Proceedings of the 13th European Wave and Tidal Energy Conference 1-6 Sept 2019, Naples, Italy

Assessment of tidal current resources in Banks Strait, Australia

Philip Marsh, Irene Penesis, Jean-Roch Nader, Camille Couzi, Remo Cossu

Abstract—**Current research conducted as part of the ARENA (Australian Renewable Energy Agency) AUSTEn (Australian Tidal Energy) "Tidal Energy in Australia – Assessing Resource and Feasibility to Australia's Future Energy Mix" project has identified the Banks Strait, Australia, an approximately 15 km wide channel located between the Furneaux Island Group and the north-eastern corner of mainland Tasmania, as highly suitable for tidal turbine deployments. To perform a site resource assessment of this region, two nested 2D structured mesh models were developed using the Sparse Hydrodynamic Ocean Code (SHOC) model. The model tidal elevations, current velocities and harmonic constituents were calibrated and validated against Acoustic Wave and Current profiler (AWAC) field data. Model results were then used to determine the velocity flow fields and resource area at depths suitable for tidal turbine deployments, determine annual energy production in the Strait, and examine wave / current interaction effects. Simulation results indicate that considerable tidal resources exist in the Banks Strait region, with maximum tidal currents in excess of 2 m/s found in both the westward and eastward directions over a large contiguous area, with water depths suitable for large-scale tidal turbine array installations. All modelling was conducted to International Electrotechnical Commission (IEC) Stage 1 resource assessment specifications. Due to promising results, future work will extend this work to the more detailed IEC Stage 2 specifications to advance the project / tidal turbine installation to the next feasibility stage.**

Keywords—**Tidal resource assessment, Banks Strait, Tasmania, Australia, hydrodynamic model.**

I. Introduction

TIDAL stream turbines are now approaching suitable technology readiness levels for deployment in large-scale arrays. However, the characteristics of prospective tidal energy sites in Australia are not well understood, as only low-resolution numerical models and/or very few field measurements have previously been performed, limiting the development of tidal turbines sites in Australian waters. To accelerate development, the AUSTEn project was initiated in 2017, which aims to map Australia's tidal energy resource in detail and assess its economic feasibility and ability to contribute to Australia's energy needs. This project is led by the Australian Maritime College, University of Tasmania, with research partners from the University of Queensland, the Commonwealth Scientific and Industrial Research Organization (CSIRO), and industry partners from SIMEC Atlantis and Mako Tidal Turbines. The Banks Strait, a channel that connects the south-eastern region of Bass Strait with the Tasman Sea, as shown in Fig. 1, has been identified as a promising site for tidal turbine deployments, with previous numerical studies using coarse-resolution hydrodynamic models indicating tidal currents in excess of 2.5 m/s with 2 m tidal ranges [1].

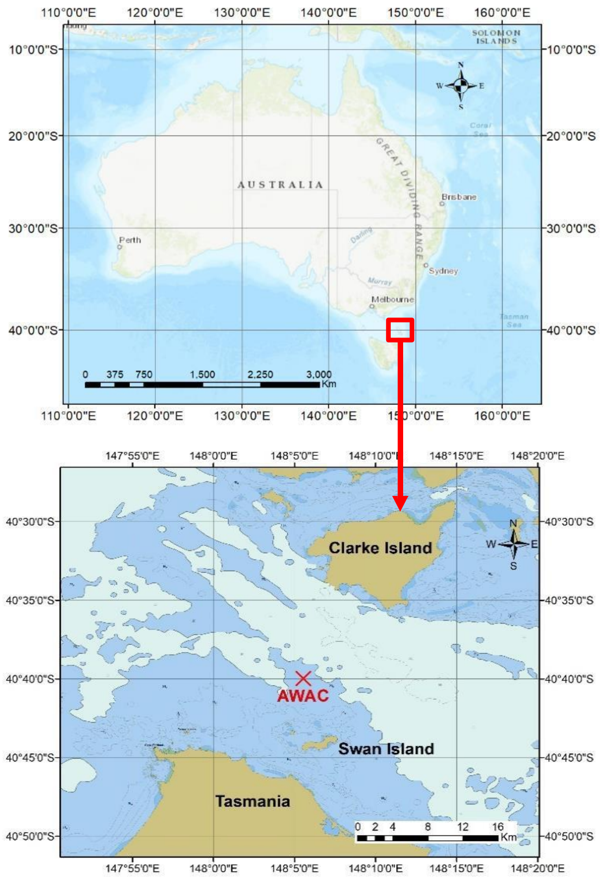

Fig. 1. Maps of (top) Australia showing the location of the Banks Strait, Tasmania, and (bottom) showing a closeup of Banks Strait between Clarke Island and Swan Island along with the location of AWAC deployment used for calibration and validation purposes.

Paper submission ID: 1485. Conference Track: TRC.

This project is co-funded by the Australian Renewable Agency (ARENA) through the Advancing Renewables Programme (grant G00902), the Australian Maritime College of the University of Tasmania, along with the University of Queensland, CSIRO Oceans and Atmosphere, CSIRO Energy, industry partners: SIMEC Atlantis Energy and MAKO Tidal Turbines Ltd, and international collaborators: Prof. Richard Karstens from Acadia University, Canada, and Dr Matt Lewis from Bangor University, UK.

P. Marsh, I. Penesis, J.R. Nader and C. Couzi are with the Australian Maritime College, University of Tasmania, Launceston, Tasmania, 7250, Australia (e-mail: philip.marsh@utas.edu.au, i.penesis@utas.edu.au, jeanroch.nader@utas.edu.au, camille.couzi@utas.edu.au).

R. Cossu is from the School of Civil Engineering, University of Queensland, St Lucia, Queensland, 4072 Australia (e-mail: r.cossu@uq.edu.au).

The Banks Strait is an approximately 15 km wide channel between Clarke Island, the southernmost island of the Furneaux Island Group, and Swan Island, part of the Waterhouse Island Group situated close to the north-eastern coast of Tasmania, with water depths of around 25 m to more than 75 m as shown in Fig. 2 that are suitable for tidal turbine deployments, and a semi-diurnal tidal cycle. To date, fine scale modelling or field measurements in the Banks Strait region are very limited. The National Tidal Facility of the Bureau of Meteorology (BoM) uses a 1/12° resolution model to predict tides around Australia, with output of predicted time-averaged tidal currents for regions around Banks Strait. However, given the coarseness of the 1/12° grid, it was noted that *in situ* observations and predictive models with tidal turbines are needed to make assessments of extractable power [1]. In 2008 CSIRO was commissioned by BioPower Systems to model tidal currents within Franklin Sound, Tasmania to determine possible sites for their BioStream tidal energy device. As this report is commercial in confidence, details have not been included here. However, examination of the modelling methodology was conducted to aid the development of the SHOC models used in this work. Tidal currents in the Banks Strait were found to routinely exceed 2.6 m/s, although it was noted that no validation of model estimates was made as part of the numerical modelling. Limited field measurements exist in the region, with the only tidal predictions available located at Swan Island, which are based on inferred tidal constituents.

The IEC technical specification (IEC TS 62600-201 Technical Specification, Marine Energy – Wave, tidal and other water current convertors – Part 201: Tidal energy resource assessment and characterisation) [2] was developed to aid resource assessments for tidal energy projects, and is applied in this work to assess both the suitability of the Bank Strait for tidal energy deployments, and the IEC specifications themselves. The specifications outline two types of tidal energy resource assessments that can be performed: Stage 1 and 2, which examine feasibility and layout design respectively. The IEC specifications also include guidelines on reporting formats including graphical and analytical methodologies. An outline of key modelling parameters required to meet IEC Stage 1 guidelines are shown in Table I, with the work outlined in this paper meeting all listed requirements.

