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IMPROVED PREDICTIONS OF EXTREME SEA LEVELS AROUND AUSTRALIA

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ABSTRACT

IMPROVED PREDICTIONS OF EXTREME SEA LEVELS AROUND AUSTRALIA

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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 was applied to the sea level data to predict Average Recurrence Intervals (ARI) at ~2km 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.

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].

With rising sea levels, damaging 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 ~2km 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 extended abstract 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 [1, 2] has successfully simulated circulation and storm surges in a broad range of coastal environments [3-6]. Other applications of the model include tsunami inundation [7] oil spill [8], and ecological studies [9]. 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) [1]. The benefits of using SCHISM for cross scale modeling are described in detail in [2]. 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 [10]. 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. 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.

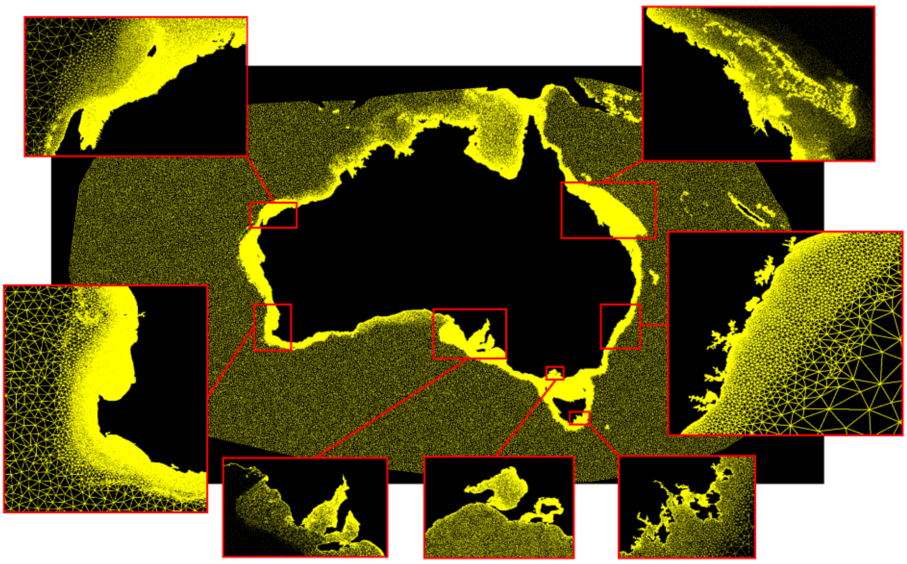

FIGURE 1. SCHISM NUMERICAL MODEL DOMAIN WITH SUBSETS ILLUSTRATING HIGHER RESOLUTION AT THE COAST. SPATIAL RESOLUTION AT THE COAST RANGED FROM 100 TO 800 METRES AND DECREASED OFFSHORE.

Forcing

The recently released Japanese Reanalysis JRA-55 reanalysis atmospheric model [11-15] 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 [12] dataset (1958-present) accurately reproduces broad scale synoptic and climate variability [15]. The eight primary harmonic tidal constituents (M2,S2,K2,N2,K1,O1,P1,Q1) from the 1/30 degree TPXO08 Atlas *[16]* (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 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. [17].Multi decadal simulations (1958-2016)

Multi-decadal model runs

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 evenly spaced at 2 km intervals along the entire coastline of Australia including islands. These total sea level data were adusted to include accurate seasonal variations using satellite altimetry and were validated against tide gauge observations. The data were archived for each coastal data point as individual netCDF files available through the website.

Extreme value analysis

Extreme value theory is a statistical method that allows for the calculation of the probability of the occurrence of extreme events. 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 [18] 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.

The final extreme sea level products contained ARI levels that merged ARI values from Haigh et al. 2014 [19] in tropical cyclone affected areas with ARIs derived directly from the SCHISM model. Combining the two datasets in this way allowed for best estimate of extreme values all around Australia (Figure 5).

RESULTS

TIME SERIES

A subset of the data from around the continent is shown here to illustrate the model results (Figure 2). Main outputs are total sea levels that include tides, storm surges, and longer term sea level variability. Sea level extremes, 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 2) enable the identification of individual storm surge events, i.e. higher periods of water levels caused by high winds and reduced air pressure.

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 3) and non-tidal residuals (Figure 4) 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.

