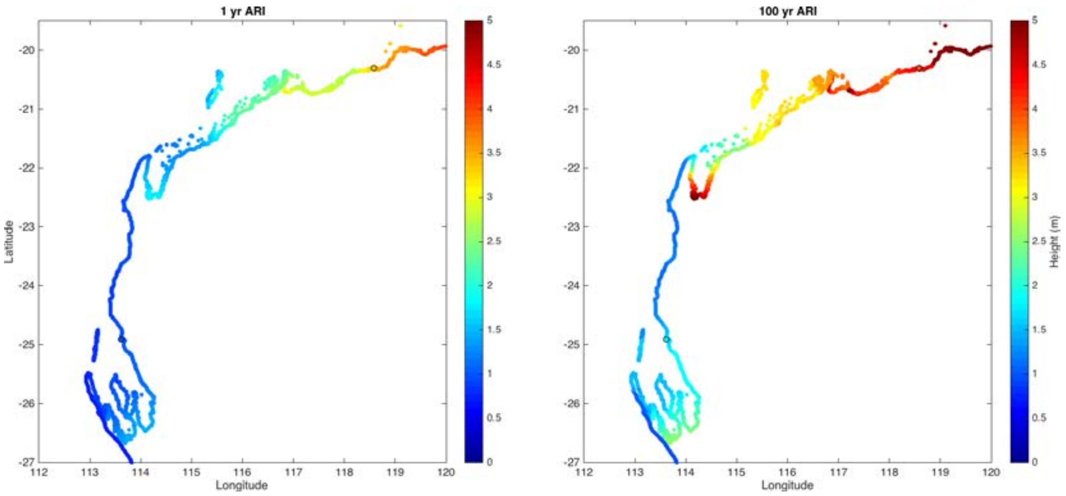

FIGURE 13. ESTIMATES OF 1YEAR AND 100 YEAR TOTAL SEA LEVEL ARI FOR NW WESTERN AUSTRALIA DERIVED FROM THE NUMERICAL MODEL (COLOURED DOTS) AND TIDE GAUGE OBSERVATIONS (BLACK BORDERED CIRCLES).

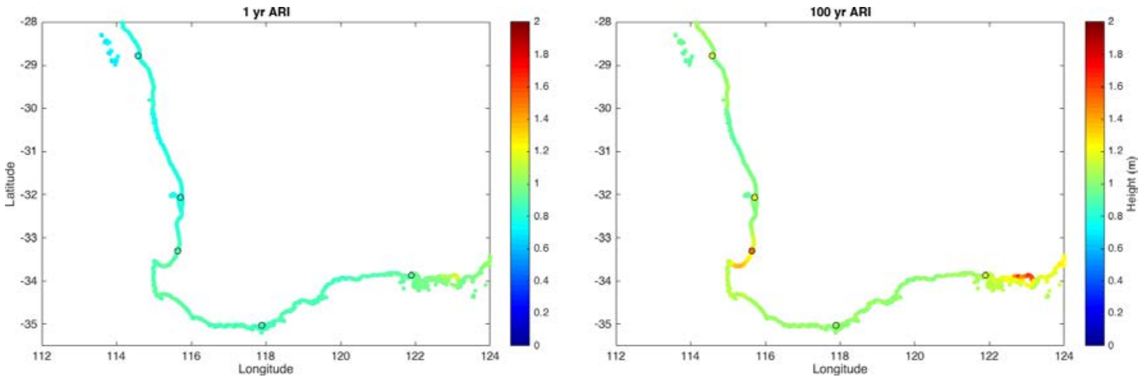

FIGURE 14. ESTIMATES OF 1YEAR AND 100 YEAR TOTAL SEA LEVEL ARI FOR SW WESTERN AUSTRALIA DERIVED FROM THE NUMERICAL MODEL (COLOURED DOTS) AND TIDE GAUGE OBSERVATIONS (BLACK BORDERED CIRCLES).

