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Midwest Zone Aquaculture Modelling Calibration Report

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Midwest Zone Aquaculture Modelling Calibration Report

Prepared for:	Cardno Level 9 The Forum 203 Pacific Highway St Leonards NSW 2077	
Prepared by:	BMT WBM Pty Ltd	(Member of the BMT group of companies)

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Synopsis:	**A report detailing the calibration of a hydrodynamic, water quality and sediment quality model of the Abrolhos Islands, as part of the Midwest Zone Aquaculture Study.**	

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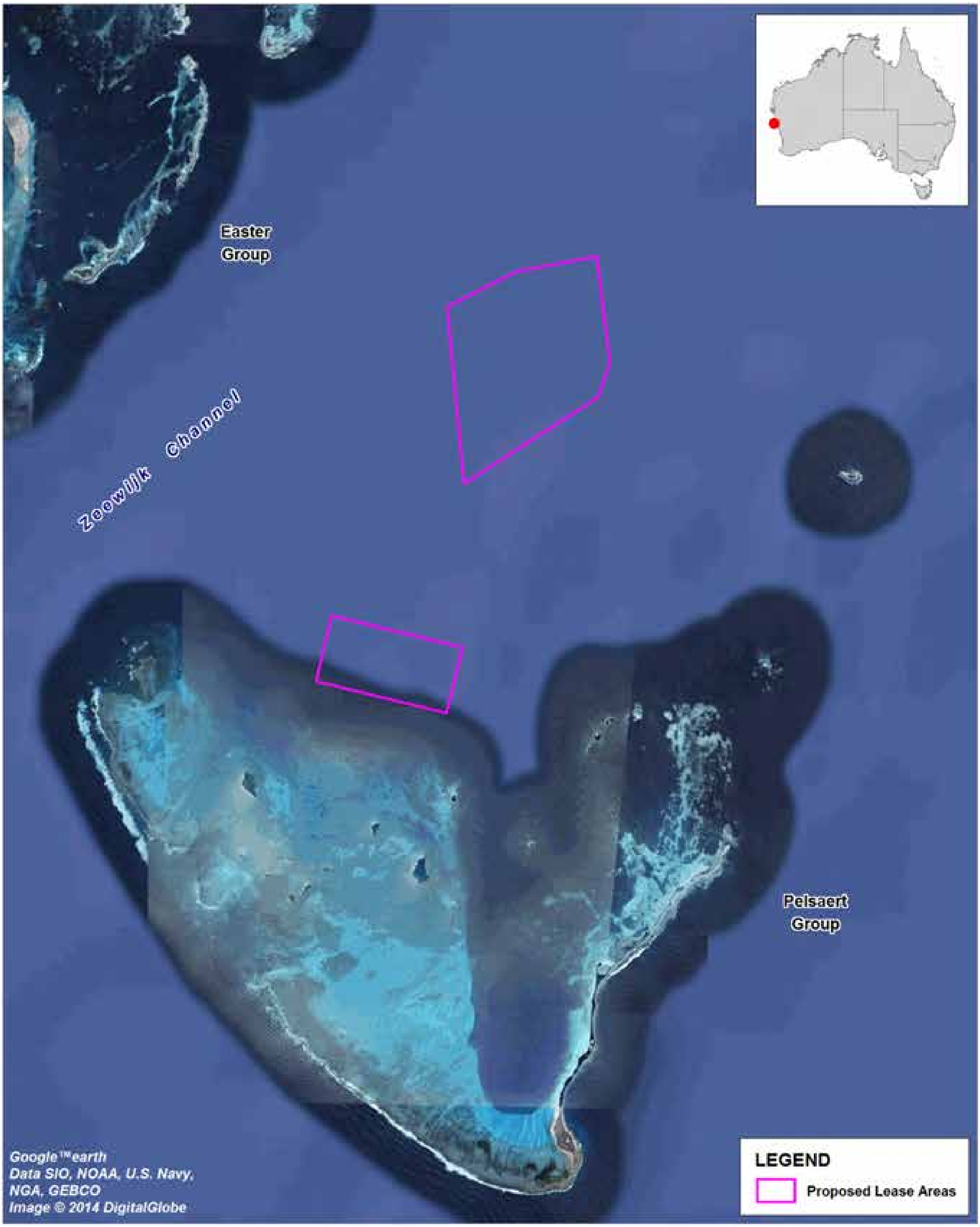
1 Introduction

The Department of Fisheries, Western Australia (DoF), on behalf of the Minister for Fisheries, proposes to create an 'Aquaculture Development Zone' to provide a management precinct for prospective aquaculture proposals within the State Waters off the Houtman Abrolhos Islands (HAI) Fish Habitat Protection Area (FHPA), which is approximately 75 kilometres west of Geraldton. DoF has engaged BMT Oceanica, alongside BMT WBM and the University of Western Australia, to undertake the technical studies for the environmental impact assessment (EIA) associated with operations within this proposed Midwest Aquaculture Development Zone (MWADZ).

A map of the area of interest, including the proposed aquaculture lease areas, is presented in Figure 1-1. The region surrounding the Abrolhos Islands is a dynamic system influenced by large-scale regional currents (e.g. Leeuwin Current, Capes Current), wind stresses, upwelling and wave dynamics (Pearce & Pattiaratchi, 1999; Feng *et al.,* 2007; Waite *et al.*, 2007; Woo & Pattiaratchi, 2008; Rossi *et al.*, 2013). Simulating such an environment is challenging, as a model must resolve the dynamic processes affecting the area on a regional scale (e.g. regional currents), the meso-scale (e.g. eddy formation) and the local scale (e.g. the influence of local bathymetric features on current velocities). Nevertheless, the impact assessment requires the development of hydrodynamic and water quality models of the area to quantify the potential impacts of aquaculture activities on water quality parameters (e.g. turbidity, nutrient concentrations, chlorophyll concentrations, etc.). The proposed methodology for the modelling component of this study was outlined in a letter dated 27th March 2015 (included in Appendix A) and this report details the development and calibration of the hydrodynamic and water quality model described in that letter.



Title:
Proposed Lease Areas

Figure: 1-1

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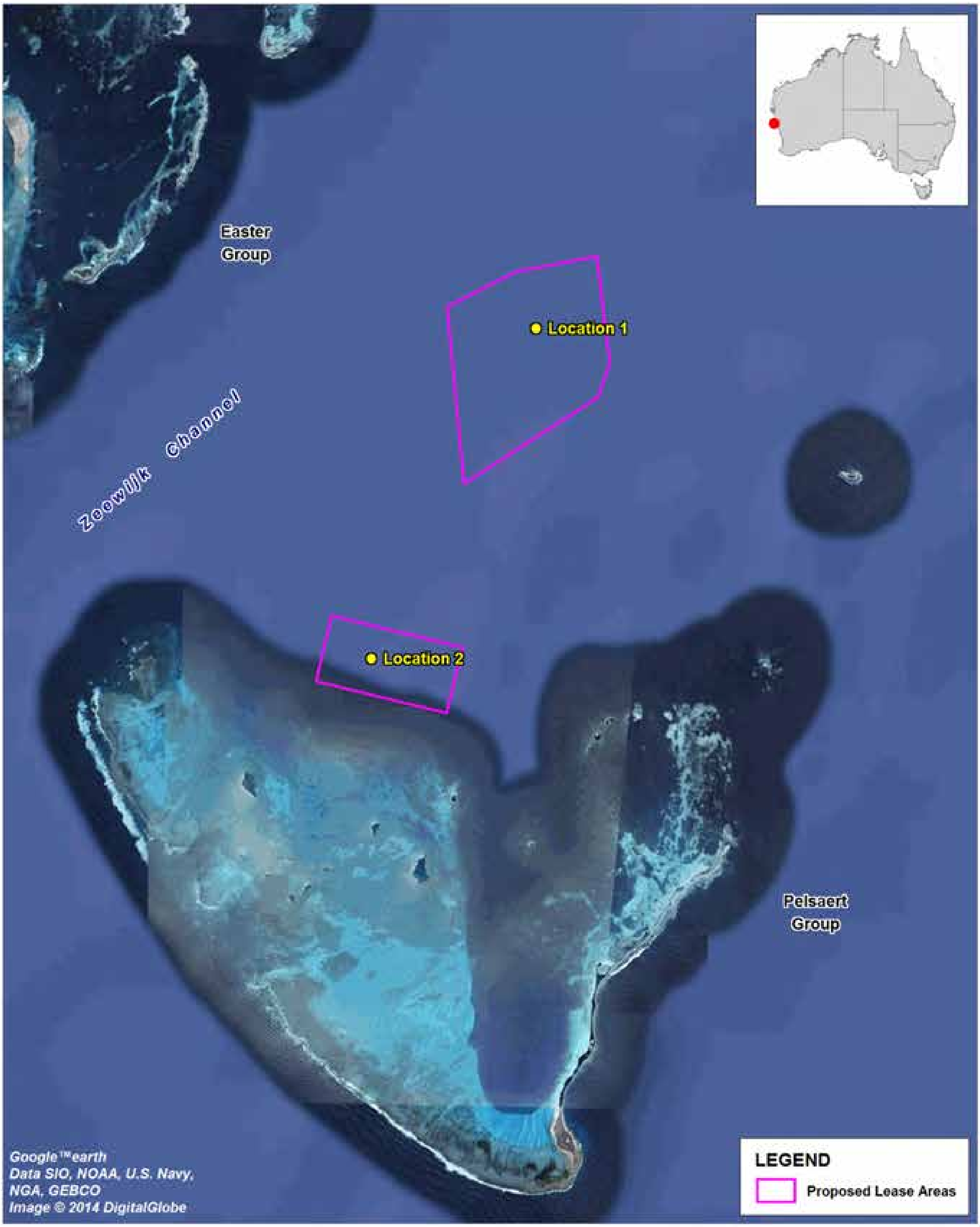
2 Sampling Program

A suite of hydrodynamic and water quality data were collected during a series of equipment deployments between May 2014 and March 2015. This section contains a summary of the data collected that is relevant to the hydrodynamic and water quality model calibrations. Full details of the sampling program are included in the letter dated 27th March 2015, which is included in Appendix A.

2.1 Hydrodynamic data

Four bottom-mounted Acoustic Doppler Current Profilers (ADCPs) were deployed in total: one in each of the MWADZ areas (hereafter referred to as the 'lease-area sites'; Figure 2-1), one to the north-east of the study area and one to the south-east (hereafter referred to as the 'regional sites'; Figure 2-2). Depth data were collected at all sites, bar the southern lease-area site during the first 3 deployments. Wave and temperature data were collected by sensors co-located with the ADCPs, although not at all times and locations. No wave data were collected during the first lease-area deployment between May and June 2014 due to a faulty sensor. The fault was repaired for subsequent deployments. A conductivity sensor was co-located with the ADCP at the northern regional site during the first deployment, although these data were not suitable for use as sand clogged the sensor during the first week. Conductivity sensors were co-located with the ADCPs at the regional sites during the second deployment, which provided approximately 3 months of data before bio-fouling introduced a clear bias. The dates of all equipment deployments were as follows:

- Lease-area sites:
  - 16th May 2014 – 19th June 2014
  - 17th August 2014 – 18th September 2014
  - 9th November 2014 – 10th December 2014
  - 9th February 2015 – 11th March 2015.
- Regional sites:
  - 17th July 2014 – 19th November 2014
  - 19th November 2014 – 18th March 2015.