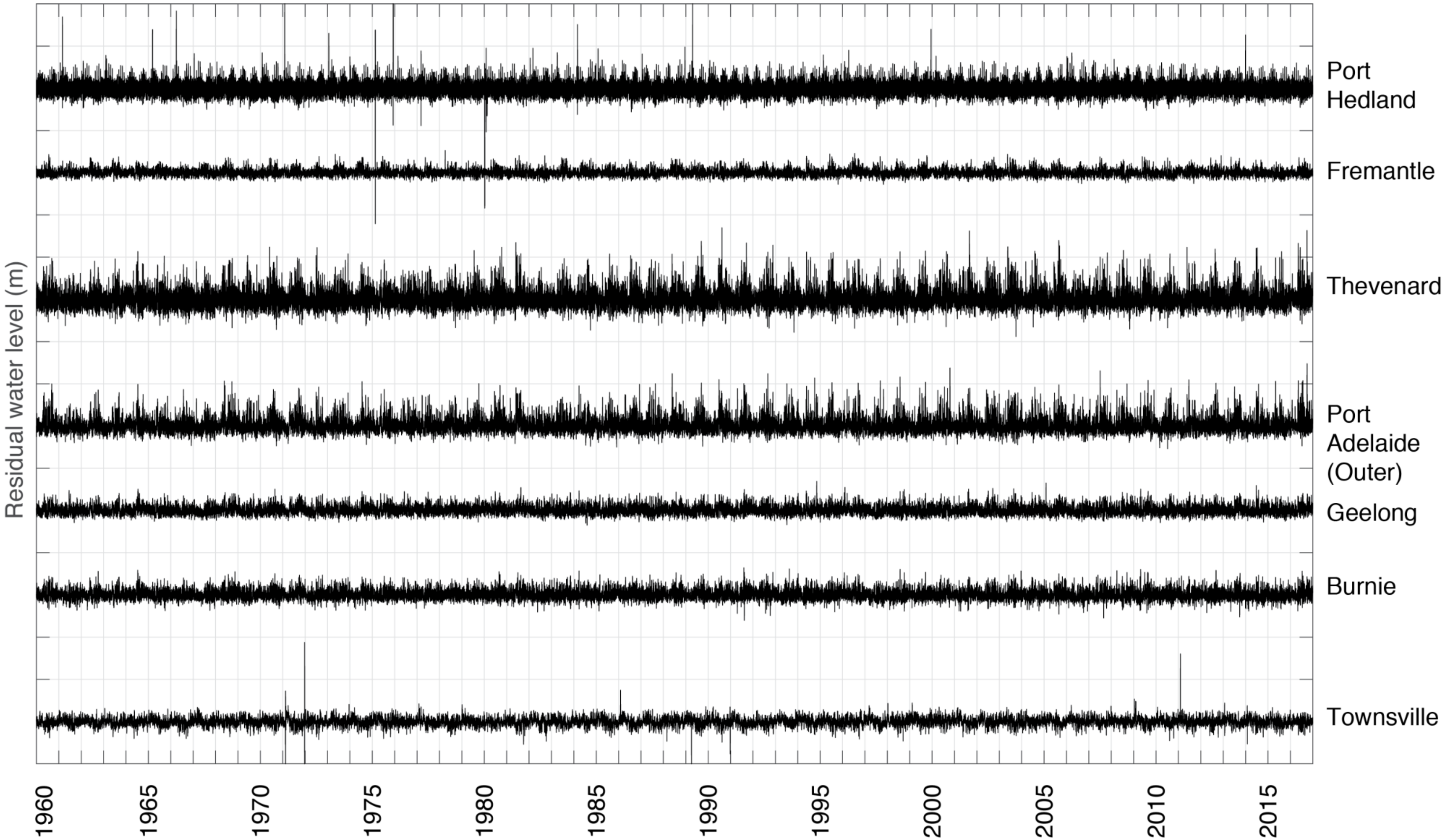

FIGURE 2. PREDICTED NON-TIDAL RESIDUAL SEA LEVELS AT A SELECTION OF SITES, STARTING IN PORT HEDLAND, WA AND MOVING ANTICLOCKWISE AROUND THE COAST. DATA ARE PLOTED WITH AN ARBITRARY OFFSET AND TICK MARKS AT 1 M INTERVALS ON THE Y-AXIS.