TABLE I
STAGE 1 IEC MODELLING GUIDELINES [2]

Main IEC Modelling Guidelines	SHOC Models
Min. 4-8 boundary forcing constituents	13
Min. grid <500 m or 10 cells /channel	2 km and 400 m
Time period >= 35 days	35 days
Min. 20 constituents for harmonic analysis	Up to 35 used
Vertical discretization	2D
Minimum number of validation instruments	1 - AWAC
Wind and Sea Level Pressure modelling	✓
Amplitude and Phase for major constituents	✓
Examination of influence of waves at site	✓
Metrological examination	✓

In order to determine the suitability of the Banks Strait for tidal turbine deployments, two nested 2D structured mesh models were developed using the Sparse Hydrodynamic Ocean Code (SHOC) model. The simulated tidal elevations, current profiles and harmonic constituents were calibrated and validated against Acoustic Wave and Current profiler (AWAC) field data collected as part of the AUSTEn project to evaluate and ensure simulation accuracy. The model results were then analysed to: find areas of maximum velocity and power density, determine Annual Energy Production (AEP), and examine any wave / current interaction effects. This work forms the first part of a broader study to evaluate IEC Stage 1 and 2 specifications to determine any differences in AEP found when using the two approaches, guiding future resource assessments.

II. METHODOLOGY

The numerical modelling approach, forcing inputs, harmonic analysis software, AWAC field measurements, calibration and validation techniques used for the numerical models are outlined in this section.

A. Numerical hydrodynamic ocean model

The numerical hydrodynamic model SHOC was used for all modelling; it is a finite difference general-purpose model based on the manuscript of Blumberg and Herring [3] which is applicable on spatial scales ranging from estuaries to regional ocean domains [4]. SHOC is based on the 2D and 3D equations of momentum, continuity and conversation of heat and salt, employing the hydrostatic and Boussinesq assumptions, with the equations of motion discretized onto an Arakawa staggered C-grid. SHOC has previously been used to model estuaries and ocean domains ranging from; the Great Barrier Reef system [5], shelf circulation off Eastern Tasmania [6], and circulation modelling in Torres Strait, Australia [7].

The SHOC model uses a curvilinear orthogonal grid in the horizontal direction and fixed z-coordinate or terrain-following σ coordinates in the vertical direction, with the 'z' system allowing for wetting and drying of surface cells. Mode splitting is used to separate the 2D and 3D modes, allowing the fast-moving gravity waves to be solved independently of the slower moving internal waves. It also allows separate time-steps for 2D and 3D models, resulting in significantly reducing computational load. Forcing inputs for the SHOC model include wind, elevation gradients, inflows, surface fluxes, density gradients, bottom friction, bathymetry changes and mixing. For vertical mixing, several turbulence closure schemes are included, whilst Smagorinsky mixing coefficient are available for horizontal mixing. Available advection schemes include 1st and 2nd order schemes, with the QUICKEST advection scheme for tracers in conjunction with the ULTIMATE limiter recommended, as it is characterized by very low numerical diffusion and dispersion [4].

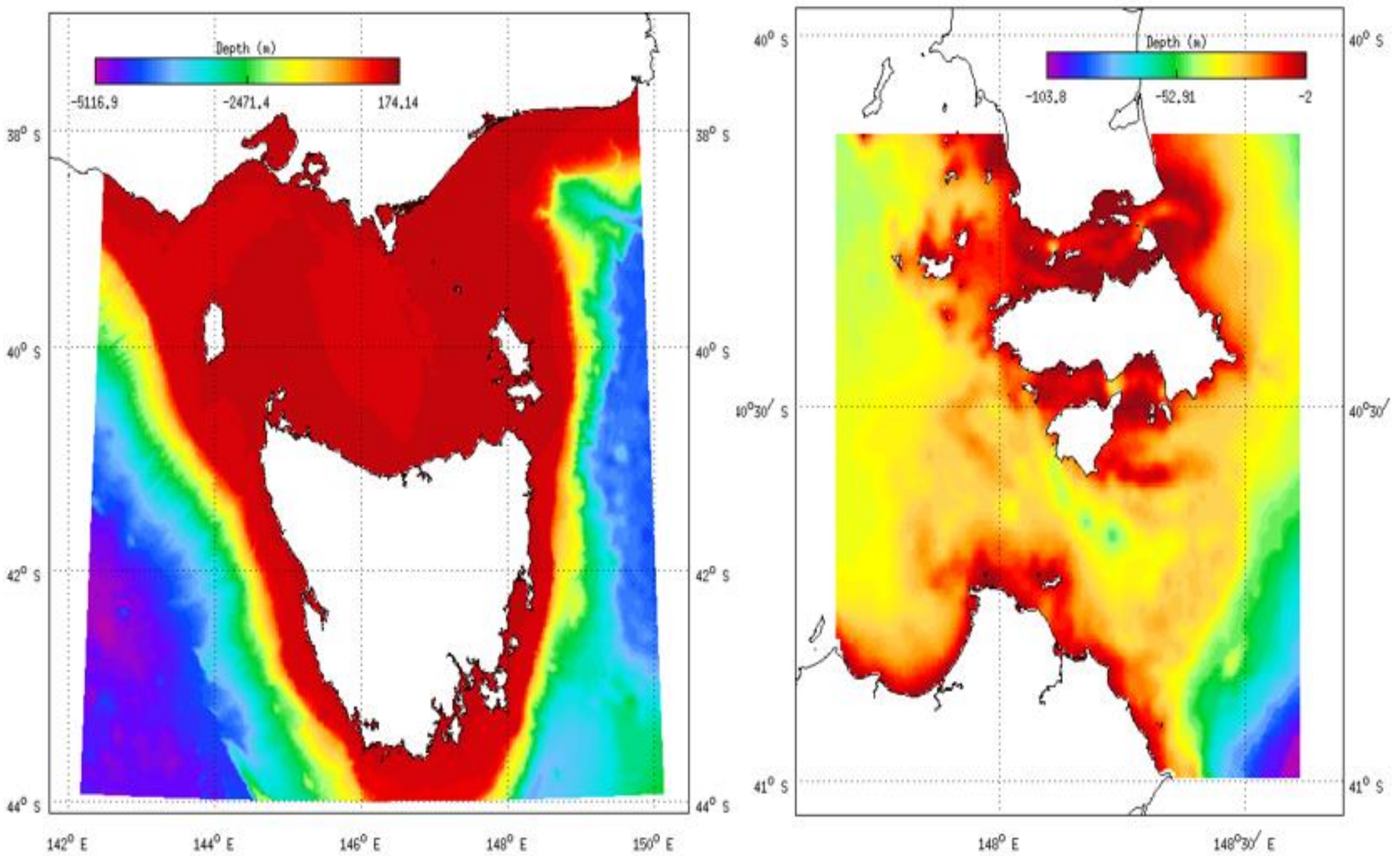

Fig. 2. Grid regions and bathymetry for (left) 2 km and (right) 400 m mesh resolution structured grids showing reduction of domain size of the 400 m model when compared to the 2 km model.

B. Model Domain, Coastline and Bathymetry

The numerical model SHOC uses a nested mesh methodology to increase mesh resolution in areas of interest. For this study based on Stage 1 IEC specifications, two meshes were developed with mesh grid densities of 2 km and 400 m respectively as shown in Fig 2. The 2 km model domain consists of the Tasmanian and Victorian coastlines, with offshore regions to the continental shelf and slope as recommended by IEC specifications to ensure accuracy of the lateral open boundaries [2]. The mesh domain of the 400 m grid was chosen to focus on the middle of the Banks Strait where the depths, ranging from 25 m to 60 m, are suitable for tidal turbine installation. Nesting ratios of approximately 5:1 were used between the successively refined meshes to ensure numerical accuracy as recommended for nested models. Future work will increase nested mesh resolutions to 80 m and 20 m to meet IEC Stage 2 mesh guidelines.