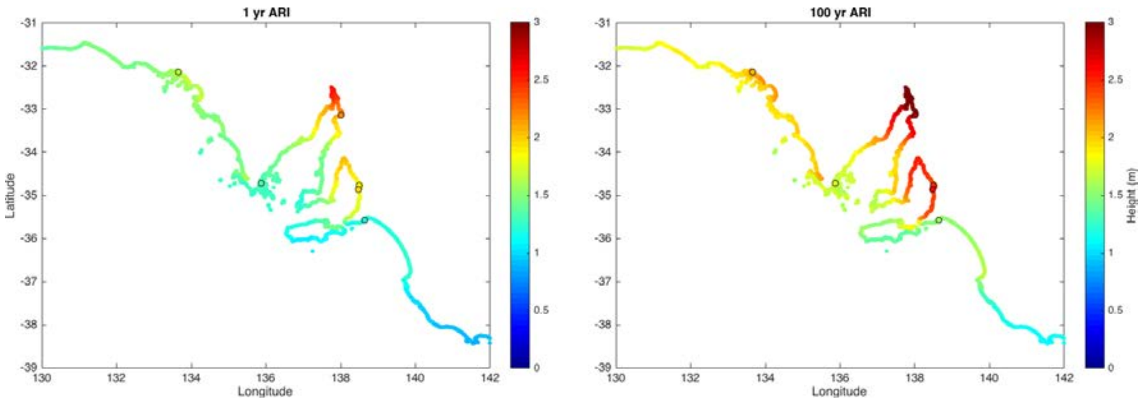

FIGURE 15. ESTIMATES OF 1YEAR AND 100 YEAR TOTAL SEA LEVEL ARI FOR SOUTH AUSTRALIA DERIVED FROM THE NUMERICAL MODEL (COLOURED DOTS) AND TIDE GAUGE OBSERVATIONS (BLACK BORDERED CIRCLES).

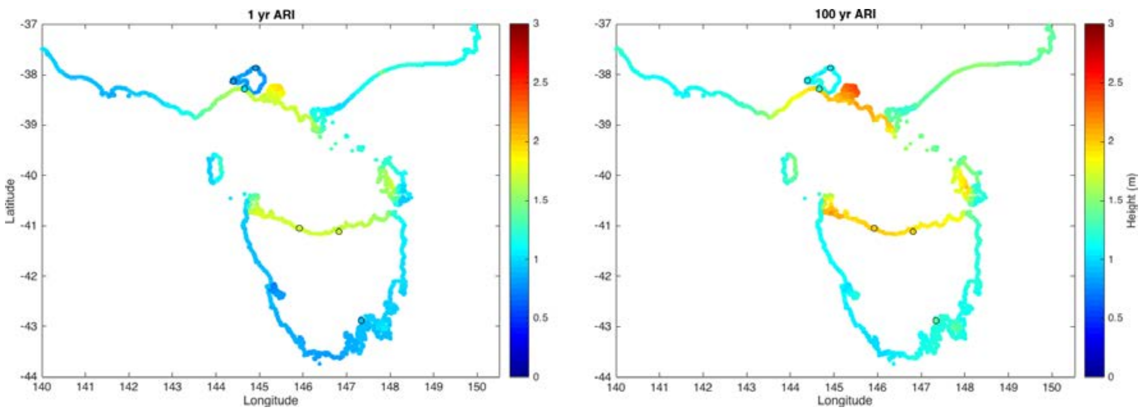

FIGURE 16. ESTIMATES OF 1YEAR AND 100 YEAR TOTAL SEA LEVEL ARI FOR SOUTH EAST AUSTRALIA DERIVED FROM THE NUMERICAL MODEL (COLOURED DOTS) AND TIDE GAUGE OBSERVATIONS (BLACK BORDERED CIRCLES).

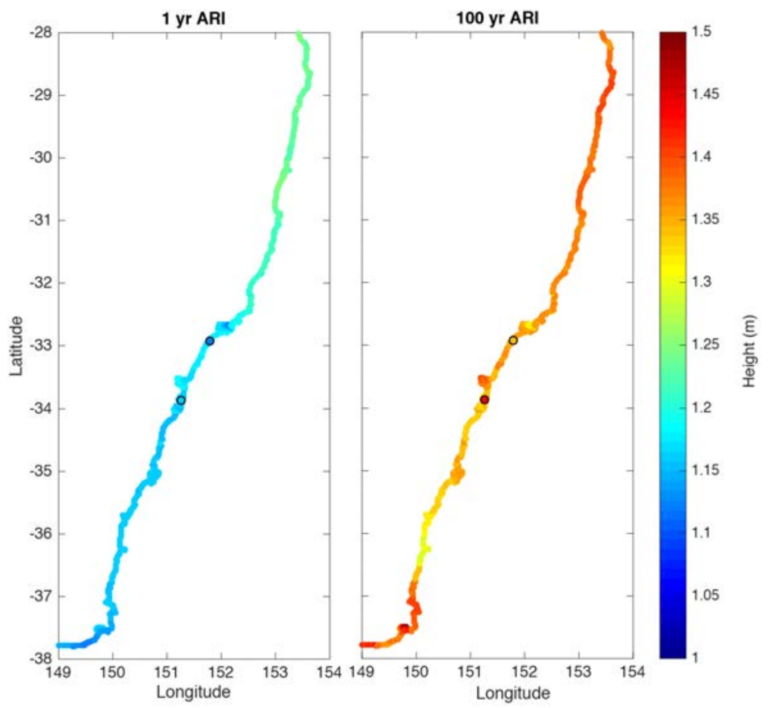

FIGURE 17. ESTIMATES OF 1YEAR AND 100 YEAR TOTAL SEA LEVEL ARI FOR NSW DERIVED FROM THE NUMERICAL MODEL (COLOURED DOTS) AND TIDE GAUGE OBSERVATIONS (BLACK BORDERED CIRCLES).