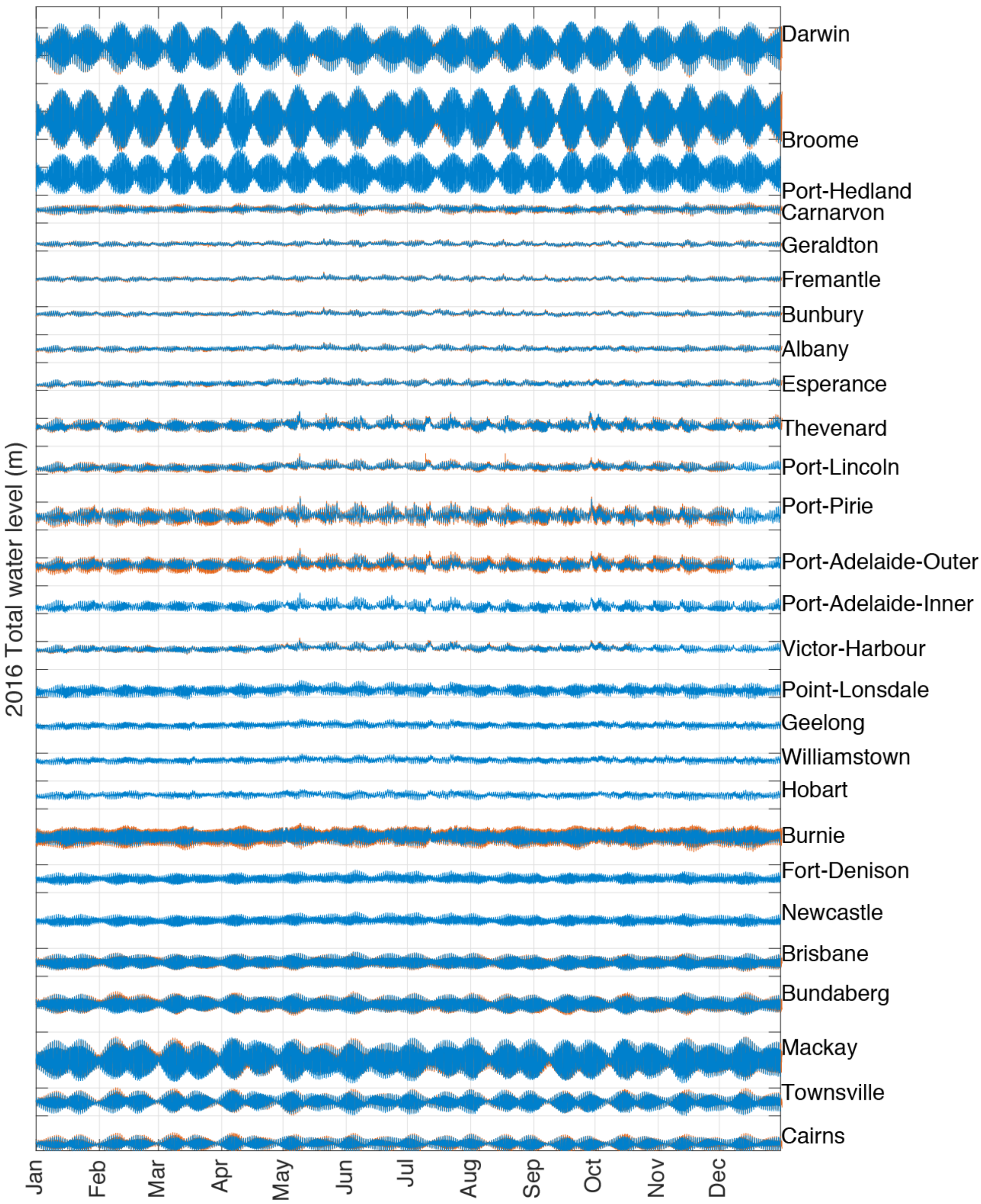

FIGURE 3. PREDICTED (BLUE) AND OBSERVED (ORANGE) TOTAL SEA LEVELS FOR 2016 PLOTTED WITH ARBITRARY OFFSET STARTING AT DARWIN AND MOVING ANTICLOCKWISE AROUND THE COAST. DATA ARE PLOTED WITH AN ARBITRARY OFFSET AND TICK MARKS AT 4 M INTERVALS ON THE Y-AXIS. THE EXTREME TIDAL RANGE VARIABILITY AROUND THE COAST CAN BE SEEN CLEARLY IN THE PLOT.

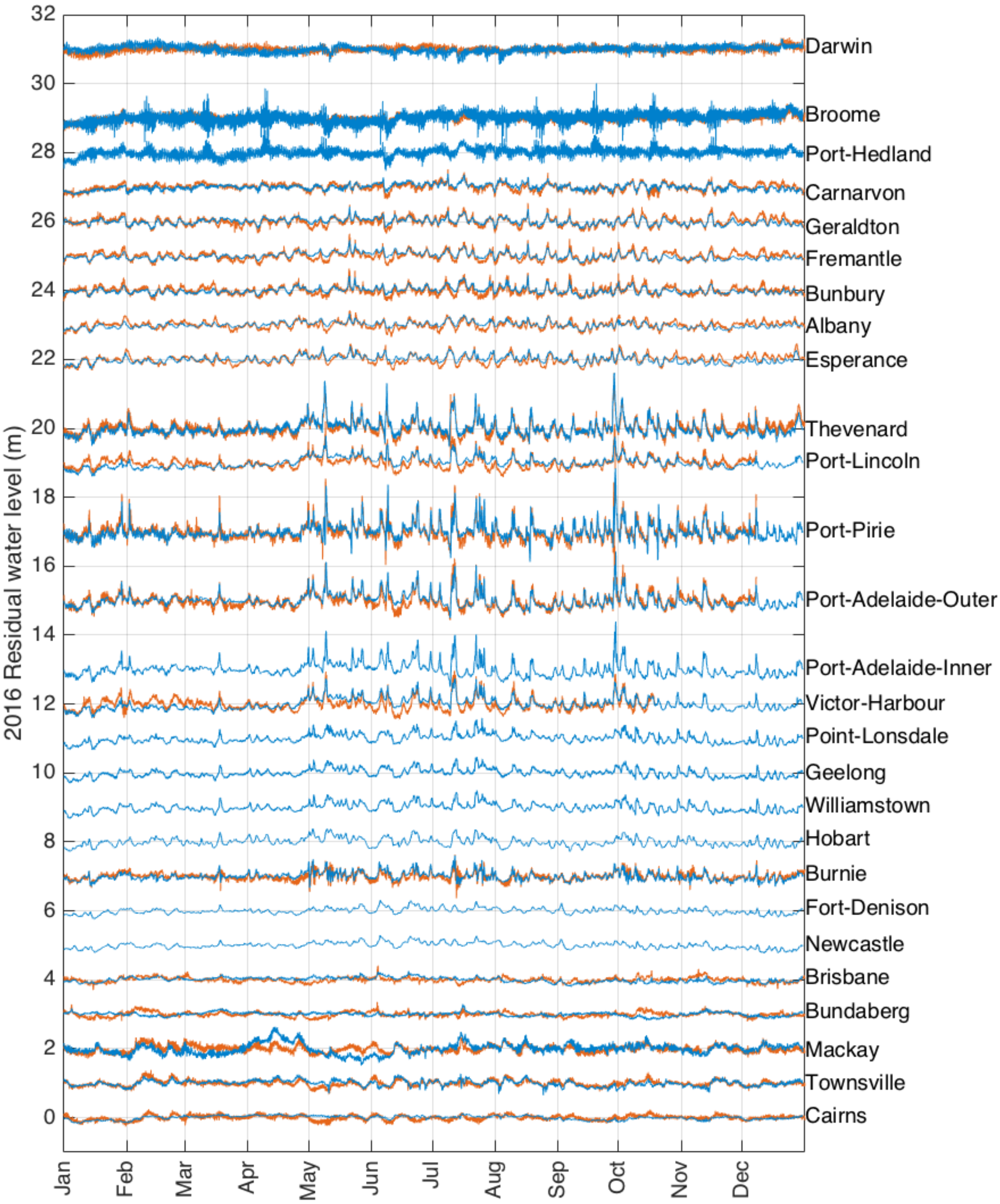

FIGURE 4. PREDICTED (BLUE) AND OBSERVED (ORANGE) NON-TIDAL RESIDUAL SEA LEVELS (STORM SURGE) FOR 2016 PLOTTED WITH ARBITRARY OFFSET STARTING AT DARWIN AND MOVING ANTICLOCKWISE AROUND THE COAST. DATA ARE PLOTED WITH AN ARBITRARY OFFSET. 2016 WAS ONE OF THE STORMIEST YEARS ON RECORD FOR SOUTH AUSTRALIA, 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. AVERAGE RECURRENCE INTERVALS AROUND AUSTRALIA.