The coastline data used to develop the model domains was collated from two sources; hydrographic charts from the Australian Hydrographic Service (AHS), and a global coastline database from the University of Hawaii. Coastline data for the 2 km grid model was collated from the full-resolution dataset of the Global Self-Consistent, Hierarchical, High Resolution Geography Database (GSHHG) [8], which contains the World Vector Shorelines database in ESRI and raw binary form referenced in WGS84 geographic (simple latitude and longitude, decimal degrees) coordinates. Five resolutions are available: full, high, intermediate, low and coarse, with the full resolution database used for this project. The AHS AusENC official Electronic Navigational Charts (AusENC) [9] were used for the 400 m grid as they offer a finer resolution of coastline and bathymetry features, with the charts containing information from Australian Navy ships, maritime safety and port authorities, including both coastline and bathymetry data in WGS84 format.

Bathymetry data for the SHOC models was collated for the 2 km grid from the Geoscience Australia 2009 (GA2009) [10] bathymetry dataset, and for the 400 m grid from Australian Hydrographic Office AusENC charts. The GA2009 dataset is a 0.0025° (approx. 250 m at the equator) bathymetric grid for Australian waters, which was updated from the 2005 grid with newly available datasets and also to correct issues from the previous versions. The grid consists of bathymetry data in WGS84 coordinates for locations lying between 92° and 172° East, and 8° to 60° South. Similar to the 2005 grid, the 0.0025° grid resolution is only supported where direct bathymetric observations were sufficiently dense, otherwise in areas where no sounding data was available the grid was based on 2 arc minute and 1 arc minute satellite observations. Bathymetry for the 400 m grid was generated using AHS AusENC charts (440147, 440148, 441147 and 4411480) [9], as they offer reduced sounding spacing in areas of changing bathymetry gradients. Linear interpolation was used to transfer the depths onto the mesh grids.

C. Model Forcing

The lateral open boundaries of the 2 km grid were forced using only surface elevation, generated by the OSU tidal model[11]. Using the newly-formulated Dirichlet OBC forcing method in SHOC [12], boundary surface elevations were prescribed using an adjust flux parameter just above the 2D time step to ensure numerical stability. Using the tidal prediction software TMD [13], along with additional scripting in Matlab, predictions of the tidal height along the boundaries corresponding to the cell centres of the SHOC grid were performed to provide the tidal boundary forcing input using the Ohio State University (OSU) TPXO9-ATLAS 1/30° global tidal model [11]. This model is a fully-global model of ocean tides, which best-fits, in a least-squares sense, the Laplace Tidal Equations and altimetry data collected from TOPEX and Poseidon joint satellite mission. The TPXO9 forcing used eight primary, two long period, and three non-linear harmonic constituents, with boundaries located off the continental shelf as recommended by IEC standards. At the land boundaries a free-slip condition was imposed with zero normal momentum and tracer flux. The model surface boundaries were forced using the ERA5 climate reanalysis dataset, which includes hourly estimates of atmospheric fields including 10 m U and V wind components, sea surface temperature and mean sea level pressure on a 31 km (0.28125°) grid in a .grib and .nc file format [14].

D. SHOC Model Settings

In order to ensure simulation accuracy, a second order momentum scheme was utilized for all models, with the QUICKEST advection scheme for tracers used in conjunction with the ULTIMATE limiter. The horizontal mixing coefficients were estimated using internal SHOC computations, with base values reduced by approximately 2/3, along with Smagorinsky values of 0.1. To calibrate the SHOC model, the bottom friction and horizontal mixing coefficients were varied, with results compared to AWAC field data. All models were initialized from zero surface elevation, with all forcing variables ramped over a one-day period to ensure numerical stability. Passive CFL monitoring was used to examine numerical stability, with 3D(2D) time steps of 45(3) and 10(0.5) for the 2 km and 400 m models respectively, with timestep independence studies completed to ensure model accuracy. Due to the high current velocities in the region of interest, a large degree of mixing is expected. All hydrodynamic models were therefore run using a barotropic model with no salinity or temperature variations included to reduce computational requirements. Additionally, given that the focus of this work is on tidal power, the influence of small changes in salinity and density are not expected to impact the results significantly. The overall run time-period of the models was 50 days to meet minimum Stage 1 IEC specification numerical simulation lengths of at least 35 days [2], with runs taking approximately 5 days and 2 days for the 2 km and 400 m models respectively.

E. Tidal Analysis Software

The Matlab program T-Tide [15] was used to generate tidal harmonic constituents from the time-series of surface elevation and current velocities obtained from both the SHOC simulations and AWAC field measurements. Examination of the effect of the length of the time-series used to determine the harmonic constituents was evaluated as part of the AEP determination procedure.

F. Method for AEP estimation

The main objective of any resource assessment is to generate estimates of annual velocity probability distributions and hence the Annual Energy Production (AEP). The AEP was determined using the IEC methodology [2], where:

$$AEP = N_h . TECA . \sum_{i=1}^{N_B} P_i(U_i) . f_i(U_i) \tag{1}$$

where: N_h is the number of hours in the simulated year, $TECA$ is the expected Tidal Energy Convertor (TEC) availability, N_B is the number of velocity bins, $P_i(U_i)$ is the power output for the i^{th} velocity bin of the TEC power curve, U_i is the mean speed of the i^{th} bin of the power curve, and $f_i(U_i)$ is the proportion of time for which the mean current velocity falls within the i^{th} bin of the TEC power curve [2]. As this study is intended as a tidal turbine design agnostic resource assessment, no specific TEC power curve ($P_i(U_i)$) or availability ($TECA$) was included in the AEP calculations.

G. Field Data Measurements

In order to validate the numerical model, field measurements from an Nortek AWAC were obtained, which was deployed as part of the AUSTEn project field deployment program to characterise the Banks Strait tidal energy resource. This Nortek AWAC was deployed on a tripod frame with over 300 kg of weight to ensure the mooring held in position throughout the deployment period, with the deployment conducted from the 15/3/2018 to the 9/6/2018. The mooring was located at coordinates (148°5′32.676″S, -40°39′59.147″S) as shown on Fig. 1 approximately 7.5 km north of Swan Island and 11 km southwest of South Head, Clarke Island. The AWAC was configured to measure currents using 180 pings spaced evenly over 60 seconds every 5 minutes. As the AWAC was also measuring waves, only 5 current ensembles were measured every hour. The unit measured currents over 1 m cell bins from 1.9 m to 31.9 m above the sea bed. Prior to the analysis, the current data was processed using the IMOS Toolbox [16], which removed any outliers and side lobe contamination data. The results for the velocities were then depth-averaged to allow for comparisons with the SHOC 2D numerical models.