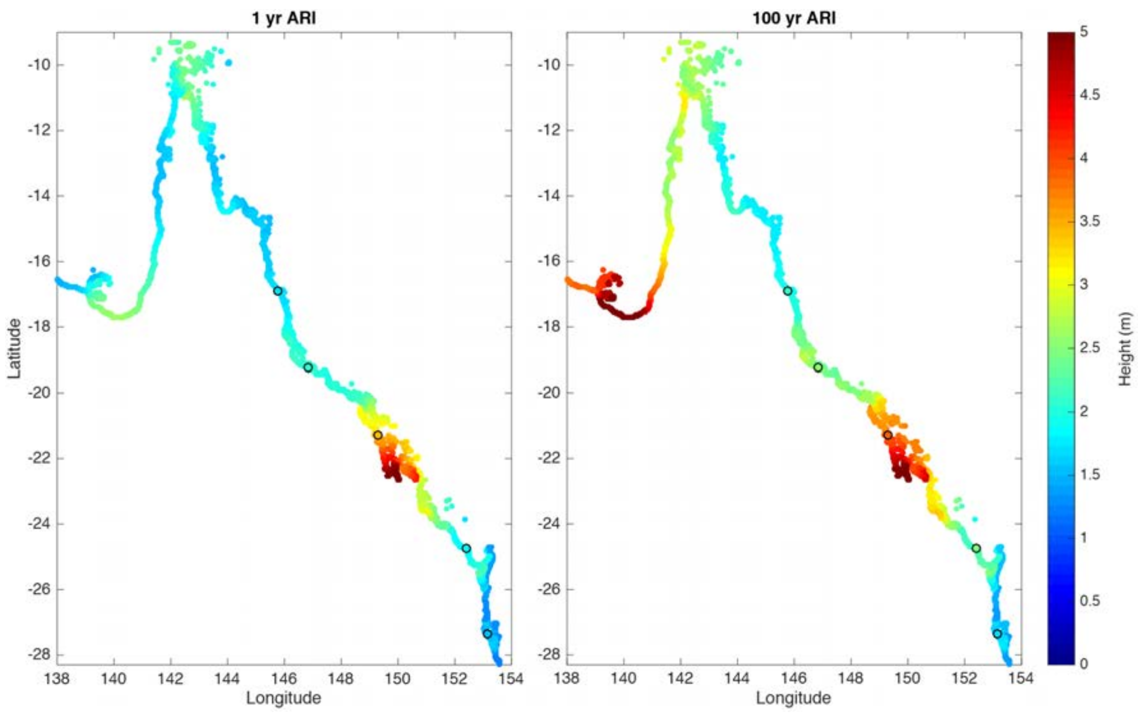

FIGURE 18. ESTIMATES OF 1YEAR AND 100 YEAR TOTAL SEA LEVEL ARI FOR QUEENSLAND DERIVED FROM THE NUMERICAL MODEL (COLOURED DOTS) AND TIDE GAUGE OBSERVATIONS (BLACK BORDERED CIRCLES).

WEBSITE

The major outcome from the BNHCRC extreme sea level project is a website (www.ozsealevelx.org (Figure 19) aimed at making the extreme sea level statistics and data easily available to a broad range of end users. The website consist of an interactive map showing the 100 year ARI as coloured dots spaced at 2 km around the coastline, including islands. The user can click on any of these 31479 points (e.g. Figure 20; Figure 21) to access 1 and 100 year ARI levels as well as a number of plots showing more details of the extremes, including: ARI curves (Figure 22); seasonal variability (Figure 23); monthly histograms (Figure 24); and submergence curves (Figure 25) showing the percentage of time certain levels are exceeded. Combined pdf files containing all plots are also available for download. Equivalent plots are also available at select tide gauge sites (blue markers) so that the user can compare the statistics derived from the model with those based on observations (Figure 26). Finally, hourly sea level time series data (model) can be downloaded as netCDF files by clicking on the link provided (Figure 27).