Title:

ADCP Locations - Proposed Lease Areas

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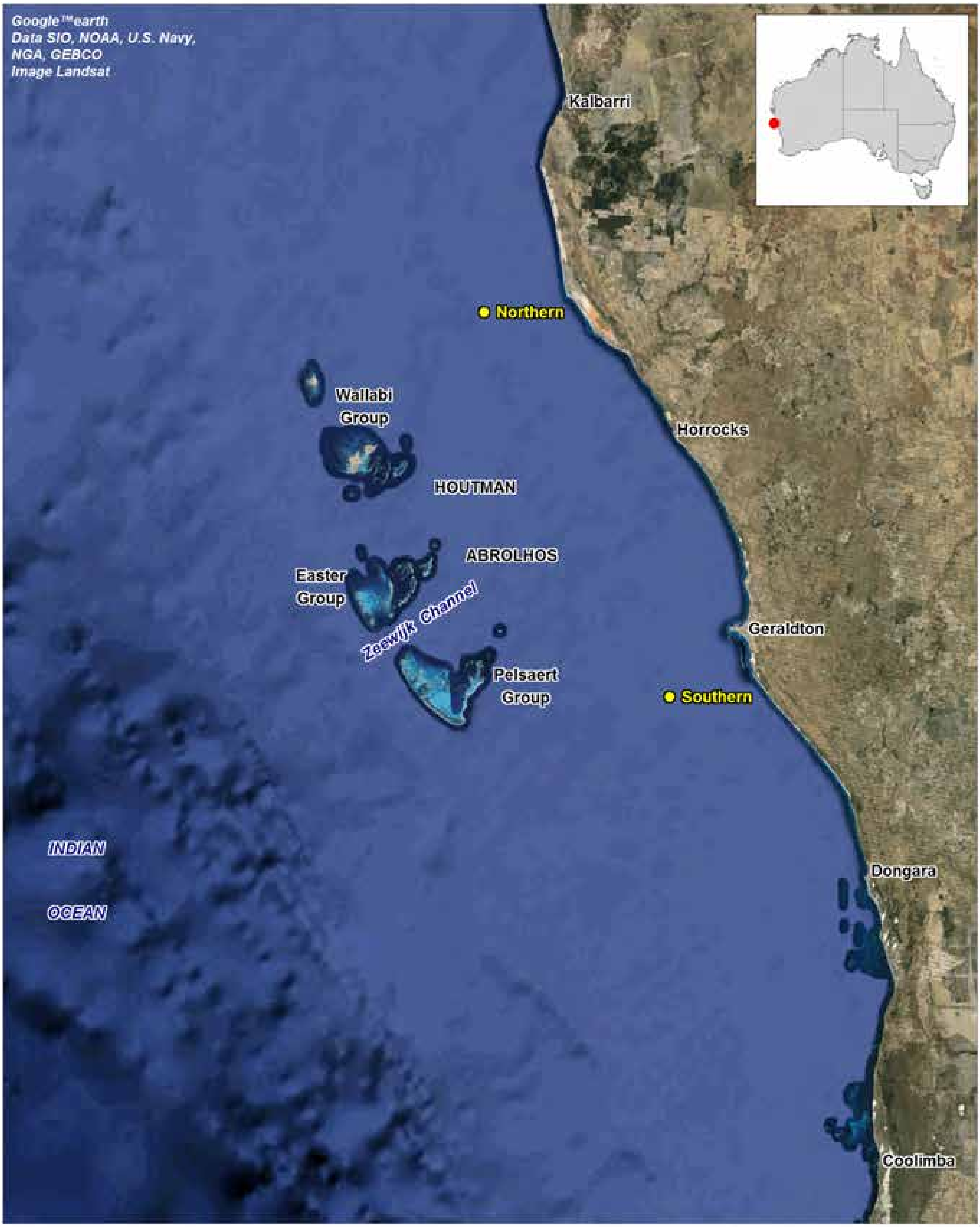

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ADCP Locations

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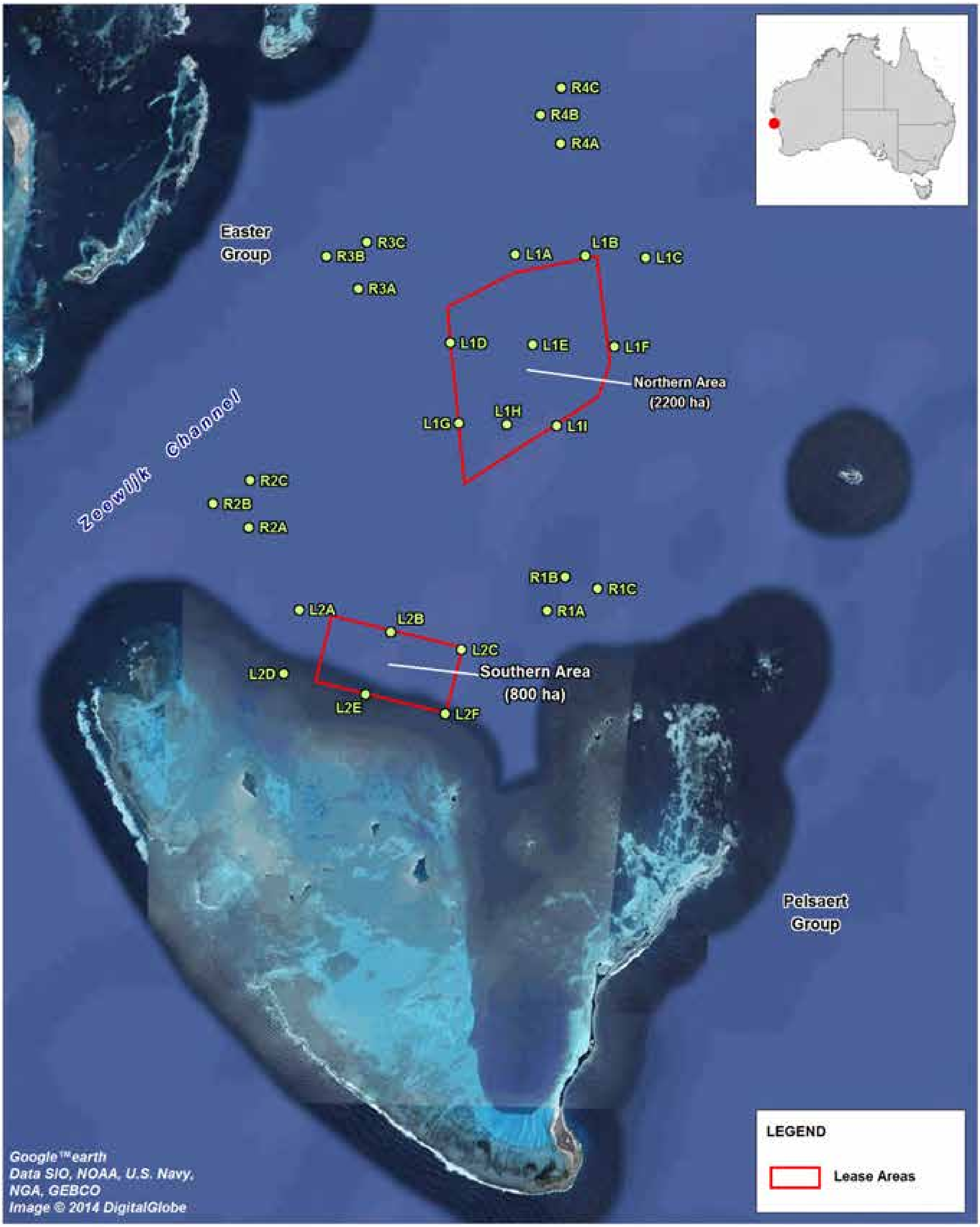
2.2 Water quality data

A suite of water quality variables were sampled at a total of 27 sites within the MWADZ areas (Figure 2-3). The suite included the following variables relevant to the modelling component of this study:

- Total nitrogen (TN)
- Total phosphorus (TP)
- Oxidised inorganic nitrogen (nitrate + nitrite)
- Ammonia
- Filterable reactive phosphorus (FRP)
- Chlorophyll-a
- Total organic carbon (TOC)
- Dissolved oxygen (DO)
- Turbidity
- TSS
- Photosynthetically active radiation (PAR).

The sampling program took place over the following dates:

- 20th-21st May 2014
- 20th June 2014
- 18th August 2014
- 18th September 2014
- 10th November 2014
- 11th December 2014
- 18th February 2015.



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Water Quality Sampling Locations and Proposed Lease Areas

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3 Model Framework

BMT WBM's letter dated 27th March 2015 outlined the proposed model framework, including the development and calibration of a hydrodynamic and water quality model of the study area (Appendix A). This section provides details on the adopted model setup, which includes some modifications (e.g. mesh changes) of the setup proposed previously.

The primary aim of the hydrodynamic model is to provide a realistic representation of currents and wave dynamics at the lease-area sites, for the purposes of determining the fate of particles released from aquaculture activities (e.g. food & faeces), and also to provide a realistic hydrodynamic regime to the biogeochemical model for water quality simulations. To this end, the model was calibrated against data collected during the sampling program detailed above, the results of which are included in Section 4.

3.1 Hydrodynamic Model

The platform used was our in-house-developed hydrodynamic modelling engine TUFLOW FV (http://www.tuflow.com/Tuflow%20FV.aspx). TUFLOW FV is a powerful hydrodynamic model engine that solves the Non-Linear Shallow Water Equations (NLSWE) on a 'flexible' (unstructured) mesh comprising triangular and quadrilateral cells. The mesh is not limited to square or rectangular grid arrangements, a feature which we believe will be critical to the successful execution of this study. This unstructured mesh approach has significant benefits when applied to study areas involving complex bathymetric features, flow paths, and hydrodynamic processes, and varying areas of interest, such as this study area. The finite volume (as opposed to finite difference (fixed grid) and finite element) numerical scheme is also capable of simulating the advection and dispersion of multiple scalar constituents within the model domain. TUFLOW FV is configured to solve the NLSWE in 2D (vertically averaged) and 3D with the ability to employ both first-order and second-order numerical solution schemes. The model can be run in both 2D vertically-averaged mode and fully 3D mode by specifying a vertical layer structure. Importantly, the TUFLOW FV engine leverages the parallel processing capabilities of modern computer workstations, using the OpenMP implementation of shared memory parallelism, such that computation capability can be used to its maximum potential.

3.1.1 Bathymetry

A digital elevation model (DEM) was developed using a regional bathymetry dataset from Geosciences Australia with 250m resolution, and a higher-resolution dataset of the Abrolhos Islands from the Western Australian Department of Transport (Figure 3-1 and Figure 3-2). This was interrogated to provide bathymetry values to the model mesh.