AVERAGE RECURRENCE INTERVALS

Analysis of the sea level data included application of Extreme Value Theory to predict Average Recurrence Intervals (ARI) at ~2km spacing around the entire Australian coastline including islands (Figure 5). These results are publicly available though a website described in the following section.

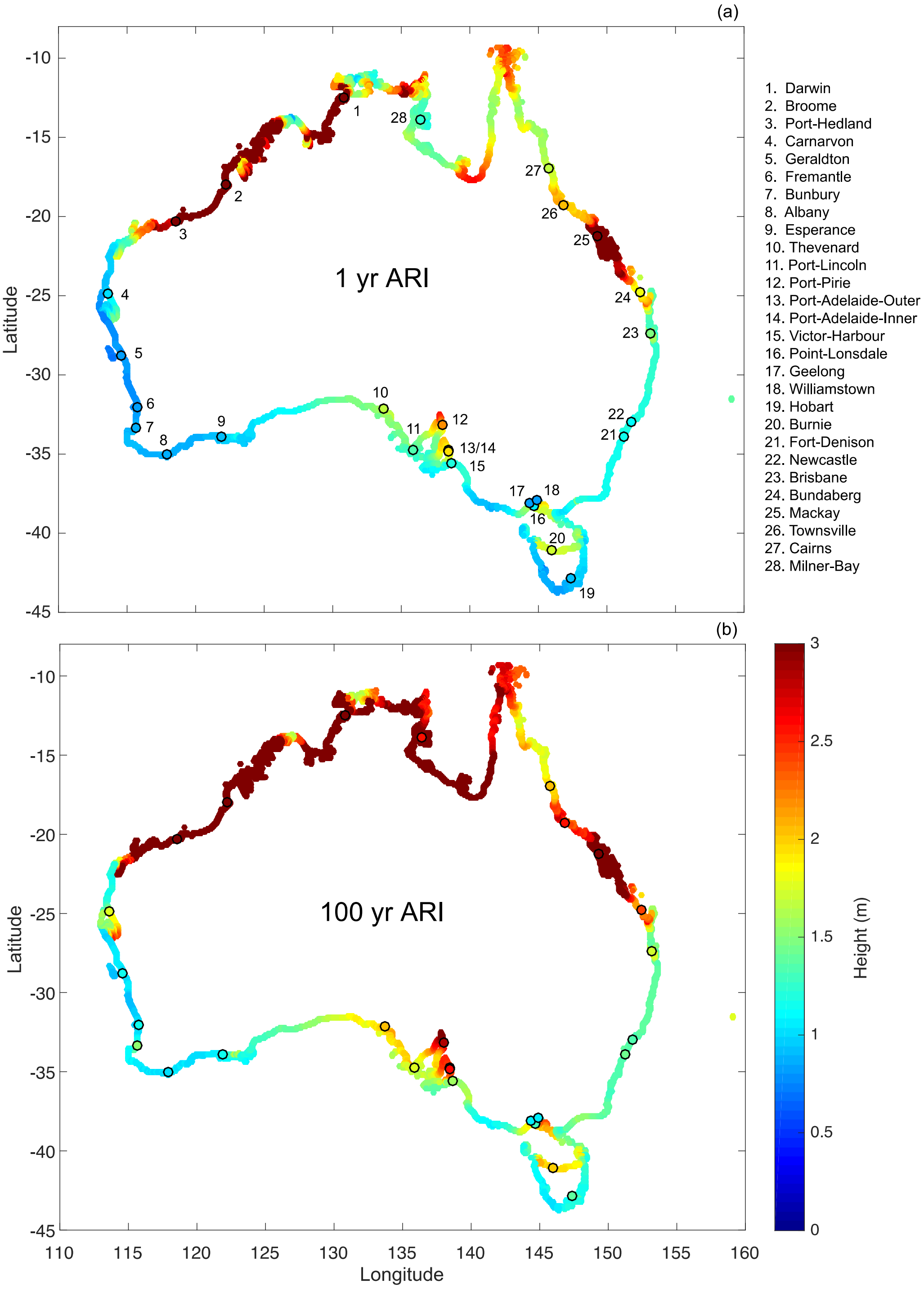

FIGURE 5. ESTIMATES OF 1YEAR AND 100 YEAR TOTAL SEA LEVEL ARI AROUND THE AUSTRALIAN COASTLINE DERIVED FROM THE NUMERICAL MODEL (COLOURED DOTS) AND TIDE GAUGE OBSERVATIONS (BLACK BORDERED CIRCLES).

WEBSITE

The major outcome from the BNHCRC extreme sea level project is a website (www.ozsealevelx.org) (Figure 6) 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 1 km around the coastline, including islands. The user can click on any of these 31479 points (e.g. Figure 7) 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 8); seasonal variability (Figure 9); monthly histograms (Figure 10); and submergence curves (Figure 11) 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 12). Finally, hourly sea level time series data (model) can be downloaded as netCDF files by clicking on the link provided (Figure 13).