H. Tidal Model Calibration and Validation

Tidal current validation was performed by comparing the SHOC simulation surface elevation and depth-averaged 2D current velocities with the AWAC field data. Previous studies using SHOC has found that simulation model results are largely insensitive to tuneable model parameters [7], however the most significant were the bottom drag coefficient, vertical mixing and seabed roughness. The simulation models were therefore calibrated by varying bottom friction, horizontal viscosity and diffusion until good agreement was found with the AWAC field survey depth-averaged current velocity data. The results from this study are similar, with bottom drag coefficient and horizontal mixing coefficients having the greatest influence on simulation accuracy. Following EMEC guidelines [17], the phase shift between the predicted and observed timeseries was removed by maximising the correlation coefficient values using time shift increments of 0.25 hours, resulting in a time shift of 0.5 hours. Comparisons between model results and AWAC field measurements were quantified using the following statistical indices: Mean (*Mean*), Root Mean Square Error (*RMSE*), Bias (*Bias*) and Correlation Coefficient (*R*), where;

$$RMSE = \sqrt{\frac{\sum (MEAS - EST)^2}{N}} \tag{2}$$

$$Bias = \frac{1}{N} \sum EST - MEAS \tag{3}$$

$$R = \frac{\sum (MEAS_i - \overline{MEAS})(EST_i - \overline{EST})}{\sqrt{(\sum (MEAS_i - \overline{MEAS})^2)(\sum (EST_i - \overline{EST})^2)}} \tag{4}$$

where: N is the number of samples, $MEAS$ is the measured values from the AWAC, and EST is the SHOC simulation values.

To ensure the accuracy of the wind forcing input, the ERA5 wind model was validated against BoM measurements at Swan Island (148.1250, -40.7292) from 1/1/2018 to the 31/12/2018. Good agreement with the field measurements of wind velocity (R=0.87, $RMSE$=1.90 m/s, $Bias$=-0.84 m/s) were found over the full-year, confirming the ERA5 wind model's suitability for surface forcing.

For both simulation model's, good agreement was found between the time-series of the AWAC derived and SHOC simulated depth-averaged current velocities and surface as shown in Fig. 3. The statistical analysis of the results returned current prediction R>0.96, $RMSE$<0.15 m/s, and $|BIAS|$<0.02 m/s as shown in Table III, and surface elevation prediction R>0.97, $RMSE$<0.15 m, and $|BIAS|$<0.04 m for the 2 km and 400 m model grids, with the model's amplitudes and phasing agreeing accurately with the AWAC measurements. The SHOC models were found to be sensitive to changes to horizontal viscosity and diffusion values, with these values tuned to remove simulation bias and maximize R. As expected, the model showed increased accuracy when compared to field measurements as the grid size reduced. The close agreement found between AWAC field measurements and SHOC simulation results is also demonstrated in the elevation and current velocity scatter plots shown in Fig. 5.

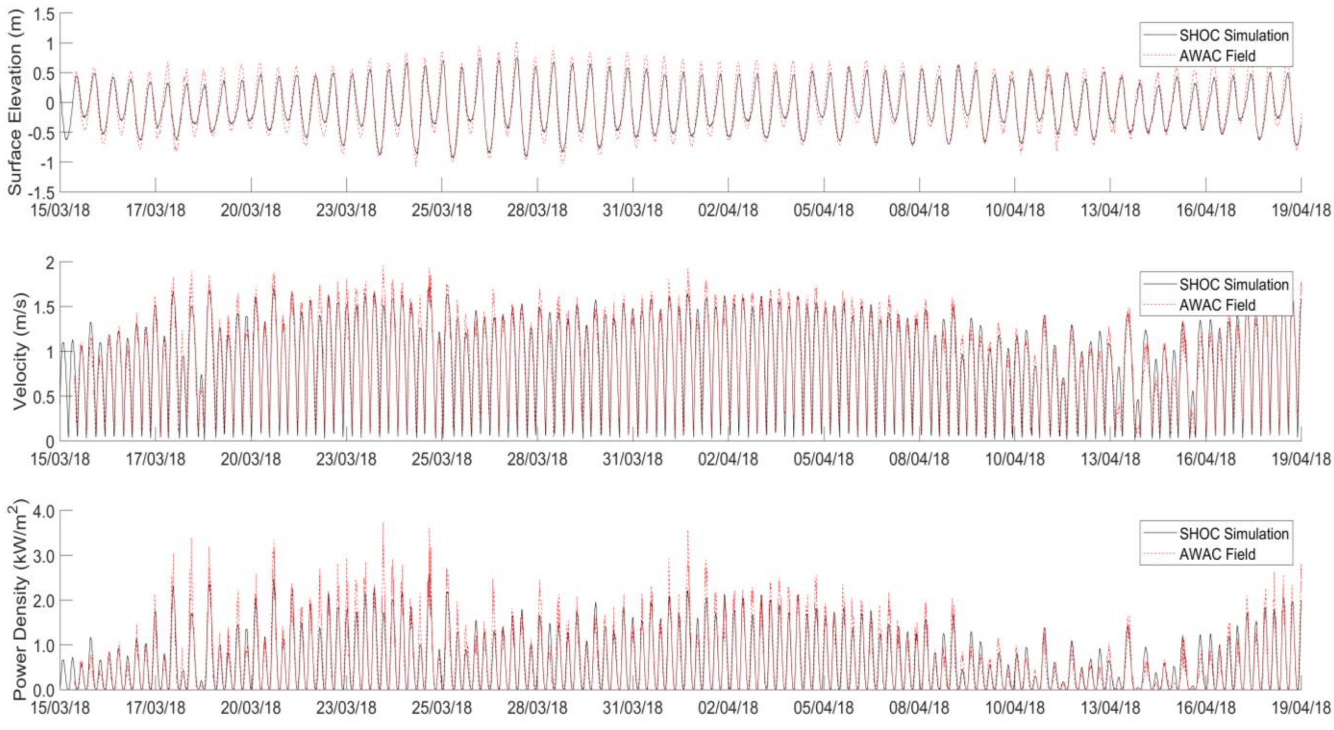

Fig. 3. Surface elevation, depth-averaged current velocity and power density at (148.0924, -40.6664) for the 400 m SHOC model and AWAC field measurements over a 35-day period from the 15/3/2018 to the 19/4/2019 showing good agreement between the model and field measurements. Note storm event 13/4/2018 onwards with resultant wave – current interaction as discussed in Section M.

TABLE II
COMPARISON OF VALIDATION STATISTICS OF CURRENT SPEED TIME-SERIES PREDICTED BY 2 KM AND 400 M SHOC MODELS OVER 35-DAY PERIOD FROM THE 15/3/2018 TO THE 19/4/2018 SHOWING IMPROVED SIMULATION ACCURACY WITH THE INCLUSION OF METROLOGICAL EFFECTS

	2 km No Metrological	2 km Metrological
R	0.89	0.96
RMSE(m/s)	0.22	0.14
Bias (m/s)	0.04	0.02

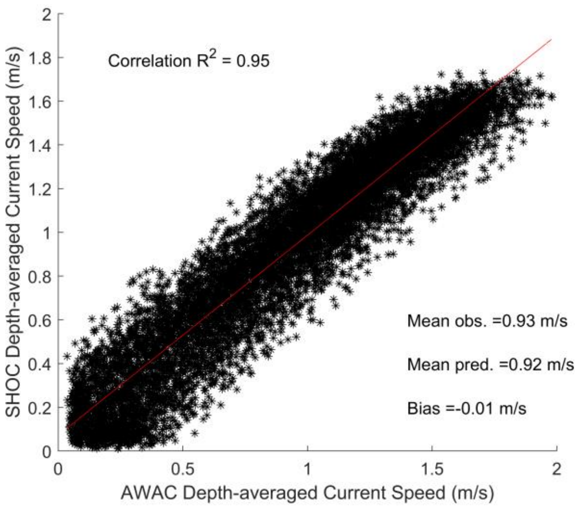

Fig. 4. Scatter plot of SHOC simulation 400 m depth-averaged current velocity with AWAC measurements at the AWAC location shown in Fig. 1 at (148.0924, -40.6664) over 35-day period from the 15/3/2018 to the 19/4/2019 showing good agreement between the AWAC and SHOC model results.