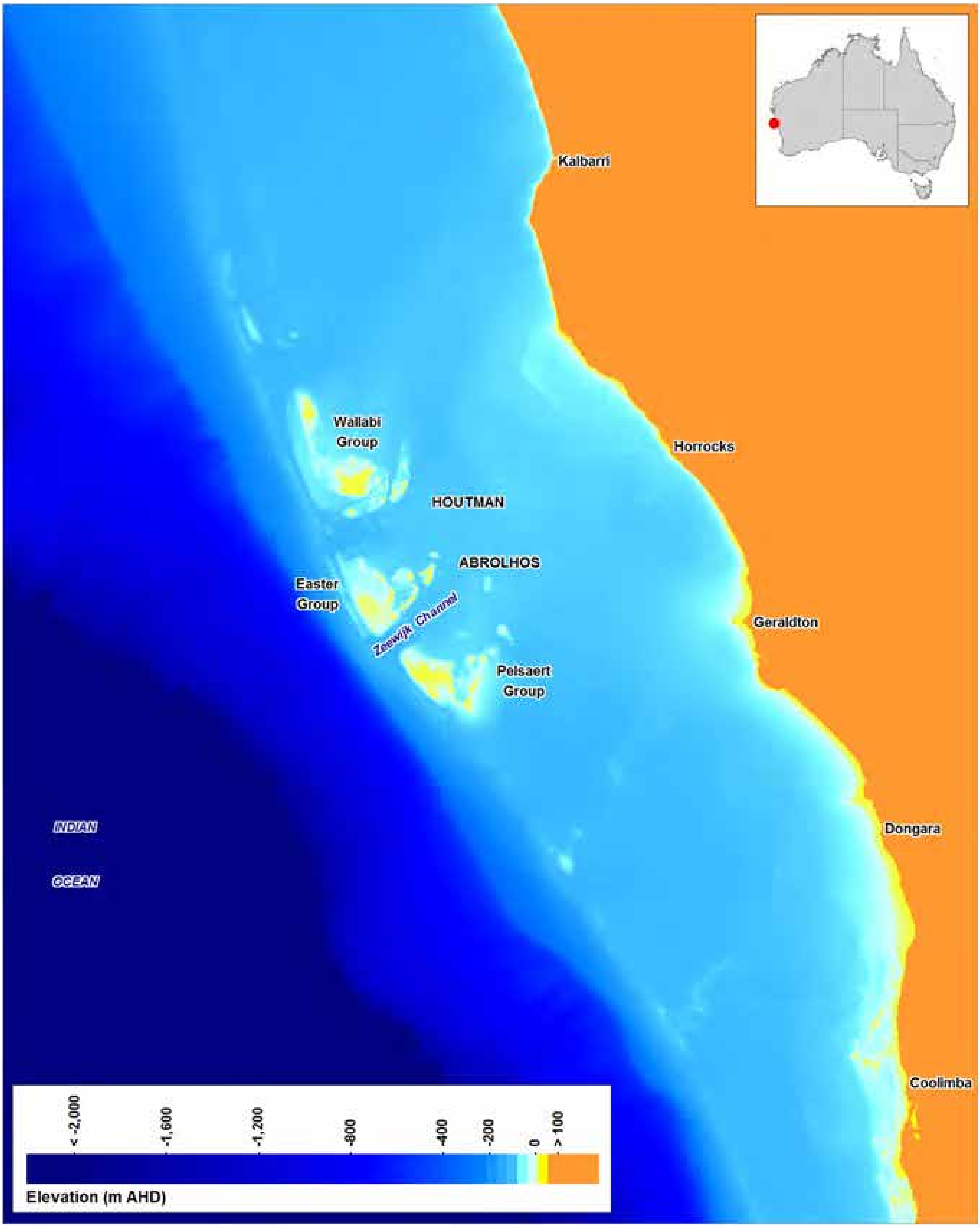
3.1.2 Model mesh

The model mesh covers an overall area of 2.7 million hectares, with a single open boundary of approximately 413 km stretching from Kalbarri in the north to Coolimba in the south. It includes 23,093 horizontal cells, ranging from resolution of approximately 3.5 km at the open boundary to approximately 40 m resolution within the proposed lease areas (Figure 3-3 and Figure 3-4). Vertical resolution comprises of up to 26 fixed-level z layers (Table 3-1) and 2 surface, variable-level sigma layers, for a total of up to 28 vertical levels with resolution increasing near the surface to approximately 1m. The seabed sits at approximately -40m AHD in the vicinity of the lease areas, meaning the model has 10 z layers plus 2 sigma layers in this region. In total there are 264,412 computational cells and the mesh resolution both horizontally and vertically compares favourably with similar models developed for aquaculture assessments in Western Australia (e.g. DHI, 2013). Time-steps in the model are scaled to an assigned Courant value (0.7) and can vary over time. Typical time-steps were approximately 0.3s.

Table 3-1 Depths of fixed-level z layers

Layer number	Depth (m AHD)
1	-2
2	-4
3	-6
4	-8
5	-10
6	-15
7	-20
8	-25
9	-30
10	-40
11	-50
12	-70
13	-100
14	-150
15	-250
16	-500
17	-750
18	-1000
19	-1250
20	-1500
21	-1750
22	-2000
23	-2250
24	-2500
25	-2750
26	-3000

As can be seen in Figure 3-4, a variety of cage configurations have been included in the mesh to ensure that processes adjacent to cage clusters are highly resolved by the model. A selection of some or all of these cage configurations will be used when developing scenarios.



Title:

Digital Elevation Model

Figure: 3-1

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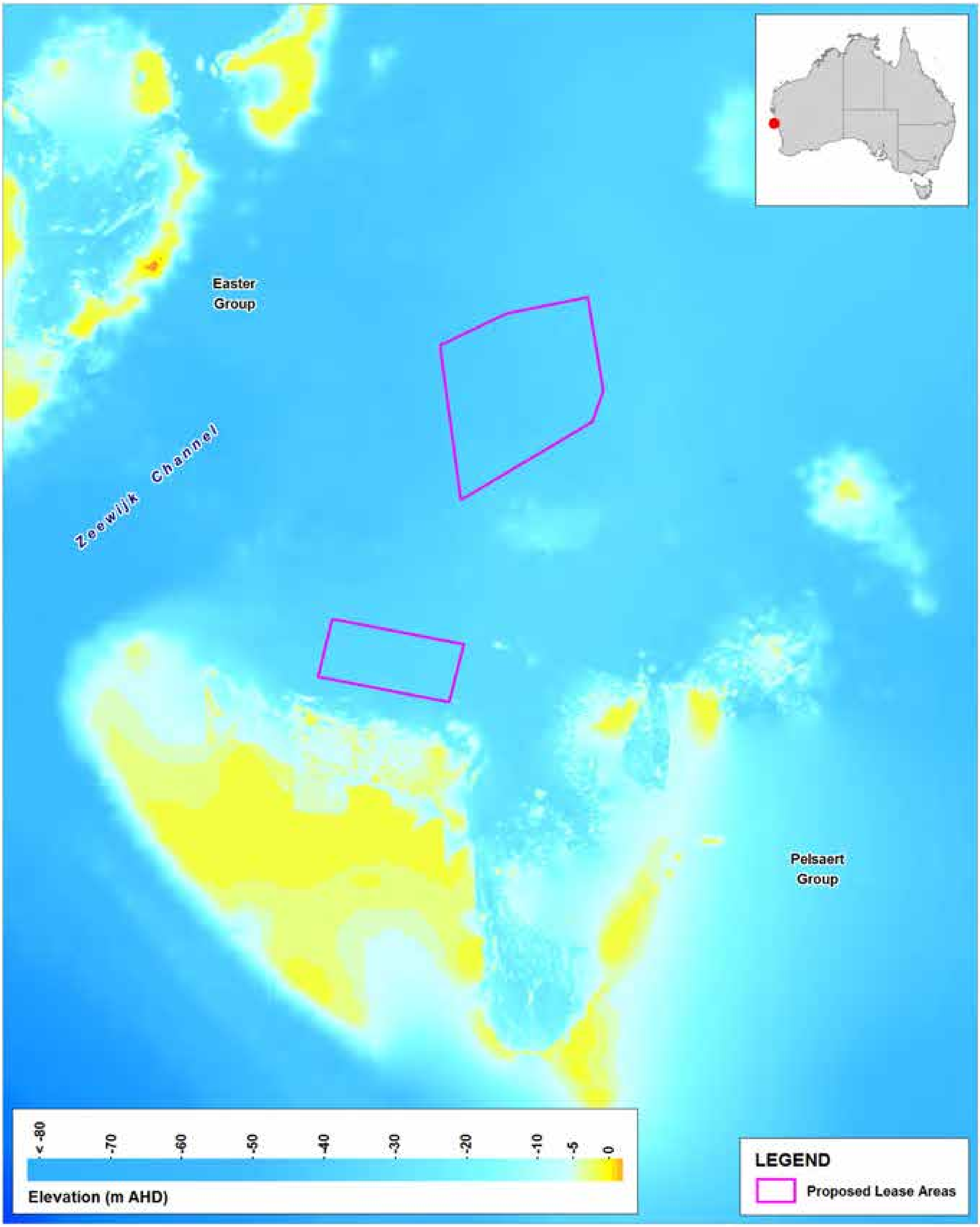

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Digital Elevation Model – Proposed Lease Areas

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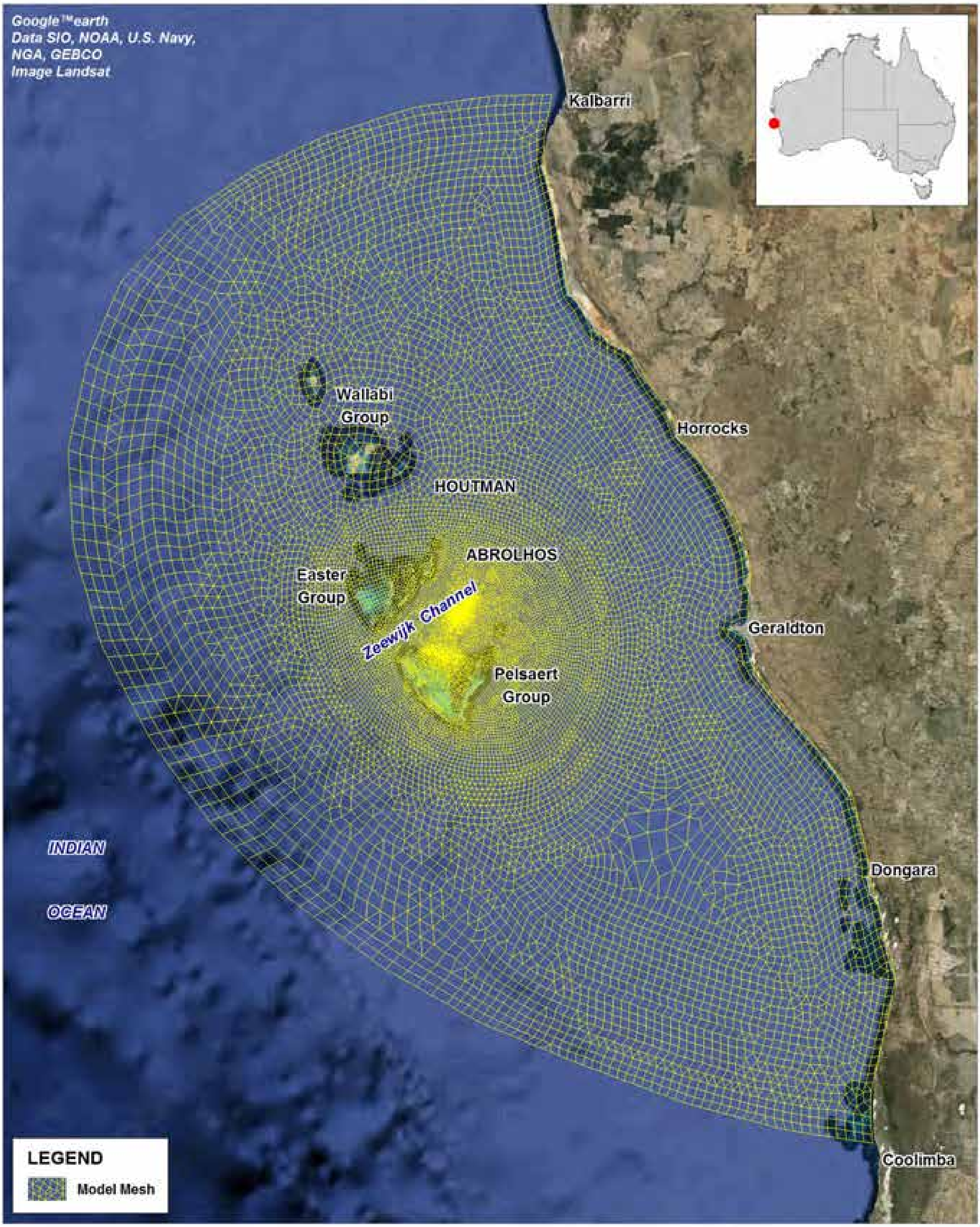