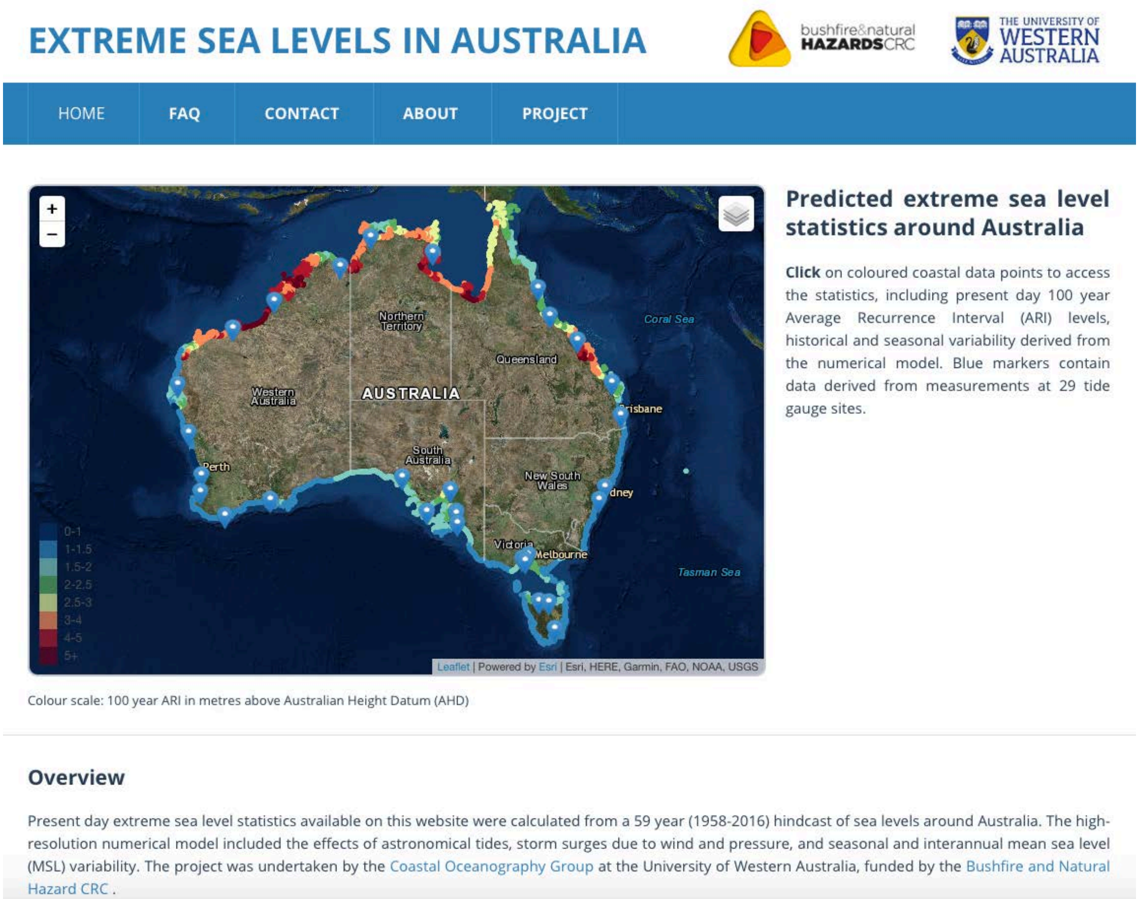

FIGURE 19 SCREEN SHOT OF THE EXTREME SEA LEVEL WEBSITE DEVELOPED DURING THE BNHCRC PROJECT " IMPROVED PREDICTIONS OF EXTREME SEA LEVELS. THE INTERACTIVE MAP ALLOWS FOR THE USER TO EXTRACT EXTREME SEA LEVEL STATISTICS, VIEW PLOTS AND DOWNLOAD TIME SERIES DATA AT 31479 COASTAL DATA POINTS.