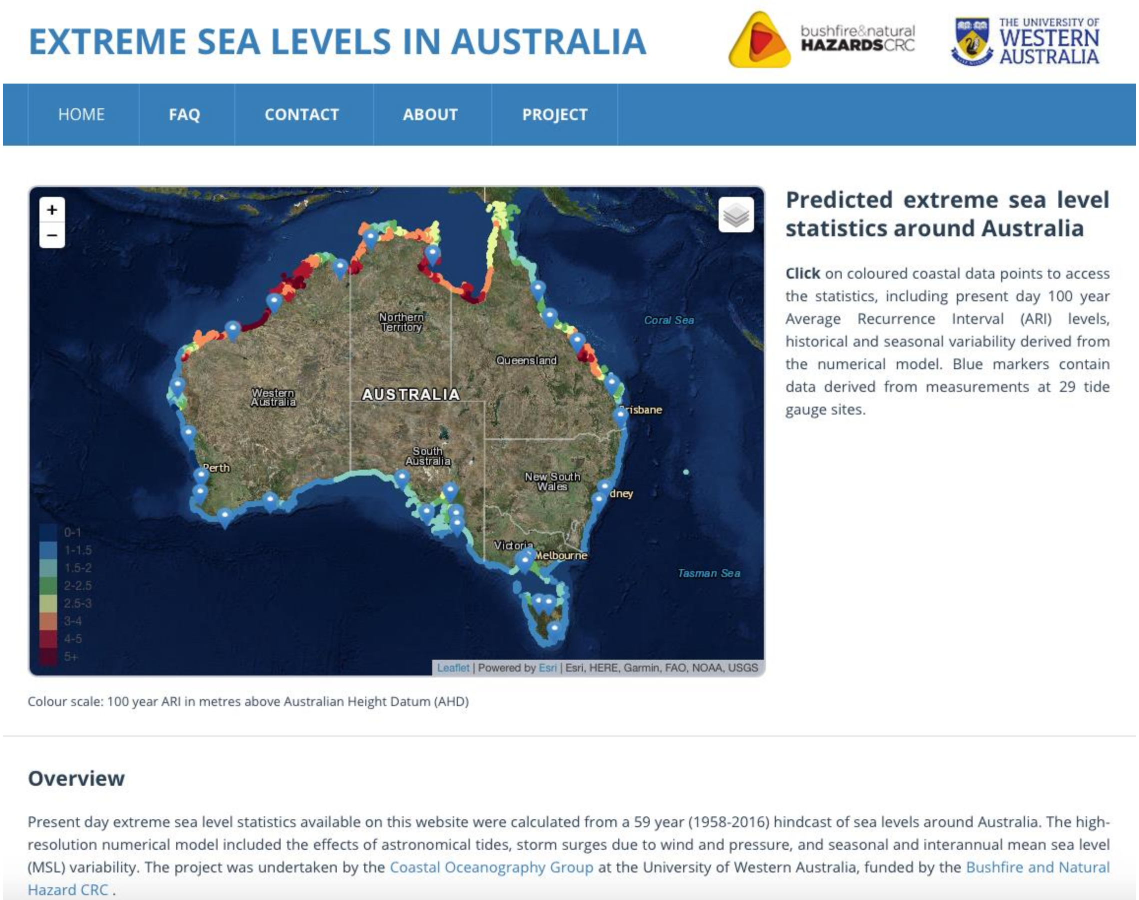

FIGURE 6 SCREEN SHOT OF THE EXTREME SEA LEVEL WEBSITE DEVELOPED DURING THE BNHCRC PROJECT " IMPROVED PREDICTIONS OF EXTREME SEA LEVELS. THE INTERACTIVE MAP ALLOWS FOR THE USER TO EXTRACT EXTREME SEA LEVEL STATISTICS, VIEW PLOTS AND DOWNLOAD TIME SERIES DATA AT 31479 COASTAL DATA POINTS.