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Model Mesh

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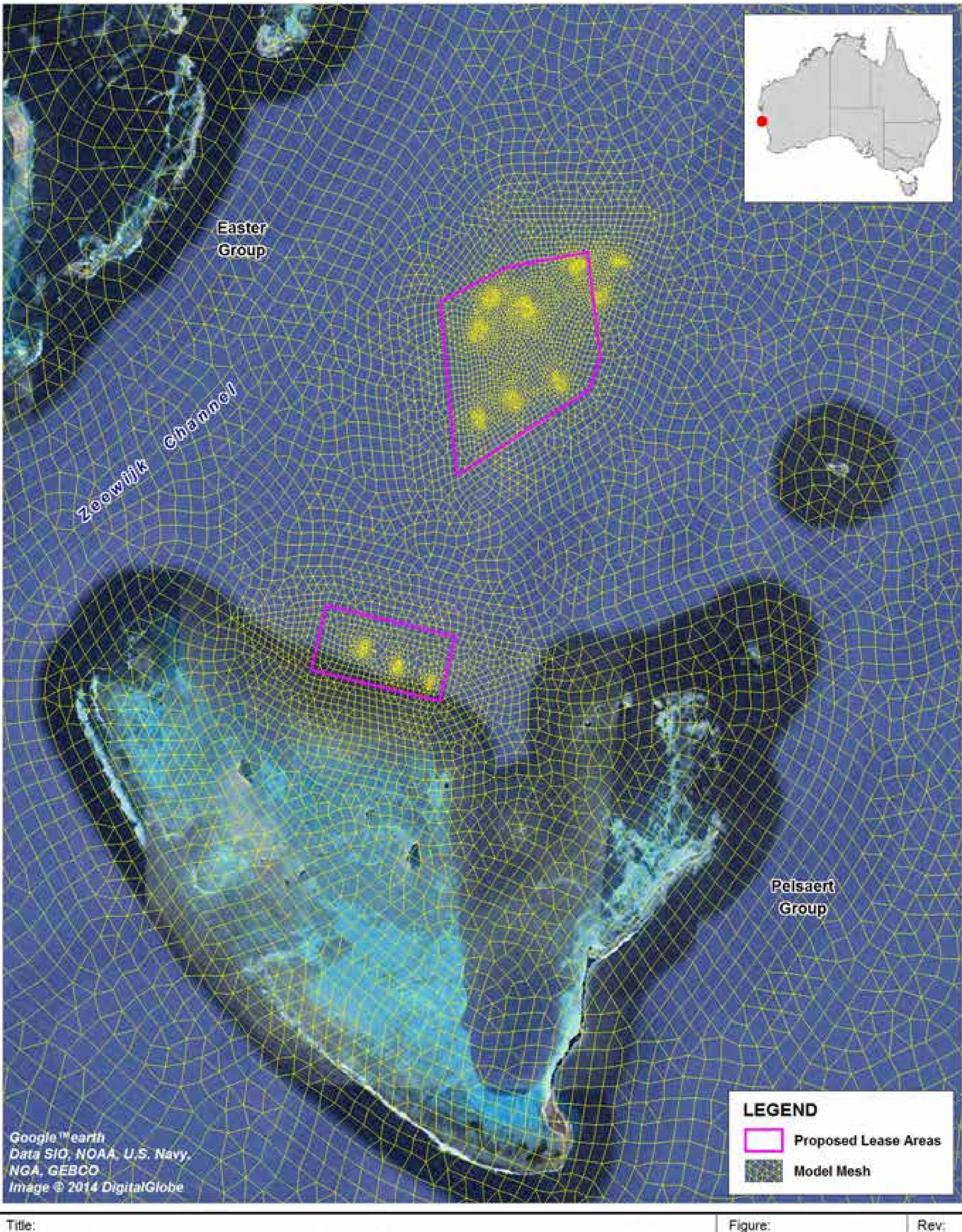

Title:
Model Mesh – Proposed Lease Areas

Figure: 3-4

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3.1.3 Boundary conditions

A number of boundary conditions were required by the model, including water levels, currents, temperature, salinity and meteorological forcing. The datasets used to provide these conditions were as follows:

- Tidal boundary conditions were provided by the TPXO71 global tide model (https://www.esr.org/polar_tide_models/Model_TPXO71.html).
- Regional currents (e.g. Leeuwin Current), residual water levels, temperature and salinity boundary conditions were provided by the global climate model HYCOM (https://hycom.org/). Salinity values provided by HYCOM were found to consistently exceed those measured during the sampling program. As such a constant offset of 0.3 PSU was applied to the salinity forcing. Details of this analysis are provided in Section 4.
- Meteorological data was taken from the US National Centers for Environmental Protection (NCEP) Climate Forecast System Reanalysis (CFSR) model. This is a global data-assimilation model which provides the full suite of meteorological data required by TUFLOW FV, namely: air temperature, rainfall, relative humidity, downward short-wave and long-wave radiation, windspeed and wind direction.
- To resolve potential wave-driven currents plus wave-induced drift and to capture suspension/deposition dynamics driven by waves, a wave field was applied to TUFLOW FV using the model SWAN. SWAN is a third-generation wave model, developed at Delft University of Technology, which computes random, short-crested wind-generated waves in coastal regions and inland waters. In addition to wind data provided by the meteorological datasets above, SWAN also requires swell to be provided on the boundaries. This was sourced from WAVEWATCH III, which is a global wave prediction model developed by the National Oceanic and Atmospheric Administration (NOAA). The SWAN model was run, using default parameters, on a regular grid with 500 m resolution.

Temperature, salinity and regional currents were taken from the HYCOM model, and water-levels were a combination of TPX (for tidal dynamics) and HYCOM (for the non-tidal components). These hydrodynamic boundaries were specified using an active Flather condition (as derived from Flather et al., 1976) which relaxes the barotropic (depth-averaged) component to ensure that the model remains internally consistent and mass conservative.

3.2 Water Quality

The water quality model utilised was the Aquatic Ecodynamics (AED) model library developed at UWA by the research group led by A/Prof. Matt Hipsey (http://aed.see.uwa.edu.au/research/models/AED/). It can simulate a number of biogeochemical pathways relevant to water quality, including nutrient, sediment and algal dynamics (Figure 3-5).

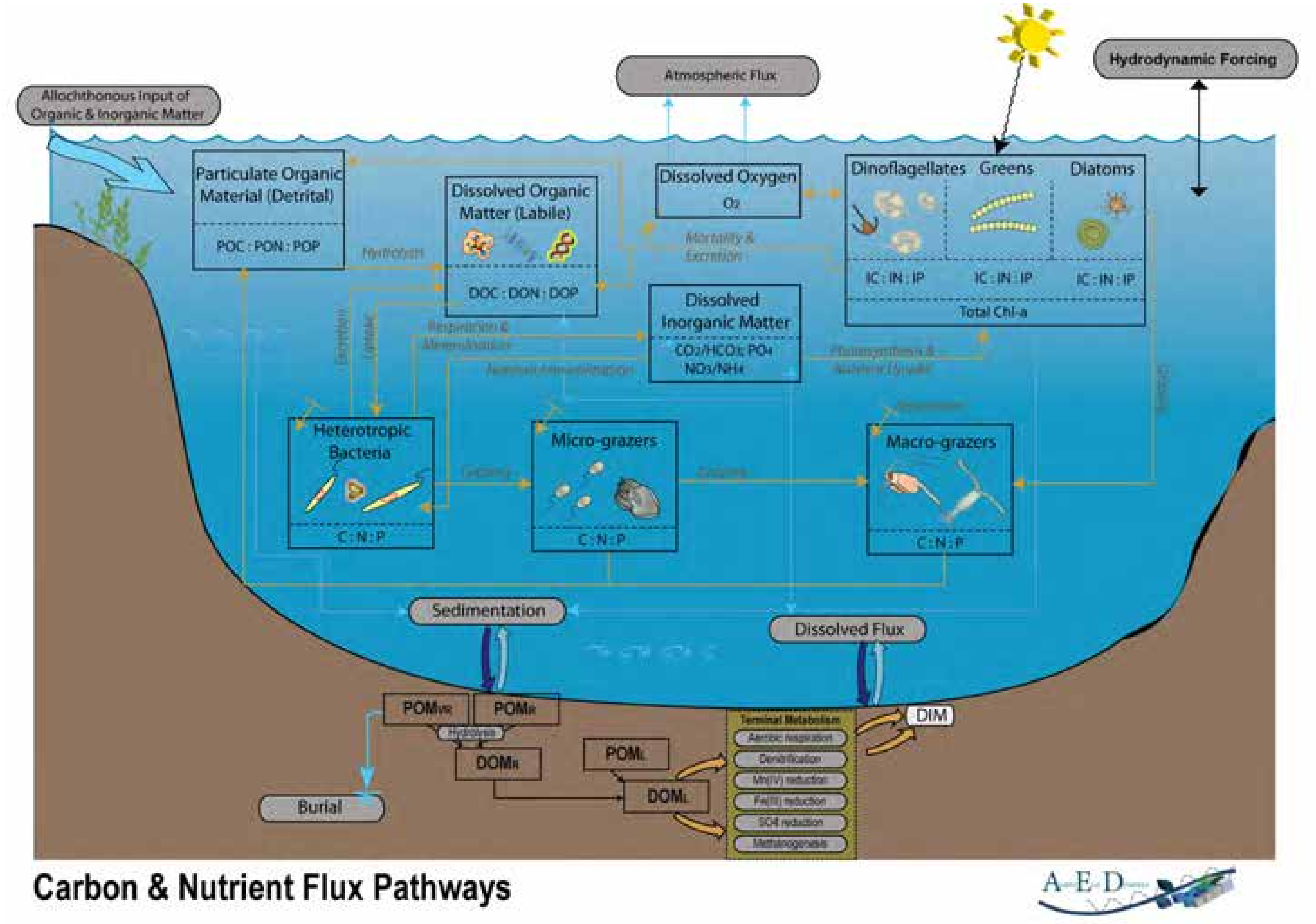


Figure 3-5 Carbon and nutrient processes simulated in AED

Boundary and initial conditions are required for each of the variables simulated by AED. These were derived from the water quality samples conducted as part of this study and are presented in Table 3-2. Rather than seasonally variable values, constant values were applied because an analysis of water quality samples indicated minimal seasonality in the water quality constituents of interest. Figure 3-6 contains time-series of TN and TP concentrations from samples taken at site L1A, from the CSIRO Atlas of Regional Seas (CARS) climatology (http://www.marine.csiro.au/~dunn/cars2009/), and averaged over all samples taken during this study. There is some variability in the samples but this is within the bounds of variability between replicates, as indicated by the two samples of TN taken on 20th June 2014 and 11th March 2014 at site L1A. Generally, however, the figures demonstrate that the CARS data are relatively poor representations of actual conditions (particularly with respect to the key biological nutrient phosphorus) and as such were not used in this study.

Table 3-2 AED variables oceanic boundary and initial conditions

Variable	Value at oceanic boundary (mg/L)
Dissolved Oxygen	6.8
Silicate	0.0281
Ammonia	0.0042
Nitrate	0.014
Filterable Reactive Phosphorus	0.0031
Dissolved Organic Nitrogen	0.09
Particulate Organic Nitrogen	0.012
Dissolved Organic Phosphorus	0.001
Particulate Organic Phosphorus	0.001
Dissolved Organic Carbon	0.204
Particulate Organic Carbon	0.204
Phytoplankton (in mg C / L)	0.006

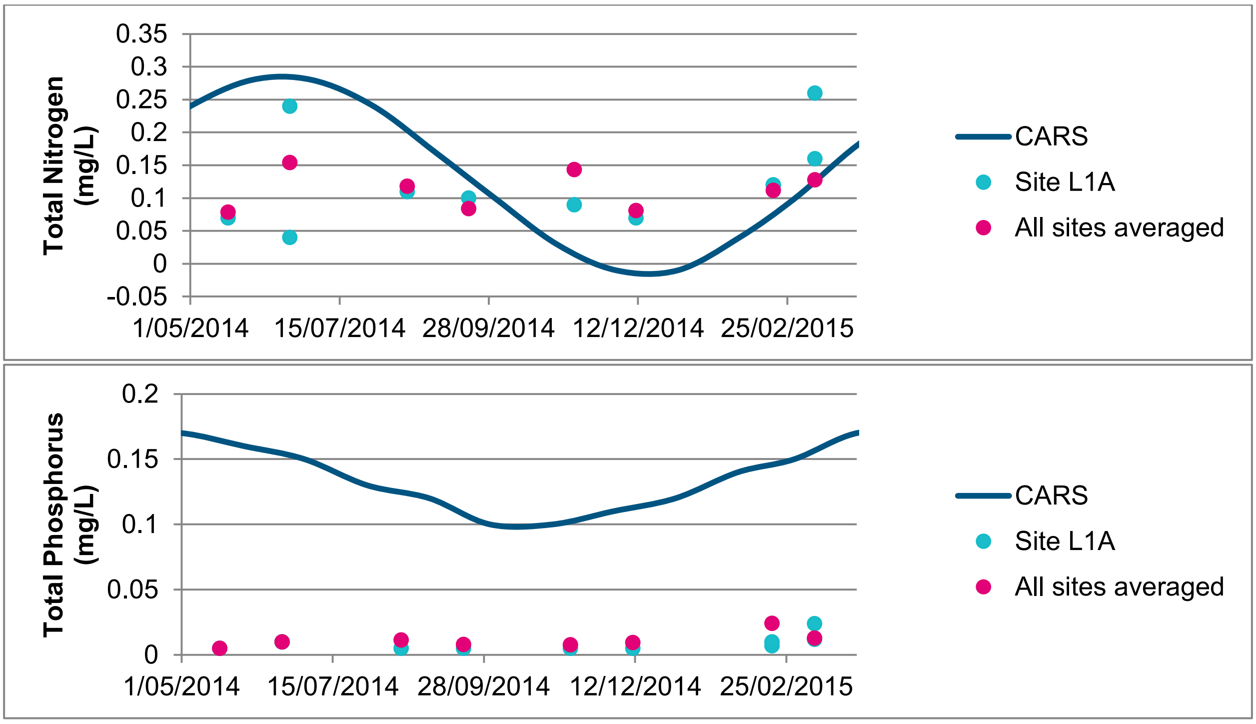


Figure 3-6 TN and TP comparisons between the CARS database and samples taken in the course of this study

4 Calibration Results

Once constructed, the hydrodynamic and water quality model was run for a period of one year from 1st March 2014 to 1st March 2015 to encompass the majority of the sampling program. The model could not be run further into the March period (to capture samples taken on 11th March 2015) as not all boundary conditions were available at the time.