Current direction was also modelled accurately by the 2 km and 400 m numerical models, with the tidal asymmetry of 16° between ebb and flood measured by AWAC field survey comparing favourably with the asymmetry of 20° determined by the SHOC numerical simulations.

Simulation with and without meteorological surface forcing wind velocity components (10-meter u and v) and Mean Sea Level pressure (MSL) were also performed on the 2 km grid model to examine the influence of atmospheric factors on simulation accuracy when compared with AWAC tidal current velocities. As shown in Table II, improvements in most of the statistical metrics were found when including meteorological forcing variables as storm wind effects were included.

The tidal harmonic prediction software T-tide was used to analyse the AWAC and half-hourly SHOC model tidal currents, with the three main tidal ellipse parameters (M2, N2 and S2) of the semi-major and semi-minor current axis and the inclination and phase of the ellipse determined. The predicted tidal ellipse results showed good agreement with the AWAC field measurement ellipse parameters as shown in Table III, again with an increase in accuracy for the higher resolution grid sizing similar to that found for the current velocity results shown in Table II. The M2 tidal constituent was found to make up more than 95% of the driving force when analysing the current velocity time-series using 35 constituents. The developed SHOC models high prediction accuracy of M2 to within 1% of the AWAC measurements increases our confidence in the models capability of accurately predicting tidal current velocities.

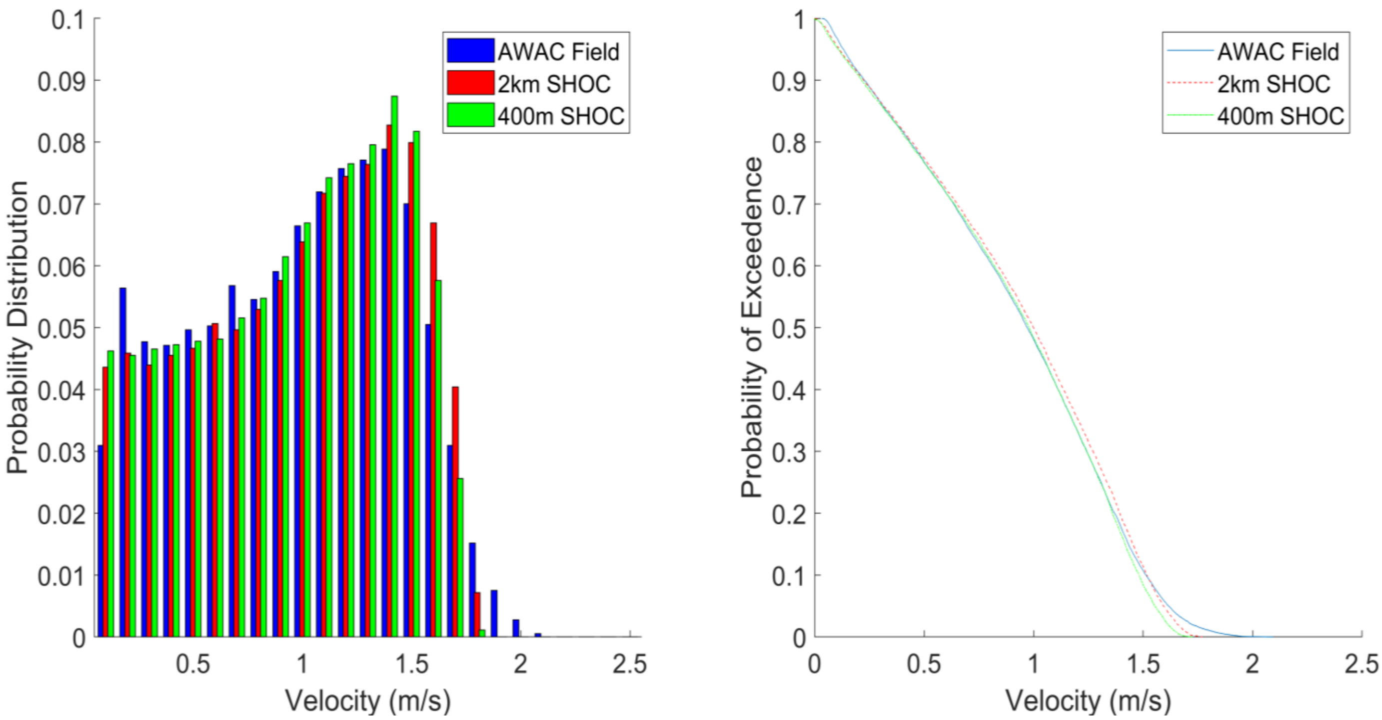

Fig. 5. (Left) Probability Distribution and (right) Probability of Exceedance for AWAC field measurements and 2 km and 400 m SHOC models at (148.0924, -40.6664) from the 15/3/2018 to the 19/4/2019 showing good agreement between SHOC model and field AWAC measurements. Storm events have not been removed from data analysis.

TABLE III
COMPARISONS OF THREE LARGEST TIDAL PARAMETERS: M2, N2 AND S2, COMPARING 85-DAY AWAC FIELD MEASUREMENTS WITH SHOC SIMULATION RESULTS AT (148.0924, -40.6664) FOR MODEL GRID RESOLUTIONS OF 2 KM AND 400 M FROM THE 15/3/2018 TO THE 19/4/2018

	Lsmaj (m/s)	Lsmin (m/s)	Inc (°)	Phase (°)
M2 AWAC	1.36	-0.025	161	290
M2 2 km	1.42	-0.003	165	294
M2 400 m	1.37	-0.014	166	295
N2 AWAC	0.25	-0.012	163	258
N2 2 km	0.21	-0.003	165	249
N2 400 m	0.20	-0.0029	165	251
S2 AWAC	0.20	-0.013	161	45
S2 2 km	0.19	-0.002	164	57
S2 400 m	0.18	-0.002	165	55

Examination of probability distribution and exceedance probability were conducted for the AWAC field and SHOC numerical model results according to IEC methods [2]. Results as shown in Fig. 5 demonstrate that the SHOC models slightly underpredict maximum velocity probability distribution, however generally good agreement was found over the velocity range.

The AEP at the location of the field AWAC as shown in Fig. 1 was calculated using the velocity predictions from the SHOC simulations, as well as velocity measurements from the AWAC field measurements. To annualize the results the 35-day SHOC simulations and AWAC measurements were multiplied by a time factor to cover a full year. Estimates of AEP were also calculated by determining the harmonic constituents from the AWAC and SHOC results over 35-day (and also 85-day in the case of the AWAC) time periods, then rebuilding the annual velocity time-series using the calculated constituent coefficients. The AEP results for all methods were similar, with AEP values ranging from 5.71 MWh/m^2 to 6.20 MWh/m^2. Results from Table IV show the close agreement between the harmonically derived AEP and the AEP derived directly from the time-series of current velocity for both the models and the AWAC data. These results indicate that using the harmonically derived AEP is suitable for a Stage 1 analysis, reducing simulation time and computational load significantly. A full Stage 2 IEC AEP determination will allow for a more detailed examination of these results, including longer time-frame AWAC deployments and full-year numerical simulations.