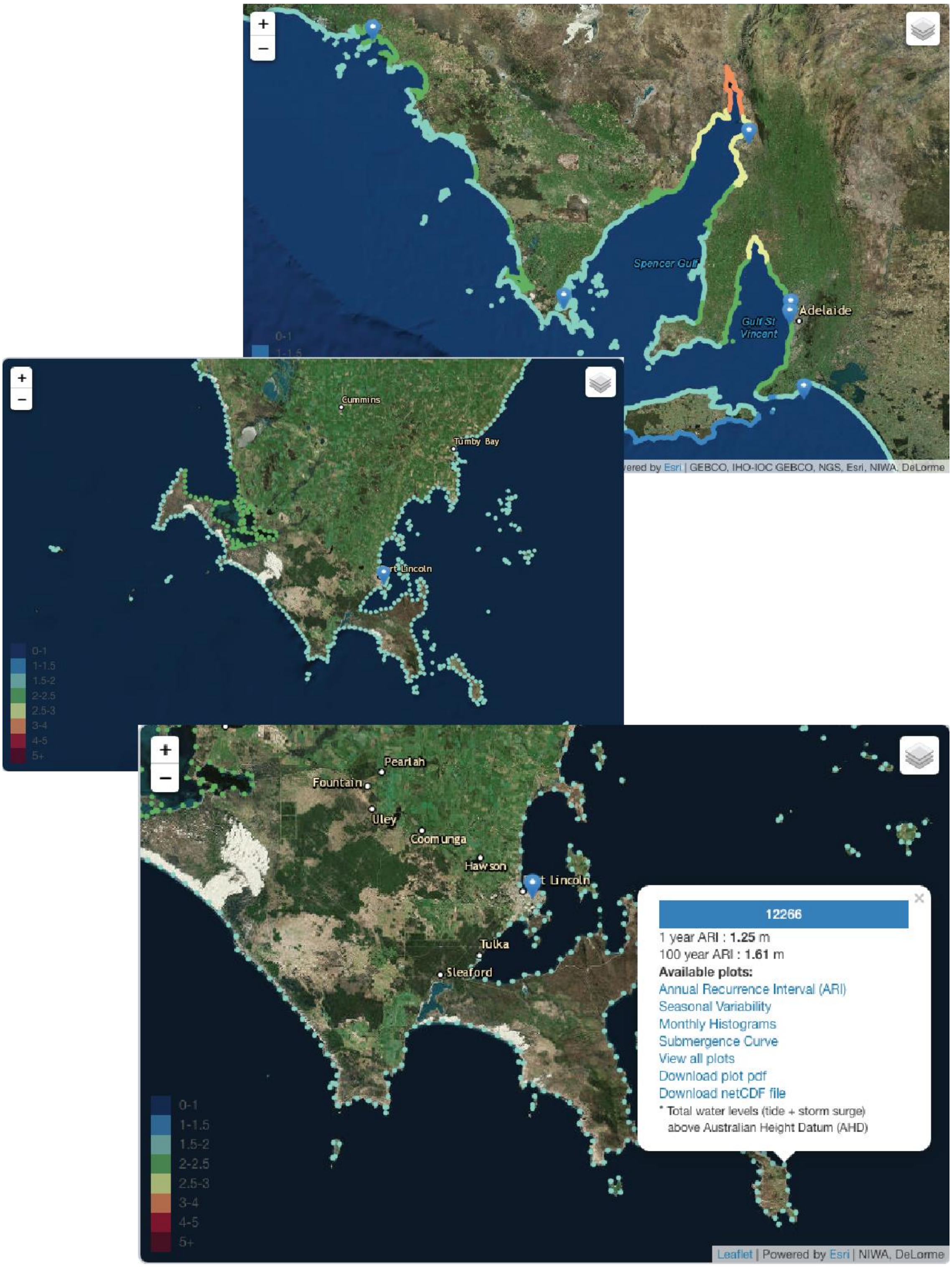

FIGURE 7. ZOOM VIEW OF SOUTH AUSTRALIA SHOWING THE INTERACTIVE MAP AVAILABLE ON THE UWA/BMHCRC EXTREME SEA LEVEL WEBSITE ILLUSTRATING AVAILABLE STATISTICS AND PLOTS AT EACH COASTAL DATA POINT.

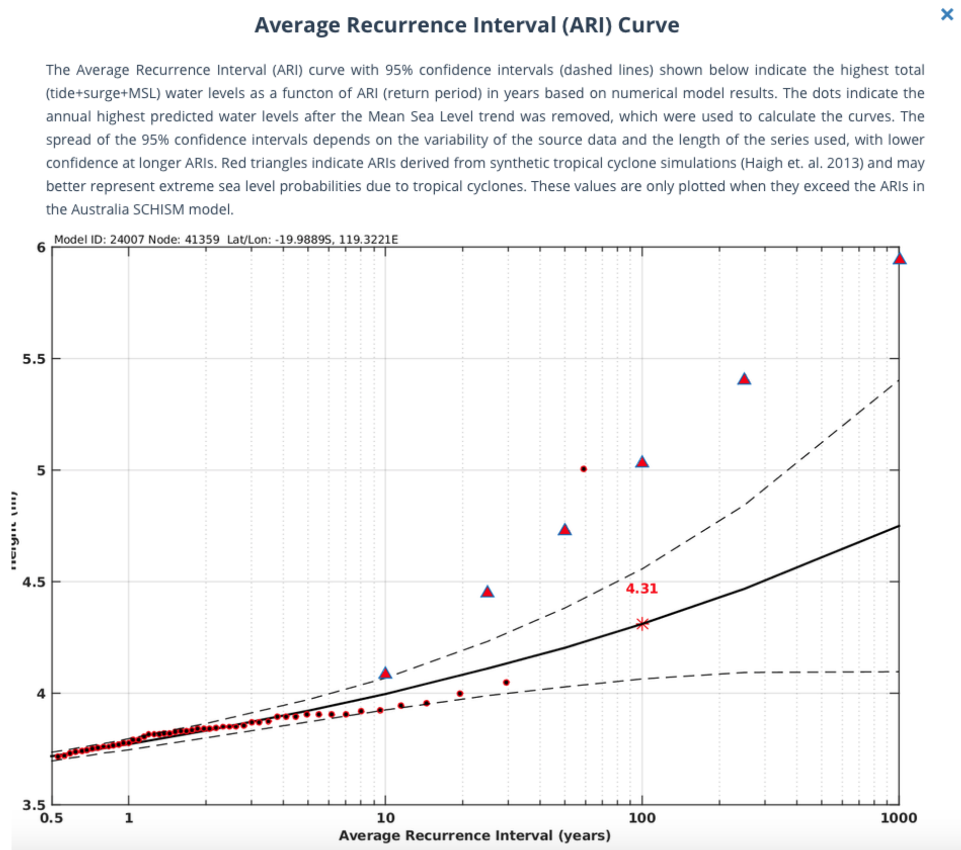

FIGURE 8. EXAMPLE PLOT OF ARI CURVE AVAILABLE FOR EACH COASTAL DATA POINT ON UWA/BNHCRC EXTREME SEA LEVEL WEBSITE WITH EXPLANATION OF CONTENTS.