Model results were compared against observations for a number of key hydrodynamic and water quality variables, as described in the sub-sections below. In addition to time-series plots, a suite of univariate statistics was used to compare model data with observations, where appropriate, using the approach outlined in Stow et al. (2009). The statistics examined were:

- The r statistic
- Average error (AE)
- Root mean squared error (RMSE)
- Absolute average error (AAE)
- Modelling efficiency (MEF).

Univariate statistics are sensitive to phase errors and should be considered in concert with the time-series plots for this reason. The suite of metrics should also be considered in their entirety, as some statistics may provide a misleading impression of the skill of the model. For example, a score of 1 for the r statistic indicates that the model varies perfectly in step with the observations, but it says nothing about any bias that may be present. Also, high scores for RMSE, AE and AAE may indicate a bias within the model, or may just be the result of one or two outlier observations that affect the overall score. The following provides some notes on interpreting each metric:

- r
  - Varies between -1 and 1, with a score of 1 indicating the model varies perfectly with the observations and a negative score indicating the model varies inversely with the observations. Model and observations do not need to match to provide a high score, as a consistent bias may be present.
- AE
  - Measures the mean magnitude and direction of the difference between model data and observations, and hence can be used to measure bias. Values near zero are desirable but negative and positive errors cancel each other out so low scores can be misleading.
- RMSE
  - Measures the mean magnitude, but not direction, of the difference between model data and observations. This accounts for the cancelling of positive and negative errors, but is weighted towards large errors and is therefore sensitive to outliers. Values near zero indicate good model skill.
- AAE

    - Also measures the mean magnitude, but not direction, of the difference between model data and observations. AAE is always equal to or lower than the RMSE and the difference between the two is a measure of the variability of the errors. If the difference between AAE and RMSE is low, this indicates a consistent bias and low error variability; if the difference is large, this indicates a small number of outliers and high error variability. Values near zero indicate good model skill.

- MEF
    - Is a measure of how well a model predicts observations relative to the mean of the observations. A value near 1 suggests the model is skilful. A value near 0 suggests the model is no better at predictions than the average of the data. A value below 0 indicates that the mean of the observations would be a better predictor than the model.

The following sub-sections contain the time-series plots, statistics and additional commentary on each of the variables compared. Each sub-section contains a brief summary of results initially, followed by more detailed analysis subsequently.

4.1 Hydrodynamic calibration

4.1.1 Water levels

4.1.1.1 Summary

The model captures the variability of water levels very well, over timescales ranging from a single tidal cycle (i.e. the timing of high/low tide) to fortnightly spring/neap dynamics and monthly variability of residual water levels. Tidal range is slightly under-predicted at both lease-area and regional sites, by approximately 4-7 cm on average. Thirteen constituents were utilised from the TPX tide model, which should be sufficient to resolve the diurnal signal in this region. The under-prediction is therefore likely due to errors in the magnitude of constituents within the TPX model.

To investigate the under-prediction of tidal range, a sensitivity test was conducted with the range increased by 30% at the open boundary. This improved the water-level calibration slightly, but tidal range was still under-predicted at the regional sites and the change proved detrimental to the velocity calibration at the lease-area sites. In the context of this study, current velocities are of greater importance than water-levels in simulating the fate of particles released from aquaculture activities. Although the tidal range was slightly under-predicted, it was decided to proceed with the original TPX tidal forcing to obtain the best possible representation of the velocity field.

4.1.1.2 Additional detail

Depth measurements were taken at the four ADCP locations outlined in Section 2.1. For comparison against the model, which is referenced to Australian Height Datum (AHD), measurements for each sensor and each deployment were referenced to the mean of the measurements. In most cases, this resulted in a clear bias (e.g. Figure 4-1) and so a constant offset was applied to the data to allow for a like-for-like comparison. The offset applied to each set of data is provided in Table 4-1.

The ADCP in the southern lease area did not collect depth data for all except the final deployment (Feb 2015 to Mar 2015). To produce comparisons for these periods, therefore, the depth data from the nearby northern lease area was used, with a further offset of 2.5m applied to account for bed elevation differences between the sites.

Note that the time-series plots below contain codes to reference each location, as follows:

- ADCP_L1 – northern lease-area site
- ADCP_L2 –southern lease-area site
- North AWAC – northern regional site
- South AWAC – southern regional site.

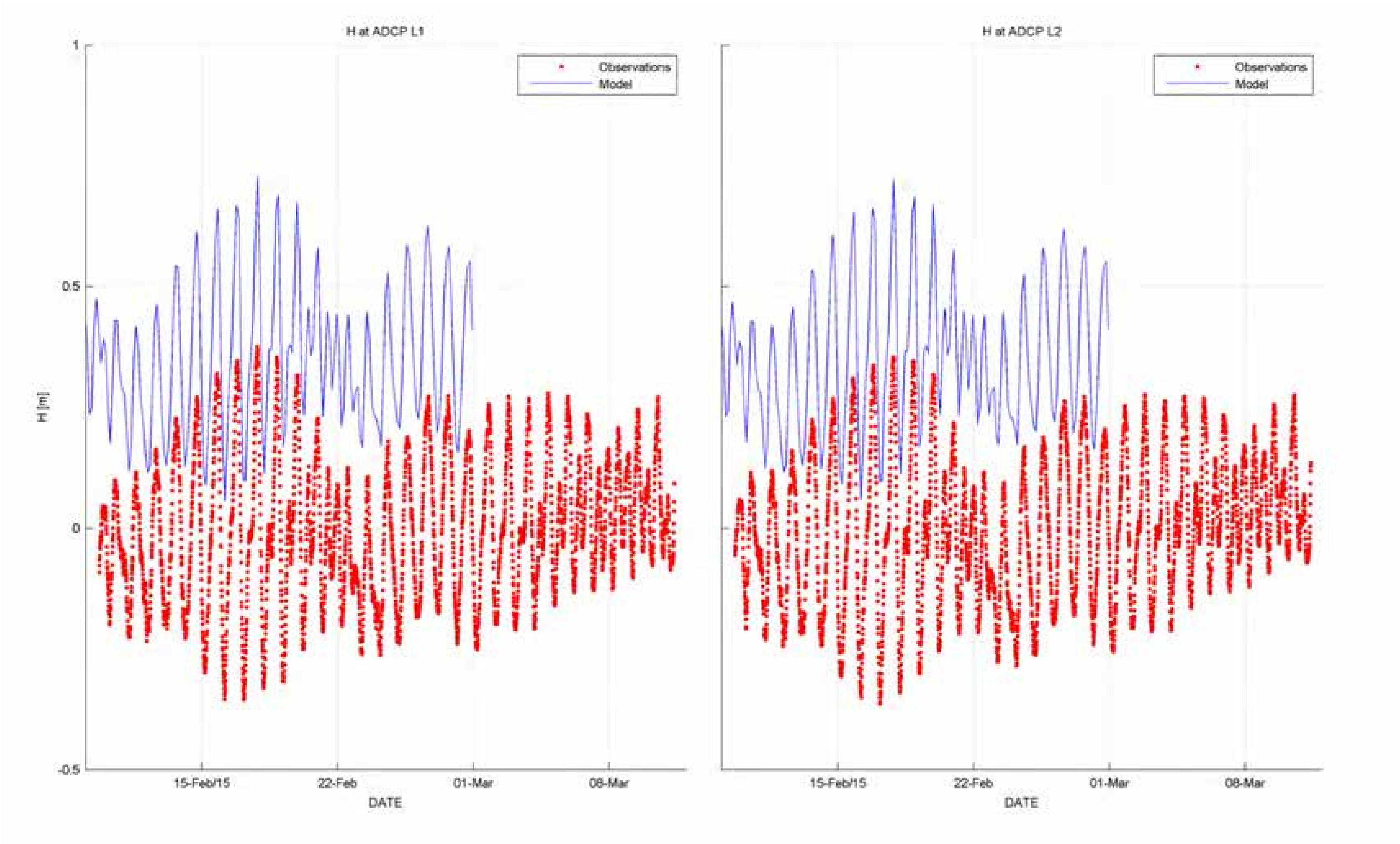


Figure 4-1 Example of bias when comparing simulated water levels (H) against depth measurements referenced to their mean

Table 4-1 Table of offsets applied to allow a comparison between model results (referenced to AHD) and depth measurements

Location (code)	Deployment	Offset (cm)
Northern lease area (ADCP_L1)	May 2014 to Jun 2014	50
	Aug 2014 to Sep 2014	35
	Nov 2014 to Dec 2014	25
	Feb 2015 to Mar 2015	25
Southern lease area (ADCP_L2)	May 2014 to Jun 2014	50
	Aug 2014 to Sep 2014	35
	Nov 2014 to Dec 2014	25
	Feb 2015 to Mar 2015	40
Northern regional (North AWAC)	Jul 2014 to Nov 2014	37
	Nov 2014 to Mar 2015	32
Southern regional (South AWAC)	Jul 2014 to Nov 2014	30
	Nov 2014 to Mar 2015	32

Water-level comparisons at the regional sampling sites outside of the lease areas (North AWAC & South AWAC) are presented in Figure 4-2 (first deployment) and Figure 4-3 (second deployment). For clarity, additional plots of the same comparison broken down into individual calendar months are presented in Appendix B.1. The plots indicate that the model does a good job of capturing variability across multiple timescales, with r values of 0.954 to 0.974. The model slightly under-predicts the tidal range in these regions, with RMSE of approximately 5-6 cm, which is small in the context of a 1 m tidal range.

Water-level comparisons within the lease areas are presented in Figure 4-4 to Figure 4-7. The model again captures variability well in this region, with r values of 0.945 to 0.972, although tidal range is also slightly underestimated, with RMSE of 4-7 cm.