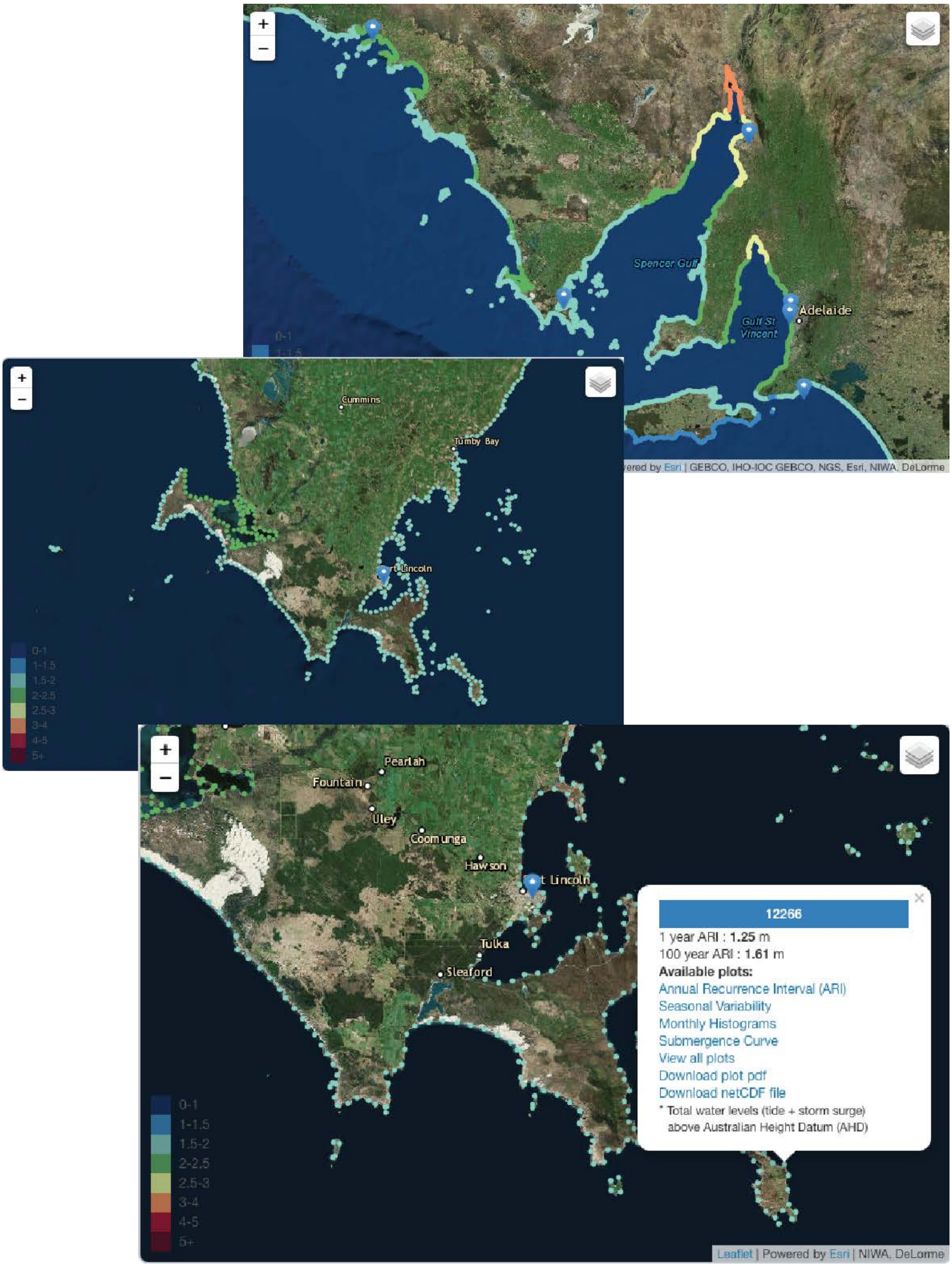

FIGURE 20. ZOOM VIEW OF SOUTH AUSTRALIA SHOWING THE INTERACTIVE MAP AVAILABLE ON THE UWA/BMHCRC EXTREME SEA LEVEL WEBSITE ILLUSTRATING AVAILABLE STATISTICS AND PLOTS AT EACH COASTAL DATA POINT.

FIGURE 21. ZOOM VIEW OF NW WESTERN AUSTRALIA SHOWING THE INTERACTIVE MAP AVAILABLE ON THE UWA/BMHCRC EXTREME SEA LEVEL WEBSITE ILLUSTRATING AVAILABLE STATISTICS AND PLOTS AT EACH COASTAL DATA POINT.

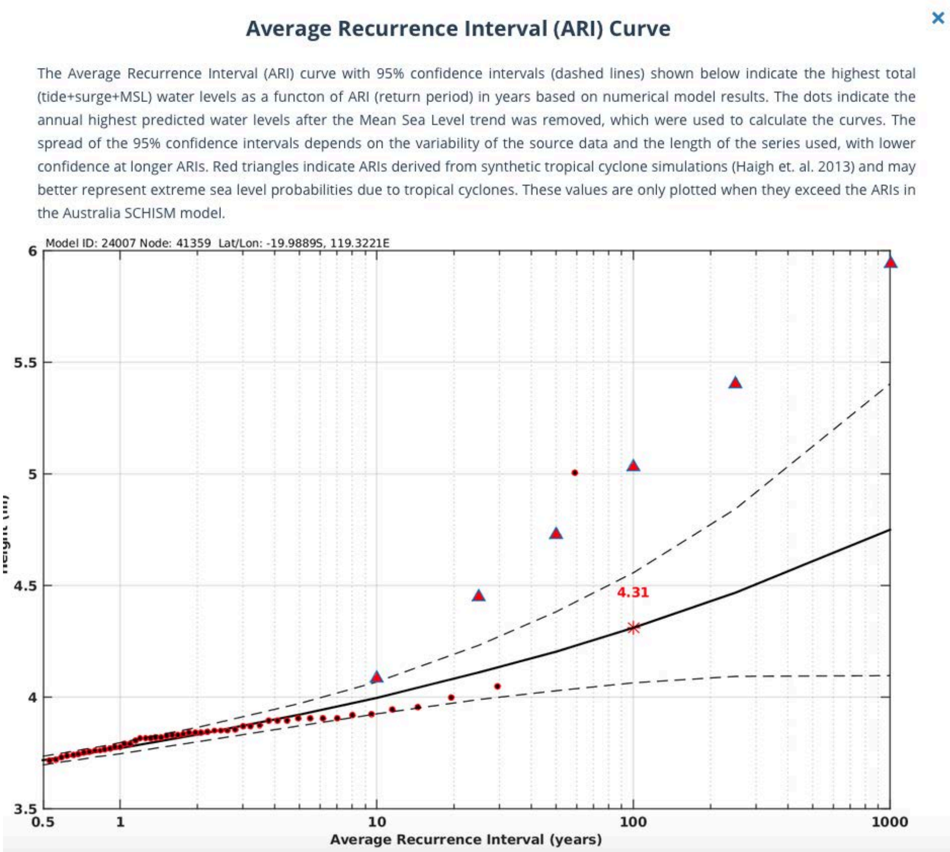

FIGURE 22. EXAMPLE PLOT OF ARI CURVE AVAILABLE FOR EACH COASTAL DATA POINT ON UWA/BNHCRC EXTREME SEA LEVEL WEBSITE WITH EXPLANATION OF CONTENTS.