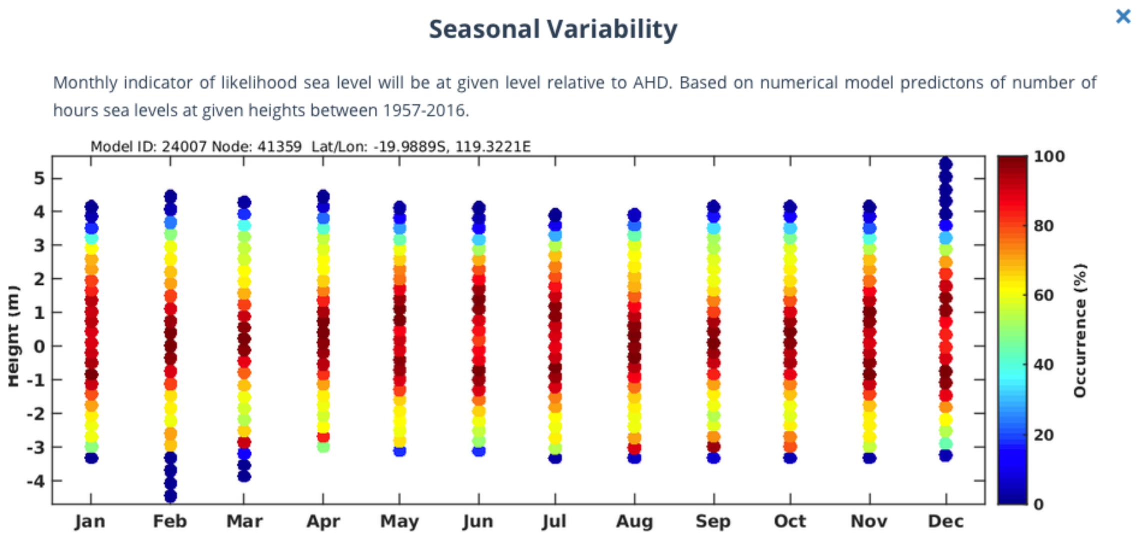

FIGURE 9. EXAMPLE PLOT OF SEASONAL VARIABILITY AND LIKELYHOOD OF OCCURRENCE AVAILABLE FOR EACH COASTAL DATA POINT ON UWA/BNHCRC EXTREME SEA LEVEL WEBSITE.

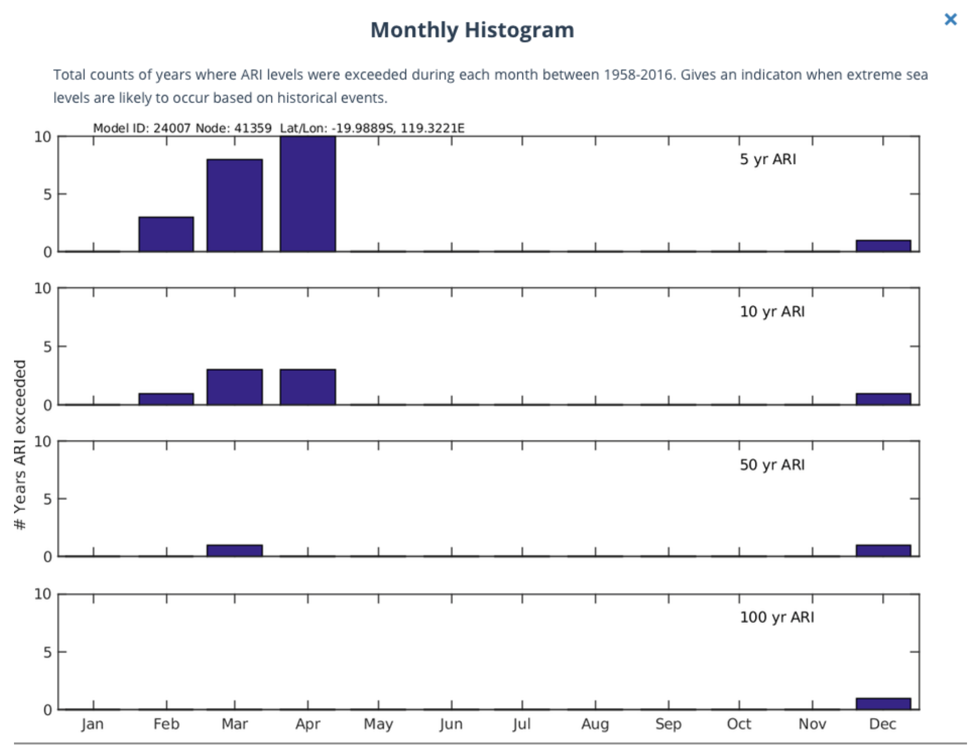

FIGURE 10. HISTOGRAM AVAILABLE ON THE UWA/BNHCRC WEBSITE INDICATING WHEN ARI LEVELS WERE EXCEEDED BETWEEN 1958-2016 IN THE SCHISM NUMERICAL MODEL SEALEVEL HINDCAST.

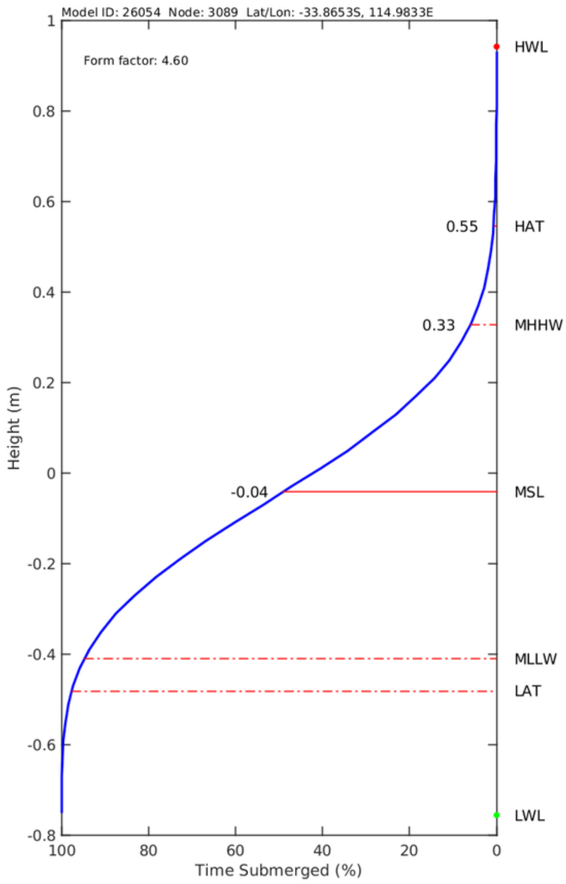

FIGURE 11. EXAMPLE SUBMERGENCE CURVE PLOT AVAILABLE FOR EACH COASTAL DATA POINT ON UWA/BNHCRC EXTREME SEA LEVEL WEBSITE. THE CURVE APPROXIMATES THE

PERCENTAGE OF TIME THE SEA LEVEL WILL BE ABOVE VARIOUS LEVELS BASED ON NUMERICAL MODEL RESULTS.