TABLE IV
COMPARISON OF ANNUAL ENERGY PRODUCTION (AEP) DETERMINED USING SHOC SIMULATION MODELS AND TIDAL CONSTITUENT HARMONIC ANALYSIS METHODS AT THE LOCATION OF THE FIELD AWAC DEPLOYMENT (148.0924, -40.6664) SHOWING GOOD AGREEMENT BETWEEN THE VARIOUS AEP CALCULATION METHODS

AEP Calculation Method	AEP (MWh/m^2)
AWAC -directly from current speed	5.97
AWAC – 85 days harmonics	5.74
AWAC – 35 days harmonics	5.76
SHOC 2 km grid - 35 days from current speed	6.20
400 m grid -35 days from current speed	5.71
400 m grid 35 days – harmonics	5.79

The high level of agreement between the 400 m SHOC model and the AWAC field data demonstrates that the numerical model is accurately simulating both the continuity and momentum / advection processes driving the current flow in the Banks Strait region, confirming the models suitability for determining power density and AEP estimates for tidal turbine deployment planning purposes. Finer resolution studies are planned to ensure that the models developed to Stage 1 IEC specifications as presented in this work have fully converged, with a study to Stage 2 IEC specifications planned to further evaluate the Bank Strait resource and evaluate the modelling accuracy of the Stage 1 IEC resource assessment presented in this work.

III. RESULTS AND DISCUSSION

Using the validated model results for the 400 m SHOC hydrodynamic model outlined in Section II, estimates of tidal current velocity, power density, probability distribution, exceedance probability and resource area determinations were performed over a 35-day period from 15/3/2018 to 19/4/2018 for the Banks Strait region, with AEP annualized from these results for 2018. For this study, ebb was defined as the tidal current flowing eastwards from Bass Strait towards the Tasman sea, with the flood direction defined as when the current flows westwards from the Tasman Sea into the Bass Strait.

I. Maximum Power Density Maps for Flood and Ebb

Maximum flow velocities of 2.10 m/s and 2.00 m/s were found for ebb and flood directions at (148°9’14.4”E,-40°37’26.4”S) and (148°9’14.4”E,-40°37’6”S) respectively by the 400 m SHOC model. The current velocity magnitudes appear to be roughly equal for eastwards and westward flow as shown in Fig 6, with both the surface area and location of maximum power density similar between the tidal ebb and flood. As expected, the highest values for current velocity and hence power density as shown in Fig. 6 were found in the middle to northern side of the Banks Strait, where the flow is constricted between Bass Strait to the west and the Tasman Sea to the east. The flow to the south of Swan Island (shown in Fig. 1) is also constricted due to the shallow water depths between Swan Island and the Tasmanian mainland, with a small increase in tidal current velocity determined through this channel.

J. Probability Distribution and Probability of Exceedance at Maximum Velocity Location

Comparison of velocity probability distribution and probability of exceedance using IEC methodology [2] at the location of maximum flow velocity (148°9’14.4”E,-40°37’26.4”S)) are shown in Fig. 7 for the 400 m grid SHOC simulations. A 50% probability exceedance was found for current velocities of more than 1 m/s.

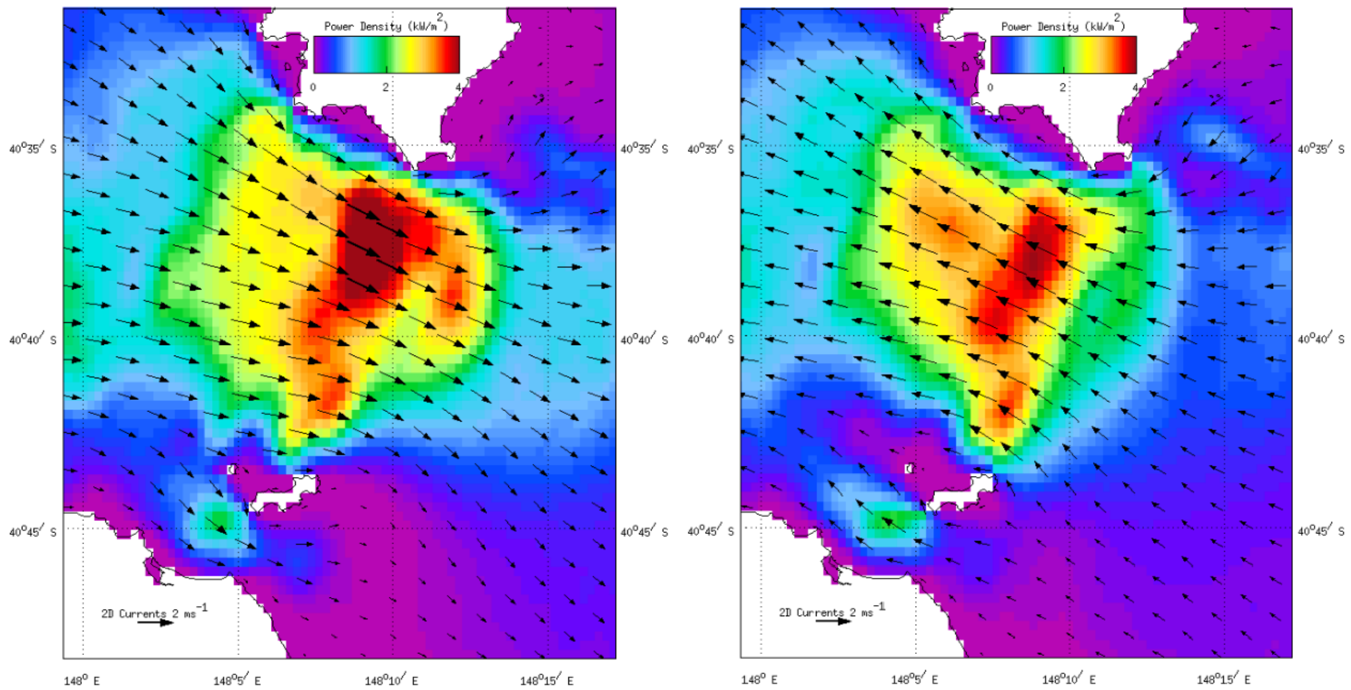

Fig. 6. Maximum power density and current direction indicators for (left) ebb and (right) flood directions determined using the 400 m SHOC model showing a large contiguous area of approximately 8.9 km² with peak power densities of more than 4 kW/m².

K. Annual Energy Production (AEP) Determination

Using the IEC methodology and the methods outlined in Section II, power density and hence AEP at the location of maximum velocity during the ebb flow at (148°9′14.4′S,-40°37′26.4″S) was derived, with an AEP of 9.22 MWh/m² using the annualising the 35-day SHOC simulation current velocities, and an AEP of 9.59 MWh/m² derived using the full-year harmonic reconstruction. This AEP range compares favourably with other prospective tidal energy sites, such as the Ria de Muros, Spain with AEP estimates of 5.3 MWh/m² [18], although estimates of AEP for the Minas Passage, Bay of Fundy, Canada, arguably the largest tidal resource in the world, ranges up to 28.2 MWh/m² [19].

L. Resource Area Determination

Using the validated 400 m SHOC model, quantification of the total area with current flow velocities greater than 1.5 m/s and 2 m/s was performed. Maximum values of more than 2 m/s were found over approximately 8.9 km² of the Strait, covering a contiguous rectangular area approximately 2 km long in the ebb-flood tidal stream direction and 4 km wide located 5 km from Clarke Island and 17.5 km from the Tasmanian mainland. The location of this area in the middle of channel, with water depth ranges from 32 m to 40 m, makes it highly suitable for the installation of current-generation design tidal turbines. Additionally, an area of approximately 195 km² was found with peak current velocities of more than 1.5 m/s, allowing the future expansion of the region for next-generation turbines that can operate at lower peak flow velocities [20].