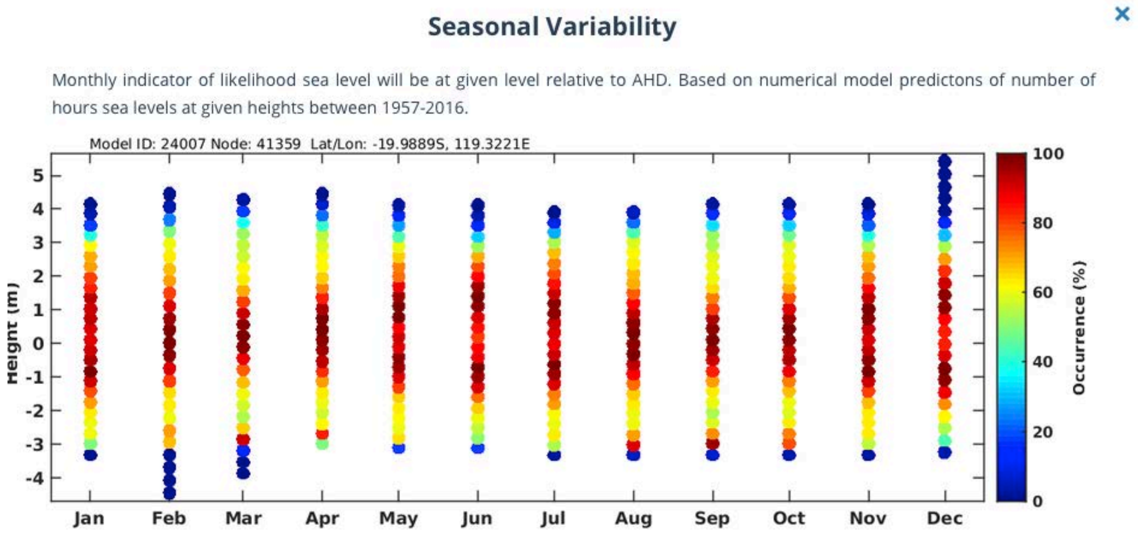

FIGURE 23. EXAMPLE PLOT OF SEASONAL VARIABILITY AND LIKELYHOOD OF OCCURRENCE AVAILABLE FOR EACH COASTAL DATA POINT ON UWA/BNHCRC EXTREME SEA LEVEL WEBSITE.