Comparison with tide gauge data at select sites:

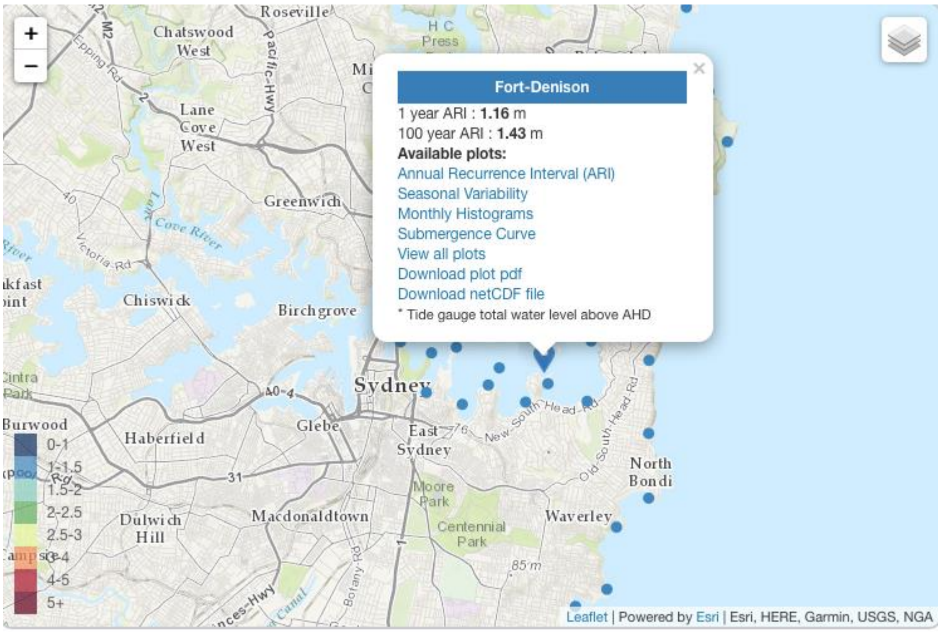

FIGURE 12. EXAMPLE POP-UP INFORMATION BOX SHOWING EXTREME SEALEVEL STATISTICS BASED ON TIDE GAUGE DATA AT SELECT SITES ENABLING THE USER TO COMPARE MODEL WITH OBSERVATIONS.

Data download option for model time series:

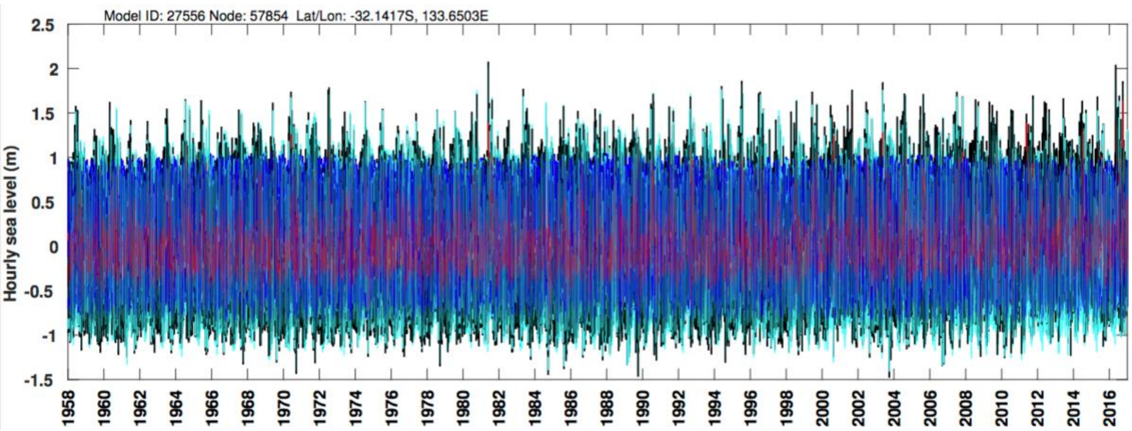

FIGURE 13. EXAMPLE TIME SERIES HOURLY DATA AVAILABLE FOR DOWNLOAD AT EACH COASTAL DATA POINT FROM THE UWA/BNHCRC WEBSITE. HERE, TIDAL ANALYSIS HAS BEEN PERFORMED ON THE DATA AND PLOTTED ARE: MSL ADJUSTED TOTAL WATER LEVELS (BLACK), PREDICTED TIDES (DARK BLUE), AND NON-TIDAL RESIDUALS (RED), AND RAW MODEL DATA (CYAN).

CONCLUSION

In order to protect life and property coastal planners and emergency managers require accurate estimates of flood risk. Providing reliable predictions of extreme sea levels for this purpose represents a significant challenge due to the range of complex processes that vary from beach to beach, town to town, and state to state around the entire Australian continent. As a result, a reliable comprehensive dataset of extreme sea levels for the entire coastline does not yet exist. Recent technological advances have allowed us to develop a high-resolution numerical model capable of analysing ocean dynamics to better understand how storms will impact local beaches on an Australia-wide scale over the past 59 years. The advanced, high-resolution (in the coastal zone ~100m) 3D finite element hydrodynamic model (SCHISM) was used to predict 59 years of hourly sea levels. Extreme value statistical analyses were then applied to determine Average Recurrence Intervals all around the coast. These data have been archived and made publicly available via a web portal, which can be practically applied to inform planning and emergency management.

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