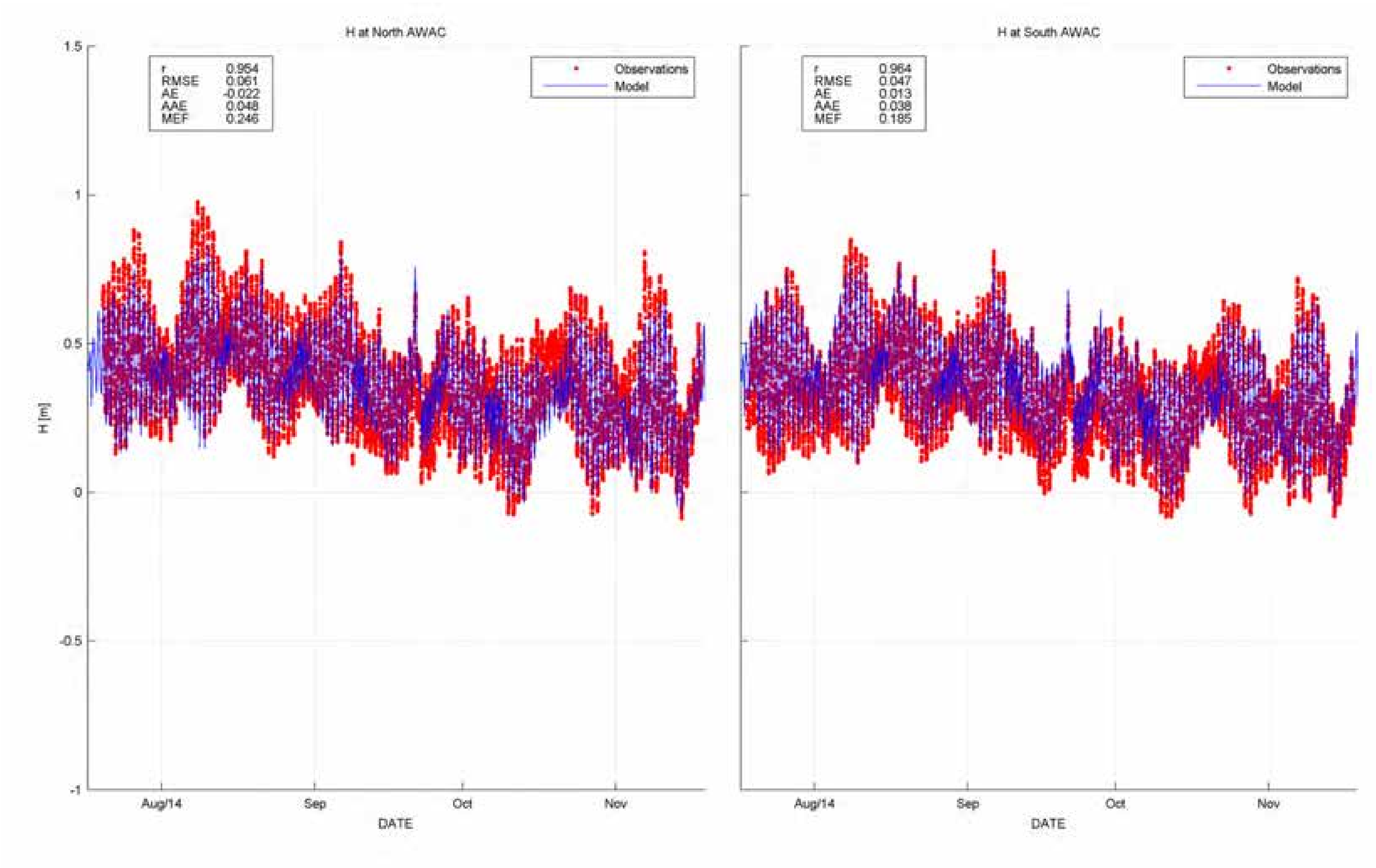


Figure 4-2 Water-level comparisons at regional sites – July 2014 to Nov 2014 deployment

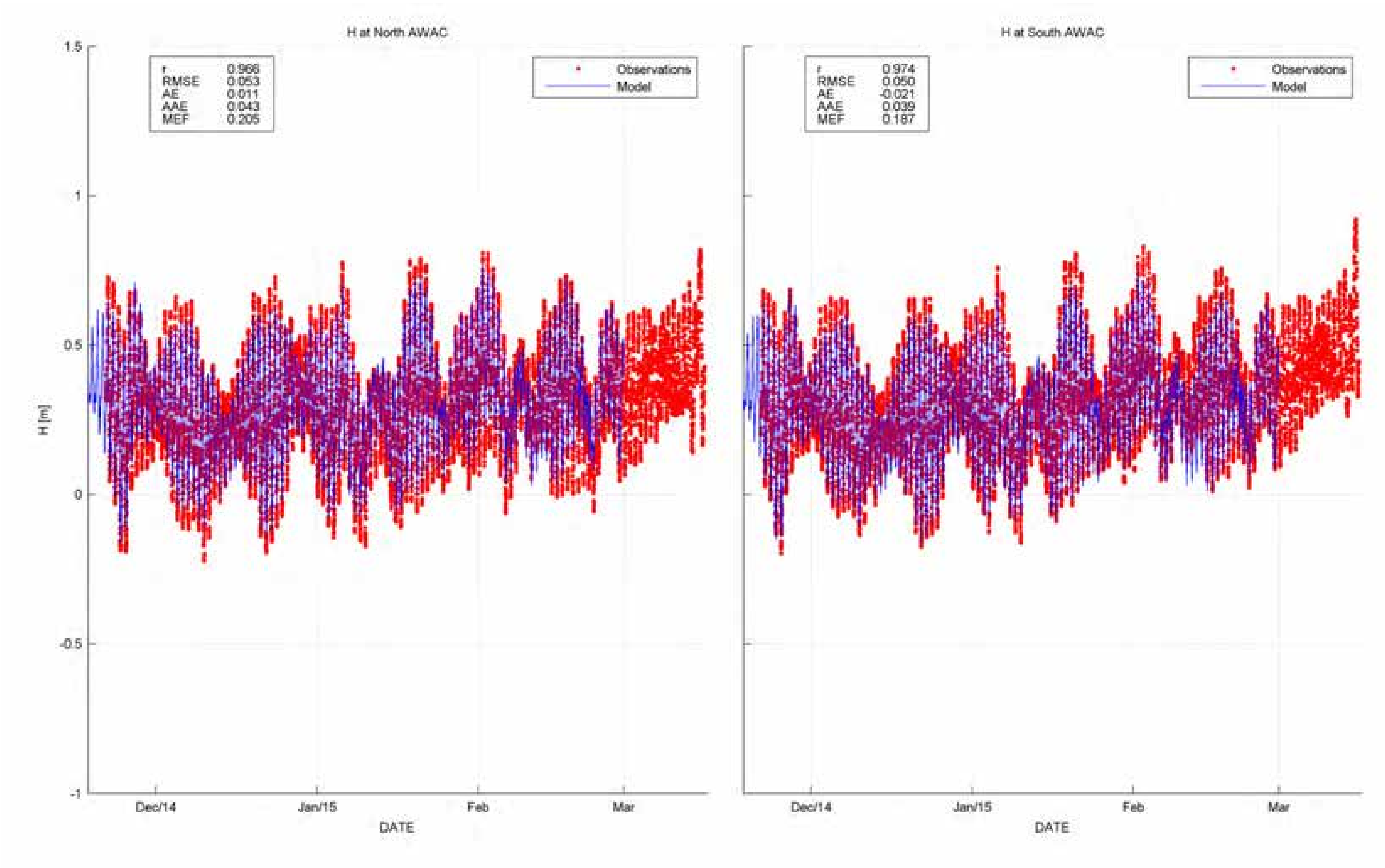


Figure 4-3 Water-level comparisons at regional sites – Nov 2014 to Mar 2015 deployment

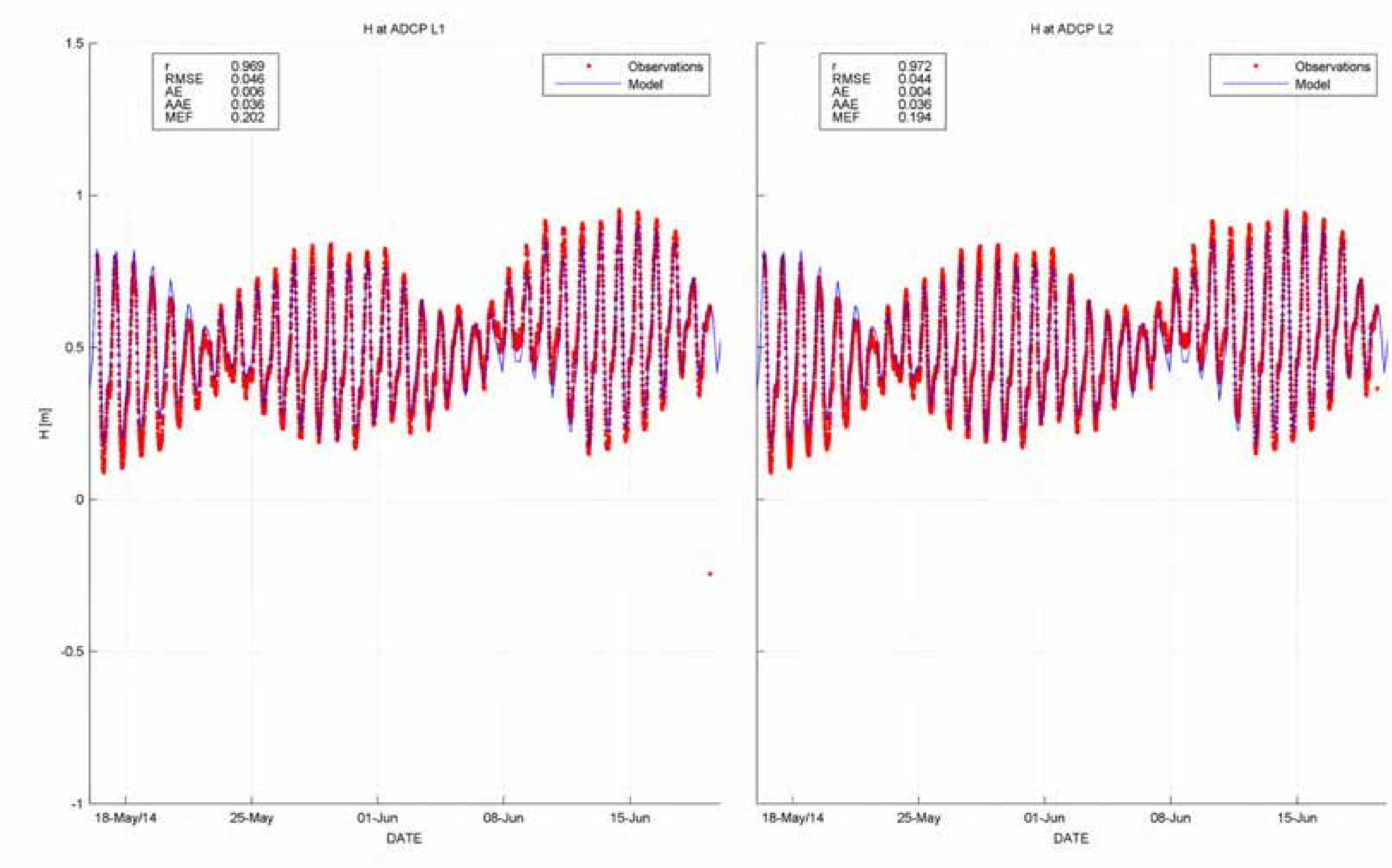


Figure 4-4 Water level comparisons at sampling sites within the proposed lease areas – May 2014 to Jun 2014 deployment

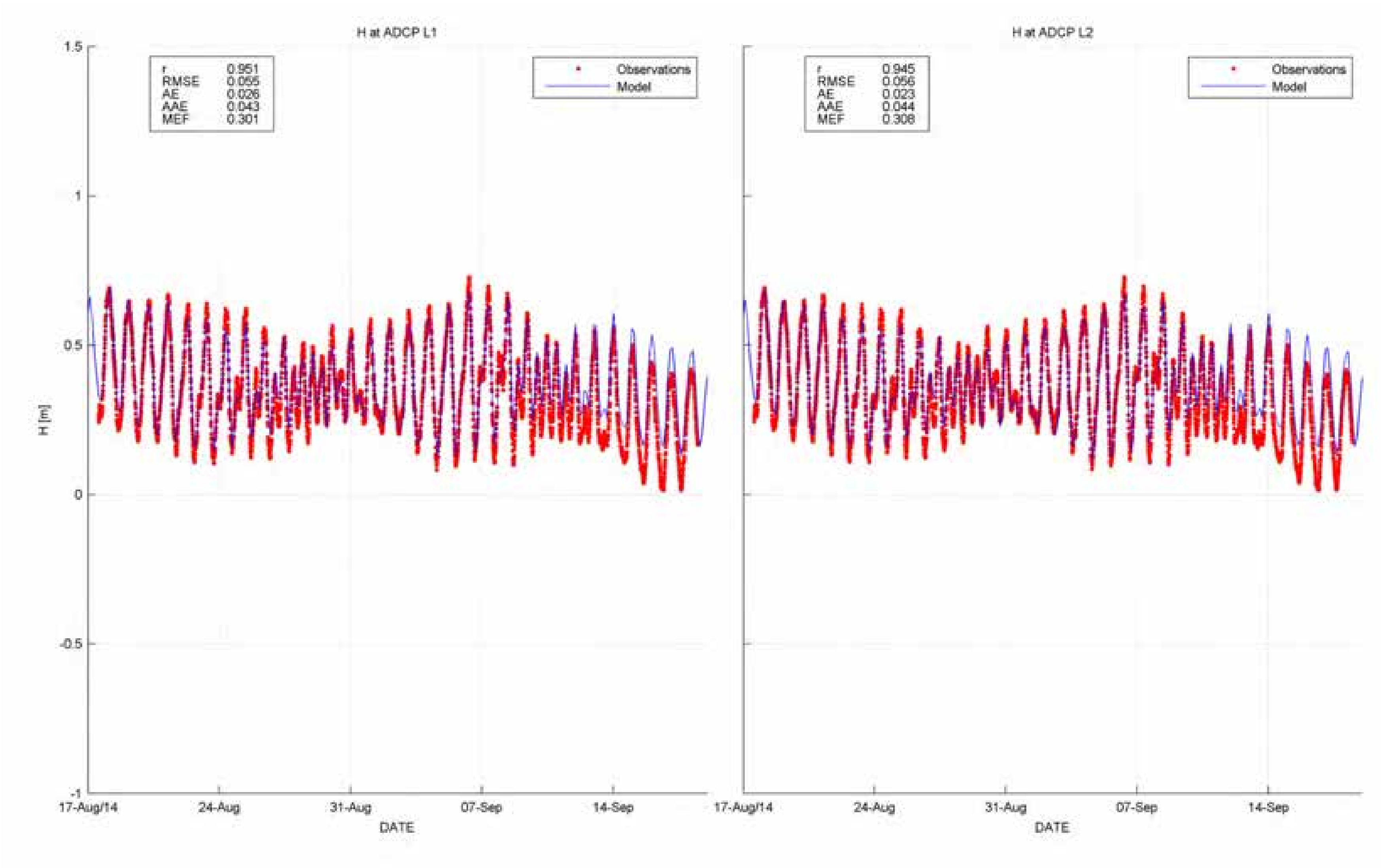


Figure 4-5 Water level comparisons at sampling sites within the proposed lease areas – Aug 2014 to Sep 2014 deployment