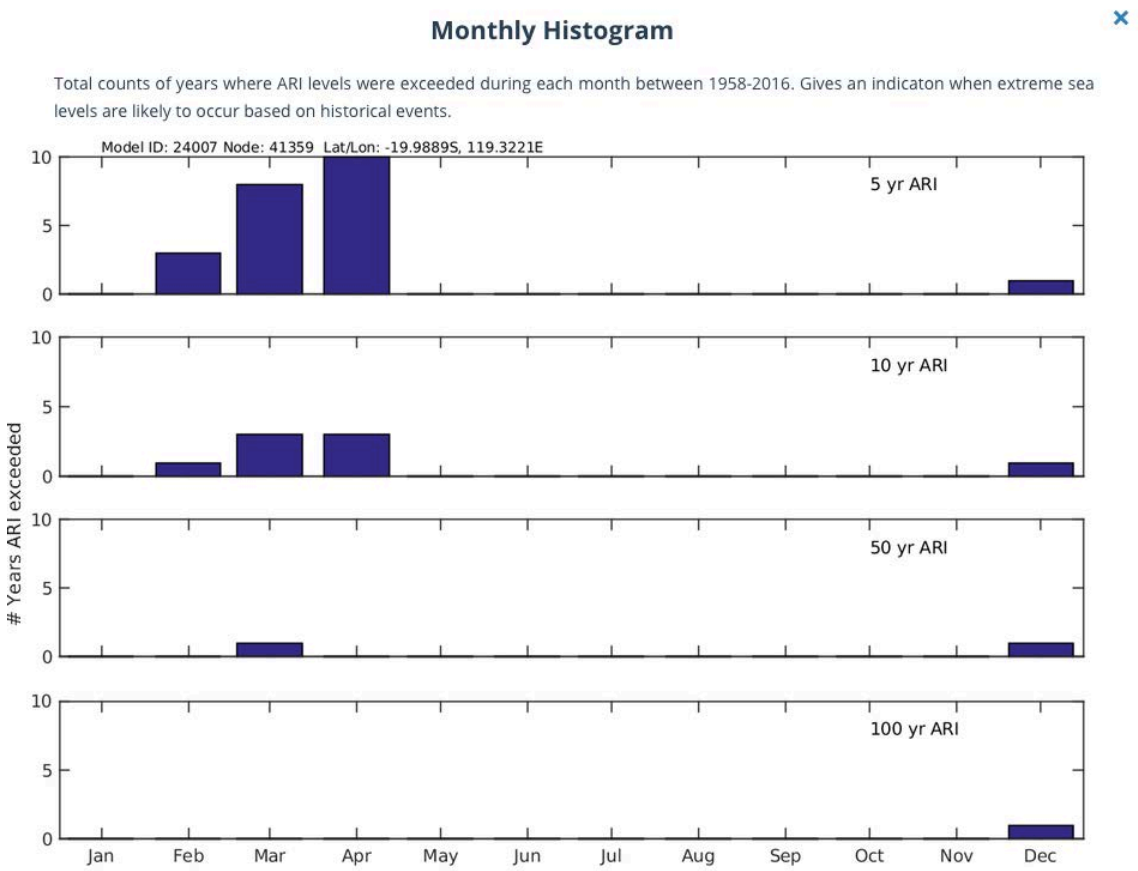

FIGURE 24. HISTOGRAM AVAILABLE ON THE UWA/BNHCRC WEBSITE INDICATING WHEN ARI LEVELS WERE EXCEEDED BETWEEN 1958-2016 IN THE SCHISM NUMERICAL MODEL SEALEVEL HINDCAST.

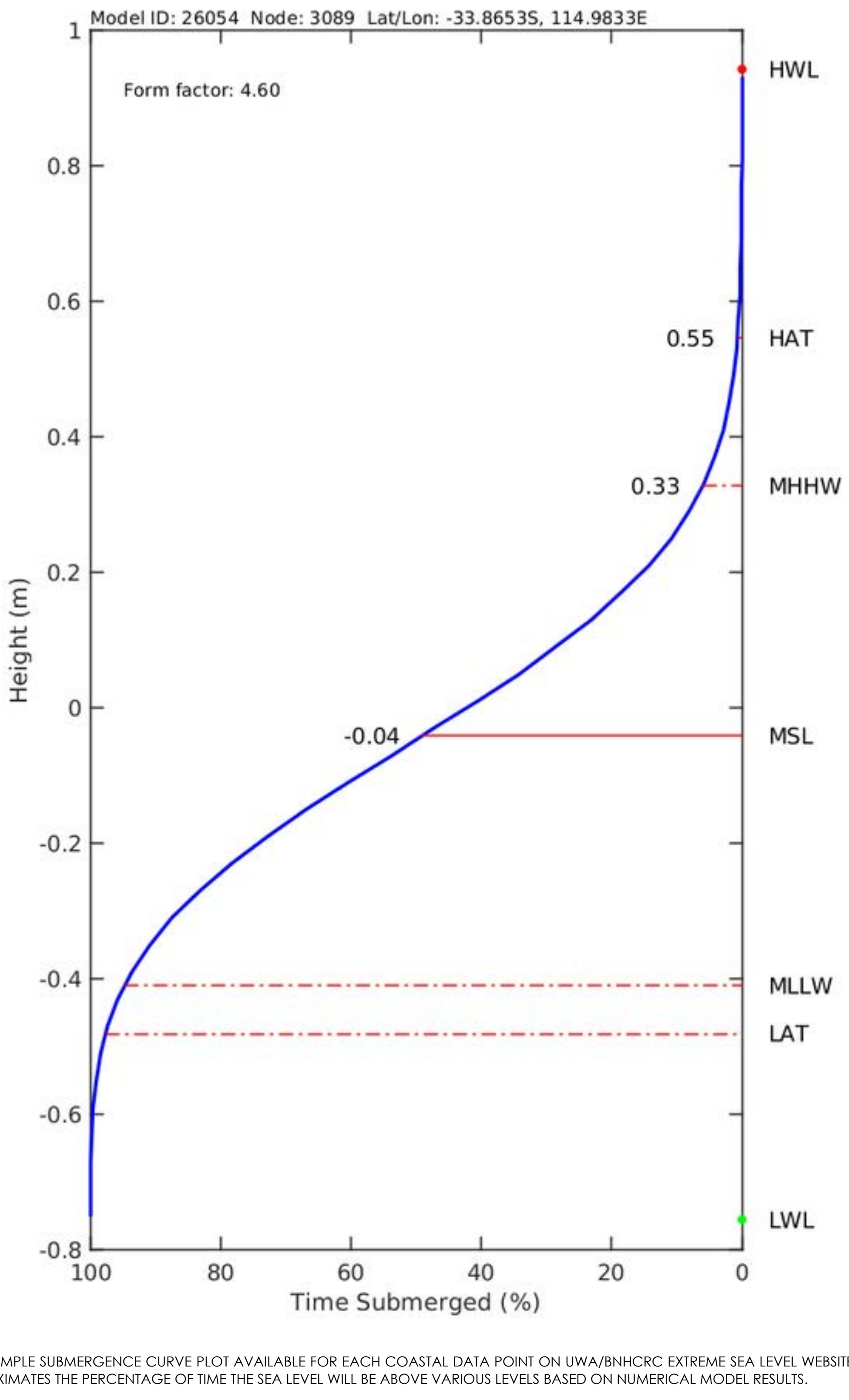

FIGURE 25. EXAMPLE SUBMERGENCE CURVE PLOT AVAILABLE FOR EACH COASTAL DATA POINT ON UWA/BNHCRC EXTREME SEA LEVEL WEBSITE. THE CURVE APPROXIMATES THE PERCENTAGE OF TIME THE SEA LEVEL WILL BE ABOVE VARIOUS LEVELS BASED ON NUMERICAL MODEL RESULTS.