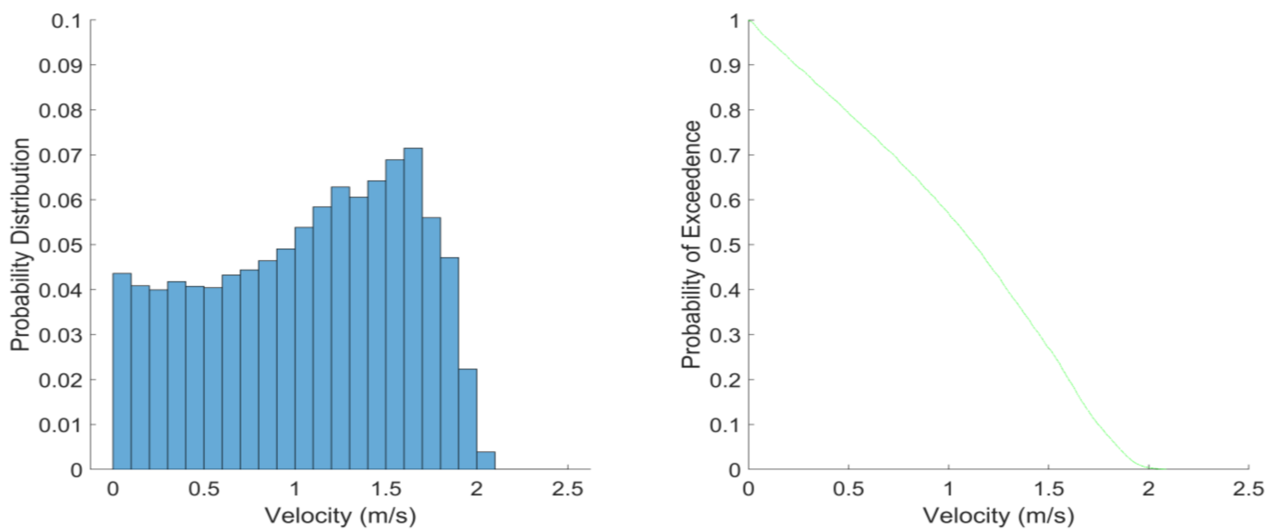

Fig. 7. Probability Distribution and Probability of Exceedance for the 400 m SHOC model at the location of maximum velocity (148.0924, -40.6664) for the 15/3/2018 to the 19/4/2019.

M. Influence of Waves on Current Velocity and Simulation Accuracy

To evaluate the influence of waves on AEP calculations, AWAC field measurements of significant wave height and current velocity were compared with SHOC model current velocities as shown in Fig. 8. The results indicate a significant correlation between wave heights and current velocity, explaining the local discrepancies between the AWAC measured and SHOC model derived (that did not account for the influence of waves) current velocities. When wave heights exceeded approximately 3 m, the maximum depth-averaged current velocities are reduced down, in some cases to less than 0.25 m/s. This reduction in current velocity is directional as shown in Fig. 8, and only occurs when the mean wave direction is opposite to the current direction, and also induces peaks in significant wave height at the time of peak current flow, due to the current flow and wave interactions. When the mean wave direction and current direction are roughly aligned, little change in depth-average current velocity can be seen in the AWAC measurements. However, given the good agreement of the AEP calculations shown in Table IV between the AWAC measurements that include the influence of waves, and the SHOC simulations without wave modelling parameters, the lack of wave modelling in the SHOC models did not significantly reduce AEP prediction accuracy over long time frames. This result however may be location and / or survey time-specific, with further research planned using Stage 2 IEC methodologies to more accurately determine the influence of waves on current velocities, and hence AEP modelling accuracy.

N. Sensitivity of Tidal Ellipse Parameters and Harmonically Derived AEP with AWAC Deployment Lengths

Examination of the sensitivity of AWAC deployment length on tidal ellipse parameters and hence harmonically-derived AEP was performed by comparing results from a T-tide analysis of time-series of current velocity for 35 and 85-day AWAC deployments, with the three largest tidal constituents shown in Table V. As shown in Table IV, using these harmonic constituents to build annual time-series of current velocity and hence AEP resulted in total AEP differences of less than 4%. The Stage 1 IEC specifications require a minimum 35-day deployment period for field measurements, which agrees well with results presented here. Minimal changes in AEP were found for the 85-day deployment which was in excess of twice the minimum IEC recommended deployment time period. However, this methodology may not capture annual variations if significant seasonal changes occur. Future work using IEC Stage 2 specifications is planned to further evaluate this effect over longer time frames to investigate the effect of any seasonal variations on AEP estimations.

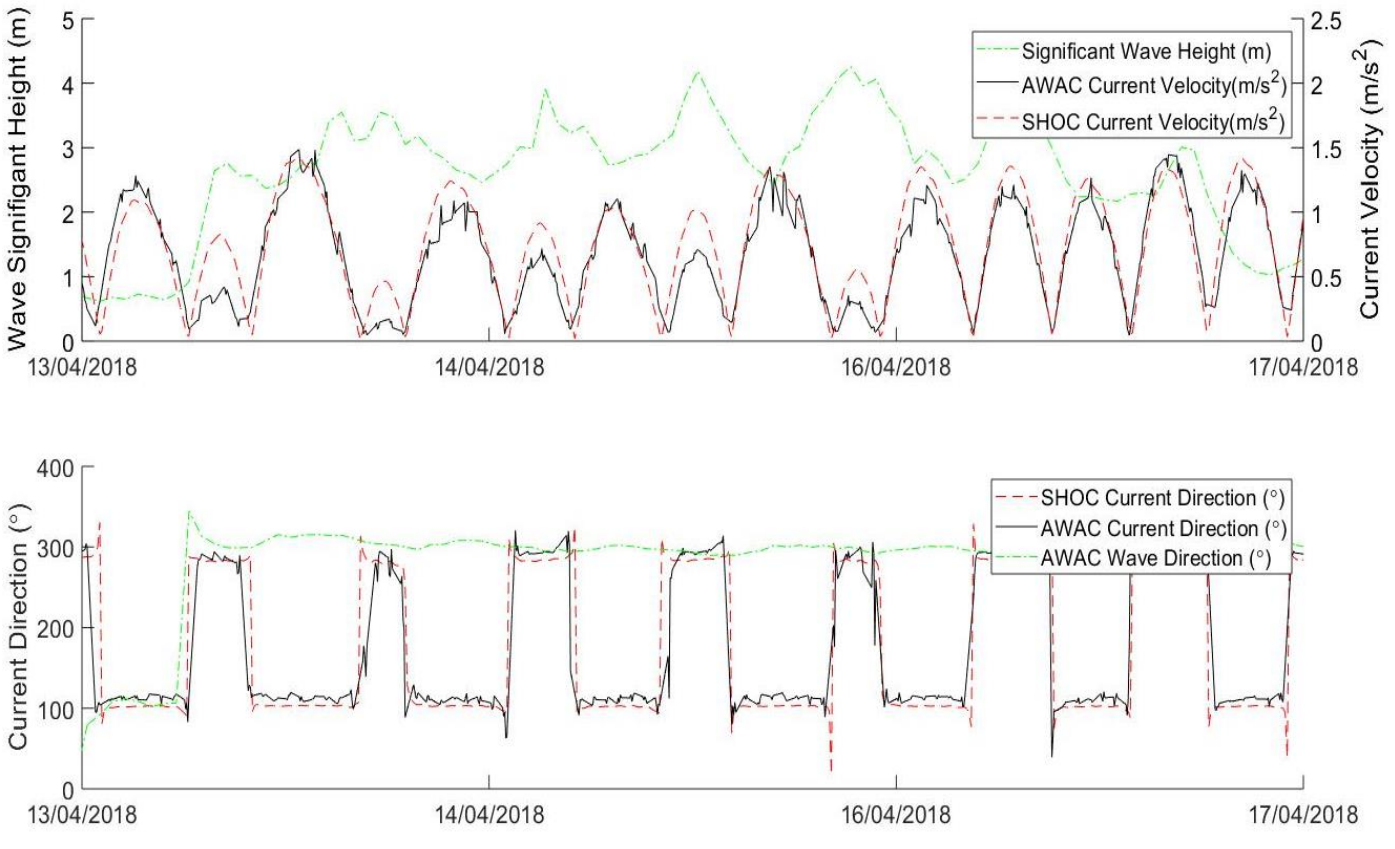

Fig. 8. Comparison of (top) AWAC significant wave height with AWAC and 400 m SHOC model current velocity, and (bottom) AWAC and 400 m SHOC model current direction at (148.0924, -40.6664) showing reduction in current velocity with significant wave heights above 3 m and mean wave directions opposing the current flow. Note: wave direction is coming from and current direction is going to.