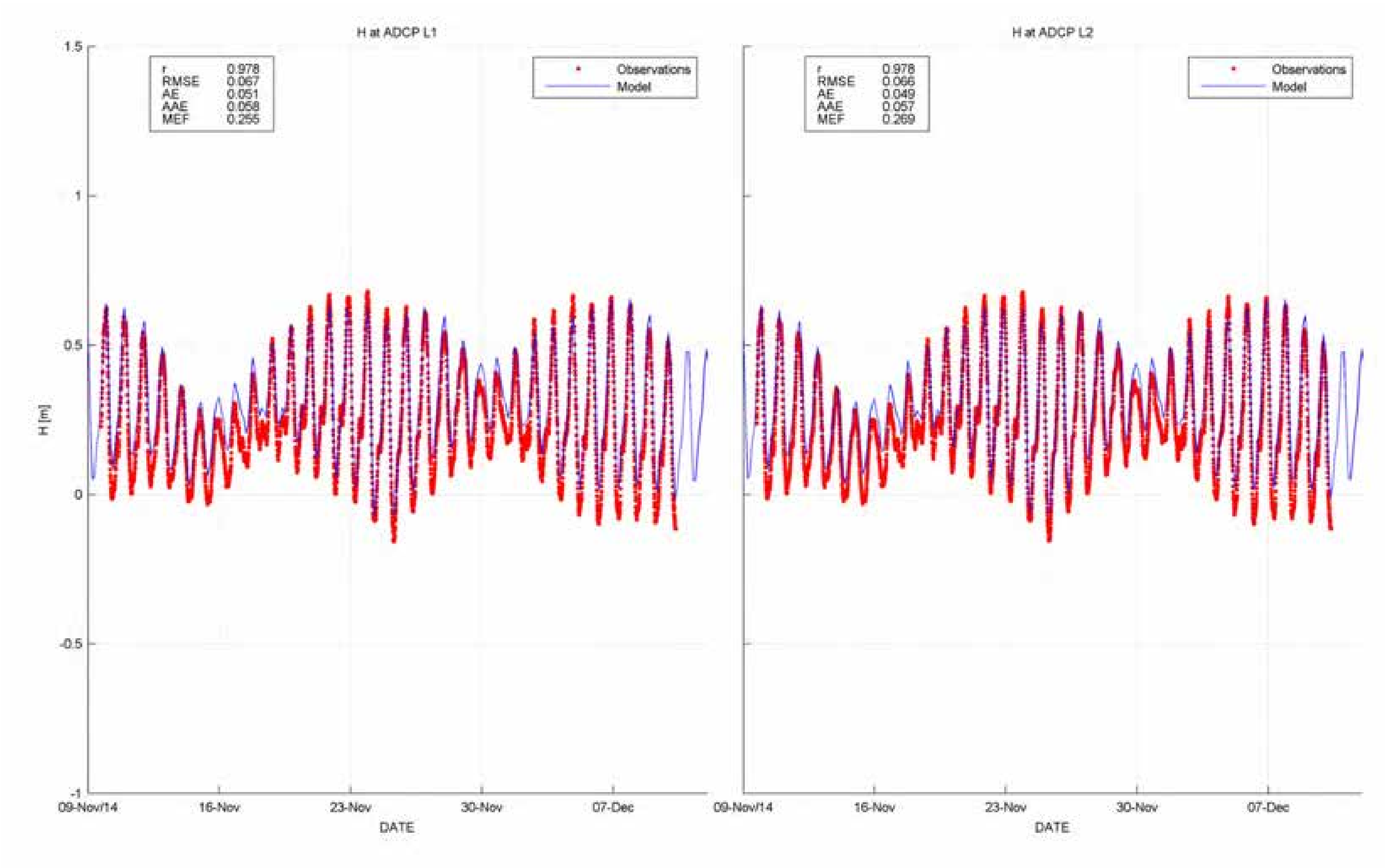


Figure 4-6 Water level comparisons at sampling sites within the proposed lease areas – Nov 2014 to Dec 2014 deployment

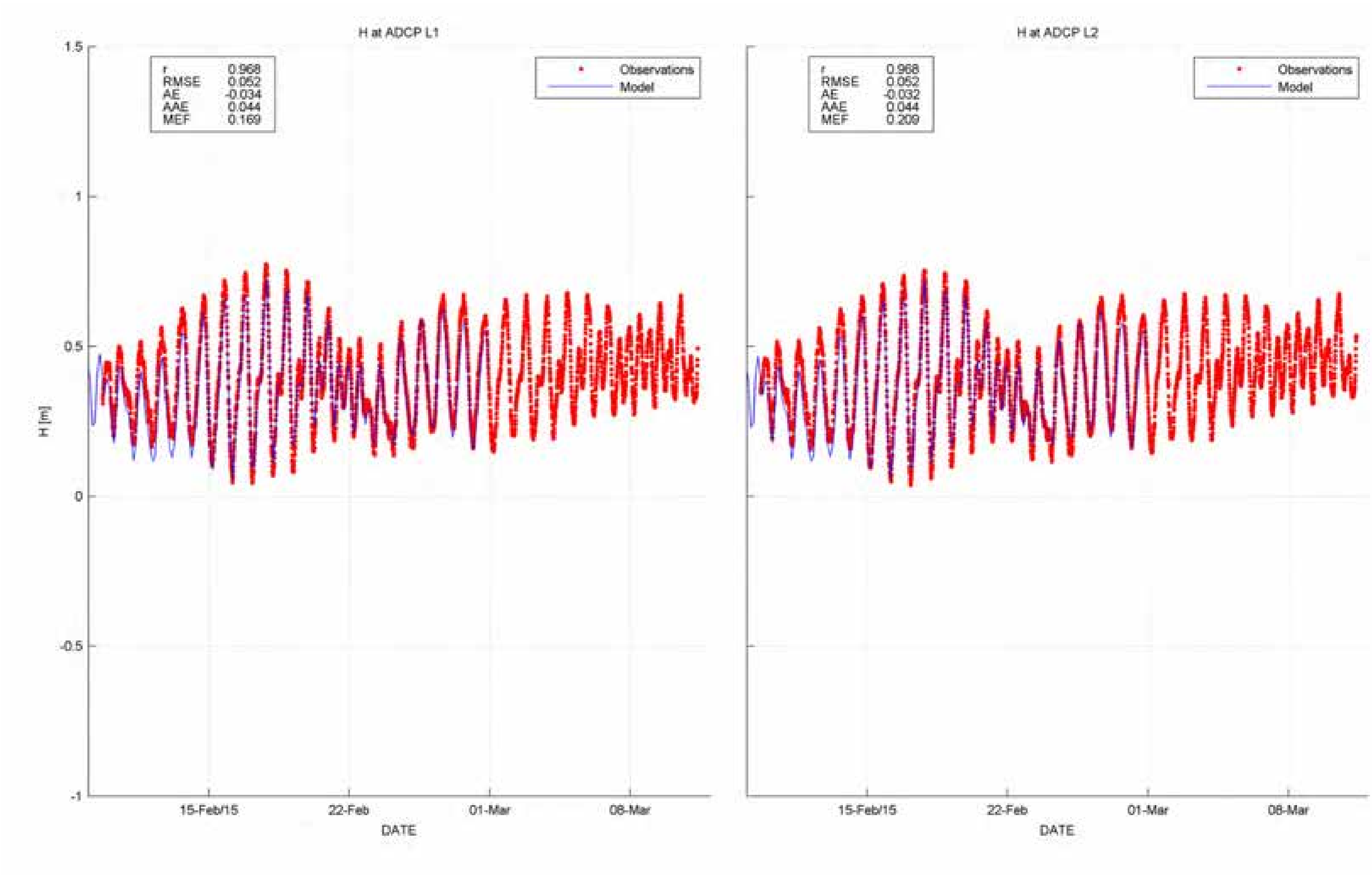


Figure 4-7 Water level comparisons at sampling sites within the proposed lease areas – Feb 2014 to Mar 2014 deployment

As noted in the summary above, to address the under-prediction of tidal range, a test run was conducted which increased the magnitude of the tide at the oceanic boundary by 30%. This improved the comparison outside of the lease areas, although the model still under-predicted the tidal range (Figure 4-8). Within the lease areas, the tidal range was then over-predicted, with a RMSE of 6-7 cm, similar to the magnitude of error in the run without modifying the tidal forcing (Figure 4-9). Furthermore, modifying the tidal forcing adversely affected the velocity calibration within the proposed lease areas. In the context of the distribution of particles arising from aquaculture activities, velocity was considered to be more important than water level. It was decided, therefore, to continue with the original tides as these provided a better velocity calibration in the area of interest. Additional plots pertaining to this analysis are presented in Appendix B.1.2.

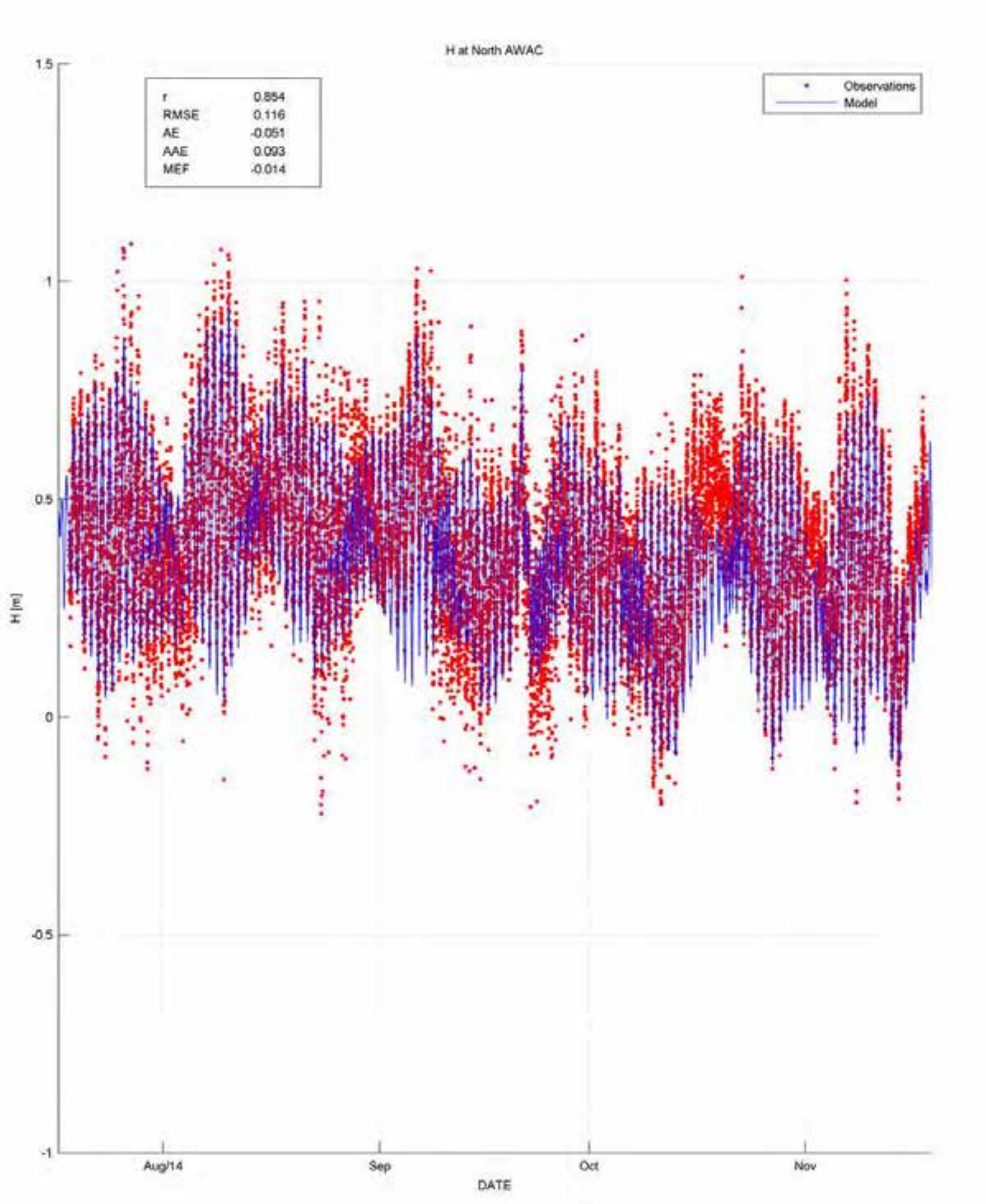


Figure 4-8 Example of under-prediction of tidal range at regional sites following modification of boundary condition