Comparison with tide gauge data at select sites:

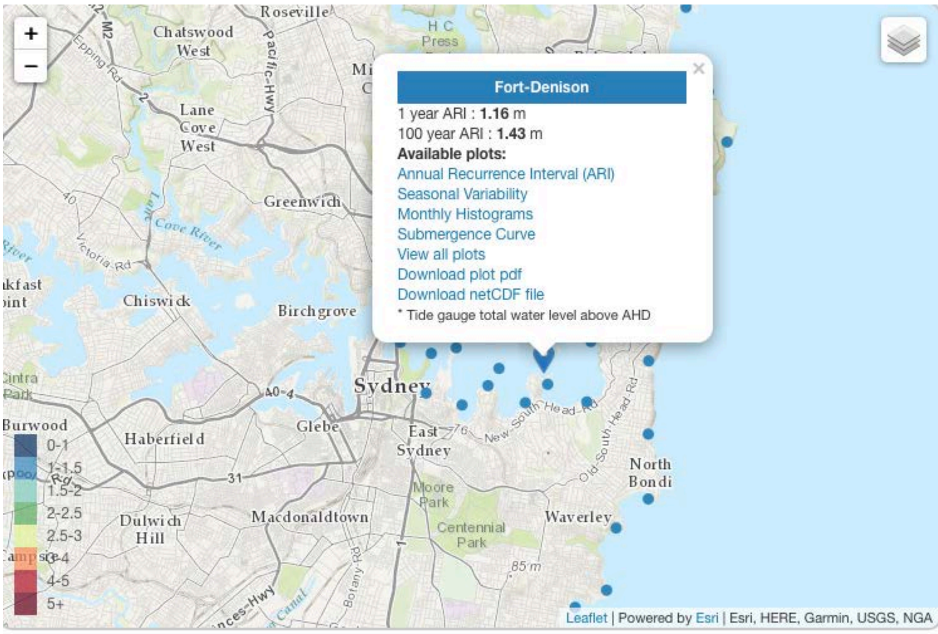

FIGURE 26. EXAMPLE POP-UP INFORMATION BOX SHOWING EXTREME SEALEVEL STATISTICS BASED ON TIDE GAUGE DATA AT SELECT SITES ENABLING THE USER TO COMPARE MODEL WITH OBSERVATIONS.

Data download option for model time series

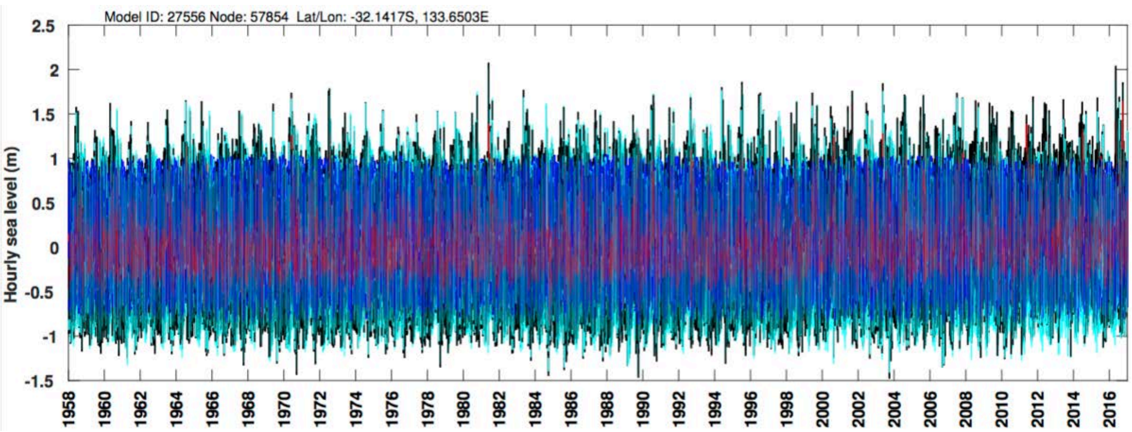

FIGURE 27. EXAMPLE TIME SERIES HOURLY DATA AVAILABLE FOR DOWNLOAD AT EACH COASTAL DATA POINT FROM THE UWA/BNHCRC WEBSITE. HERE, TIDAL ANALYSIS HAS BEEN PERFORMED ON THE DATA AND PLOTTED ARE: MSL ADJUSTED TOTAL WATER LEVELS (BLACK), PREDICTED TIDES (DARK BLUE), AND NON-TIDAL RESIDUALS (RED), AND RAW MODEL DATA (CYAN).

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