TABLE V
COMPARISONS OF M2, N2 AND S2 TIDAL ELLIPSE PARAMETERS FOR AWAC FIELD MEASUREMENTS AT (148.0924, -40.6664) SHOWING MINIMAL INFLUENCE OF DEPLOYMENT TIME ON PARAMETER PREDICTIONS

	Lsmaj (m/s)	Lsmin (m/s)	Inc (°)	Phase (°)
M2 -85 days	1.36	-0.025	161	290
M2 -35 days	1.36	-0.030	157	290
N2 –85 days	0.25	-0.012	163	258
N2 –35 days	0.22	-0.003	157	247
S2 -85 days	0.20	-0.013	161	45
S2 -35 days	0.25	-0.006	157	57

IV. CONCLUSIONS

The Banks Strait Site looks to be a very promising region for tidal energy generation, with a contiguous rectangular area of approximately 9 km^2 with maximum current flow velocities greater than 2 m/s and AEP values in excess of 9 MWh/m^2 found. In addition, a further 195 km^2 area was identified with maximum current velocities greater than 1.5 m/s for both the ebb and flood tides. The area of maximum flow was located roughly in the middle of the Bank Strait at water depths ranging from 32 m to 40 m; depths suitable for tidal turbine installations of current-generation turbine designs. Tidal asymmetry between ebb and flood of approximately 20° was found at this site, which may require turbines with yaw control to maximize power capture in this region. Significant short-term wave / current interaction effects were found; however, these appear to not significantly influence long-term AEP.

The findings in this work demonstrate that numerical models developed using the IEC Stage 1 specifications can accurately capture key resource parameters including; surface elevation, current velocities, power density and hence AEP when compared to field measurements. As a result, the authors recommend that any preliminary resource assessments be conducted to Stage 1 IEC specifications, as they provide suitable guidelines to maximize model accuracy whilst minimising computational effort.

The IEC Stage 1 resource assessment outlined in this work will in future be compared with a resource assessment performed to Stage 2 specifications to determine the suitably and accuracy of each method in determining resource size for tidal site deployments, as well as performing a higher resolution study of the Banks Strait region. This Stage 2 work will include additional AWACS, acoustic doppler current profiler and multibeam data collected as part of the AUSTEn project. The future numerical models developed will also be extended by incorporating arrays of tidal turbines into the numerical models, enabling the full examination of the feasibility of the Banks Strait region for future turbine deployments.

ACKNOWLEDGEMENT

The authors would like to thank Mike Herzfeld, John Andrewartha and Mark Hemer from CSIRO for their assistance with the initial SHOC modelling.

REFERENCES

[1] Behrens, S., Griffin, D., Hayward, J., Hemer, M., Knight, C., McGarry, S., Osman, P., and Wright, J, Ocean Renewable Energy: 2015-2050: An analysis of ocean energy in Australia, CSIRO, North Ryde, Australia, 2012.

[2] International Electrotechnical Commission, IEC TS 62600-201: Marine energy – Wave, tidal and other water current convertors – Part 201: Tidal energy resource assessment and characterization. Geneva, Switzerland, 2015.

[3] Blumberg, Alan F., and H. James Herring. "Circulation modelling using orthogonal curvilinear coordinates" in *Elsevier Oceanography Series*, vol. 45, pp. 55-88. Elsevier, 1987.

[4] Herzfeld ,M. Waring J.R., SHOC Sparse Hydrodynamic Ocean Code User Manual V5507, CSRIO Marine Research, Hobart, 2016.

[5] Brinkman, R., Herzfeld, M., Andrewartha, J., Rizwi, F., Steinberg. C., and Spagnol, S, Hydrodynamics at the whole of GBR scale: A foundation for receiving water quality models, MTSRF Final Project Report, 2011.

[6] Oliver, E. C., Herzfeld, M., & Holbrook, N. J., Modelling the shelf circulation off eastern Tasmania", *Continental Shelf Research*, vol. 130, pp. 14-33, 2016.

[7] Saint-Cast, F., "Multiple time-scale modelling of the circulation in Torres Strait—Australia", *Continental Shelf Research*, vol. 28:16, pp. 2214-2240, 2008.

[8] Wessel, P., & Smith, W. H., "A global, self-consistent, hierarchical, high-resolution shoreline database", *Journal of Geophysical Research: Solid Earth*, vol. 101:B4, pp. 8741-8743, 1996.

[9] Australian Hydrographic Office Charts, http://www.hydro.gov.au/prodserv/paper/auspapercharts.htm

[10] Whiteway, T. G., Australian bathymetry and topography grid. Geoscience Australia, Canberra, 2009.

[11] Egbert, Gary D., and Svetlana Y. Erofeeva, "Efficient inverse modeling of barotropic ocean tides", *Journal of Atmospheric and Oceanic Technology*, vol. 19, no. 2, pp. 183-204, 2002.

[12] Herzfeld, M., & Andrewartha, J. R., "A simple, stable and accurate Dirichlet open boundary condition for ocean model downscaling", *Ocean Modelling*, vol. 43, pp. 1-21, 2012.

[13] Egbert and Erofeeva, TMD, https://svn.oss.deltares.nl/repos/openearthtools/websites/trunk/matlab/applications/DelftDashBoard/utils/tmd/Documentation/README_TMD_vs1.2.pdf., 2002.

[14] Copernicus Climate Change Service (C3S), ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate . Copernicus Climate Change Service Climate Data Store (CDS), date access *1/2/2019*, 2017. https://cds.climate.copernicus.eu/cdsapp#!/home

[15] Pawlowicz, R., Beardsley, B. and Lentz, S., "Classical tidal harmonic analysis with error analysis in MATLAB using T_TIDE", *Computers & Geosciences*, vol 28, pp. 929-937, 2002.

[16] Galibert, G., IMOS Toolbox, https://github.com/aodn/imos-toolbox/wikiemec, 2018.

[17] Legrand, C., Assessment of tidal energy resource: Marine renewable energy guides. European Marine Energy Centre, 2009.

[18] Carballo, R., Iglesias, G. and Castro, A., "Numerical model evaluation of tidal stream energy resources in the Ría de Muros (NW Spain)", *Renewable Energy*, vol. 34, no. 6, pp. 1517-1524, 2009.

[19] Cornett, A., Toupin, M., Baker, S., Piche, S. and Nistor, I., "Appraisal of IEC standards for wave and tidal energy resource assessment." in *Proceedings of the International Conference on Ocean Energy*, Halifax, Canada, pp. 4-6. 2014.

[20] Lewis, M., Neill, S. P., Robins, P. E., and Hashemi, M. R., "Resource assessment for future generations of tidal-stream energy arrays", *Energy*, vol. 83, pp. 403-415, 2015.