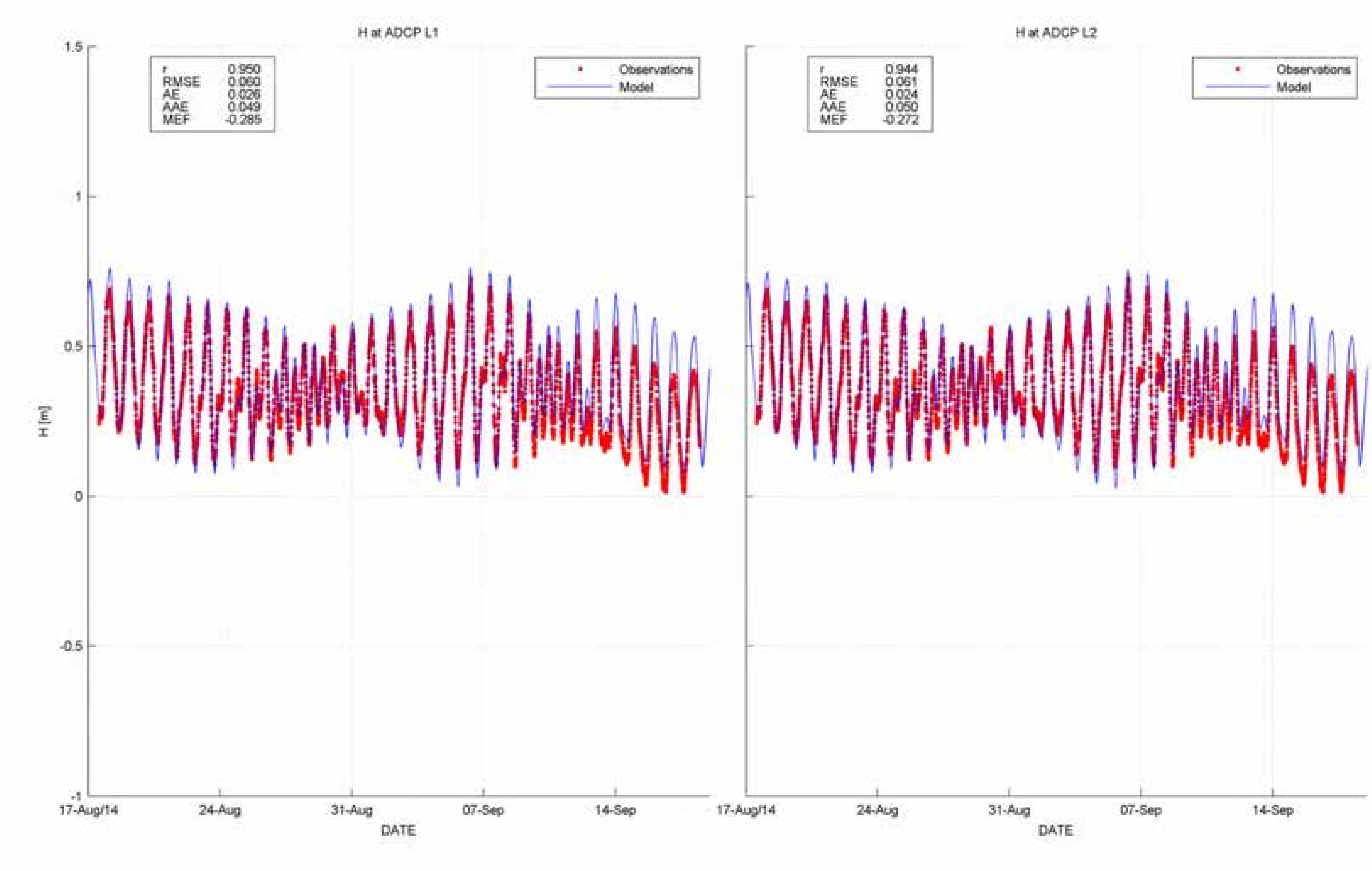


Figure 4-9 Example of over-prediction of tidal range at lease-area sites following modification of boundary condition

4.1.2 Velocities

4.1.2.1 Summary

Simulated current velocities compared very well with observations at both regional and lease-area sites. The model successfully captures both the variability and magnitude of velocities at all sites, with good scores for the skill metrics outlined at the beginning of Section 4. As noted in Section 3.1, a primary aim of the hydrodynamic model is to provide a satisfactory representation of the velocity and wave field, for the purposes of simulating the fate of particles released from aquaculture activities.

It is BMT WBM's opinion that the model does an excellent job of predicting the velocity field within this region. The choice of active Flather condition for the combination of TPX and HYCOM data at the open boundary results in a very favourable comparison with observations at the open-ocean sites. Furthermore, the local features within the Pelsaert and Easter island groups are sufficiently well-resolved to capture the important processes affecting the velocity field within this region, which is particularly challenging to simulate due to the dynamic interaction between regional currents and local bathymetric features.

4.1.2.2 Additional detail

Velocity measurements from each deployment were decomposed into X (east-west) and Y (north-south) components prior to comparison against model results, to allow for line-plot comparisons of both easterly and northerly components of velocities. Such comparisons provide greater transparency and allow for easier interpretation of model skill, when compared against, for example, rose-plot snapshots or vector plots. Each dataset was also analysed to remove values that were considered to be affected by surface noise (e.g. breaking waves), which would adversely skew depth-averaged velocity. A comparison of a velocity field pre- and post-removal of surface noise is included in Figure 4-10.

Comparisons of velocities for the regional sites are presented in Figure 4-11 and Figure 4-12. The time-series plots demonstrate that the model does an excellent job of recreating observed velocities, and that it is capturing regional currents well. This is also borne out by the univariate metrics, with r values of 0.745 to 0.915 and relatively low AAE values of 0.033 m/s to 0.077 m/s (mean observed velocities are 0.119 m/s to 0.147 m/s).

During July and August 2014, the X component of velocity in the model is positive while observations tend to zero. This may be due to a water-level gradient towards the coast that is not recreated by the model (which is ultimately driven by the third-party HYCOM data), or by slight errors in the direction of regional currents in HYCOM during this period. Some efforts were made to overcome this through modifying the X component of velocity in the boundary conditions, but this was detrimental to the overall calibration in other areas. Rose plots summarising the surface velocity fields at these locations are presented in Figure 4-13 and Figure 4-14, and additional surface and bottom velocity time-series plots are included in Appendix B.2. Other departures from observations (e.g. late August at the southern regional site) may be caused by slight errors in the HYCOM or CFSR forcing data. These errors are not consistent and, hence, are unlikely to be caused by a fixed component such as model bathymetry or parameterisation.

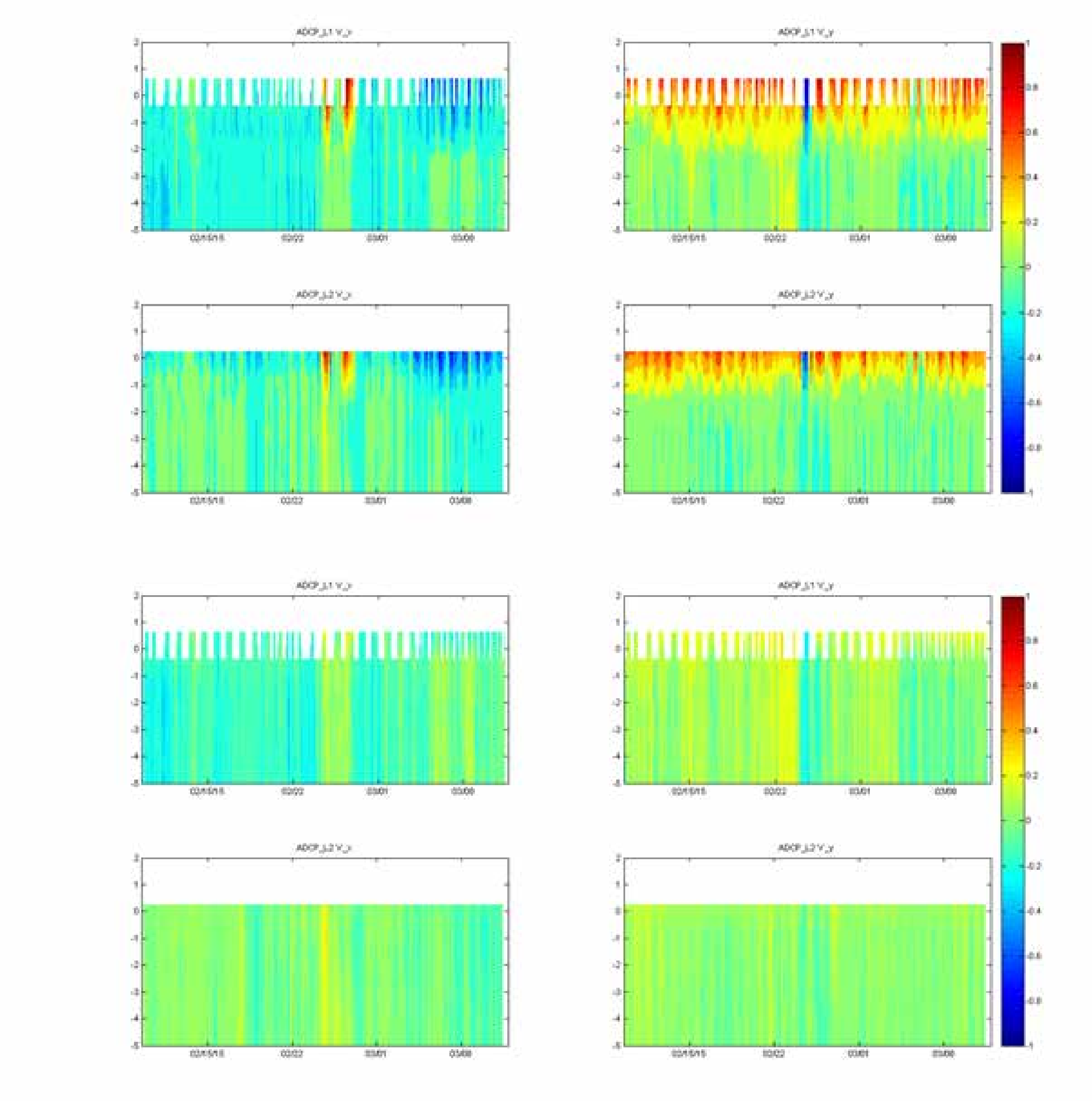


Figure 4-10 Comparisons of velocity fields (in m/s) prior to removal of surface noise (top 4 panels) and after removal of surface noise (bottom 4 panels)

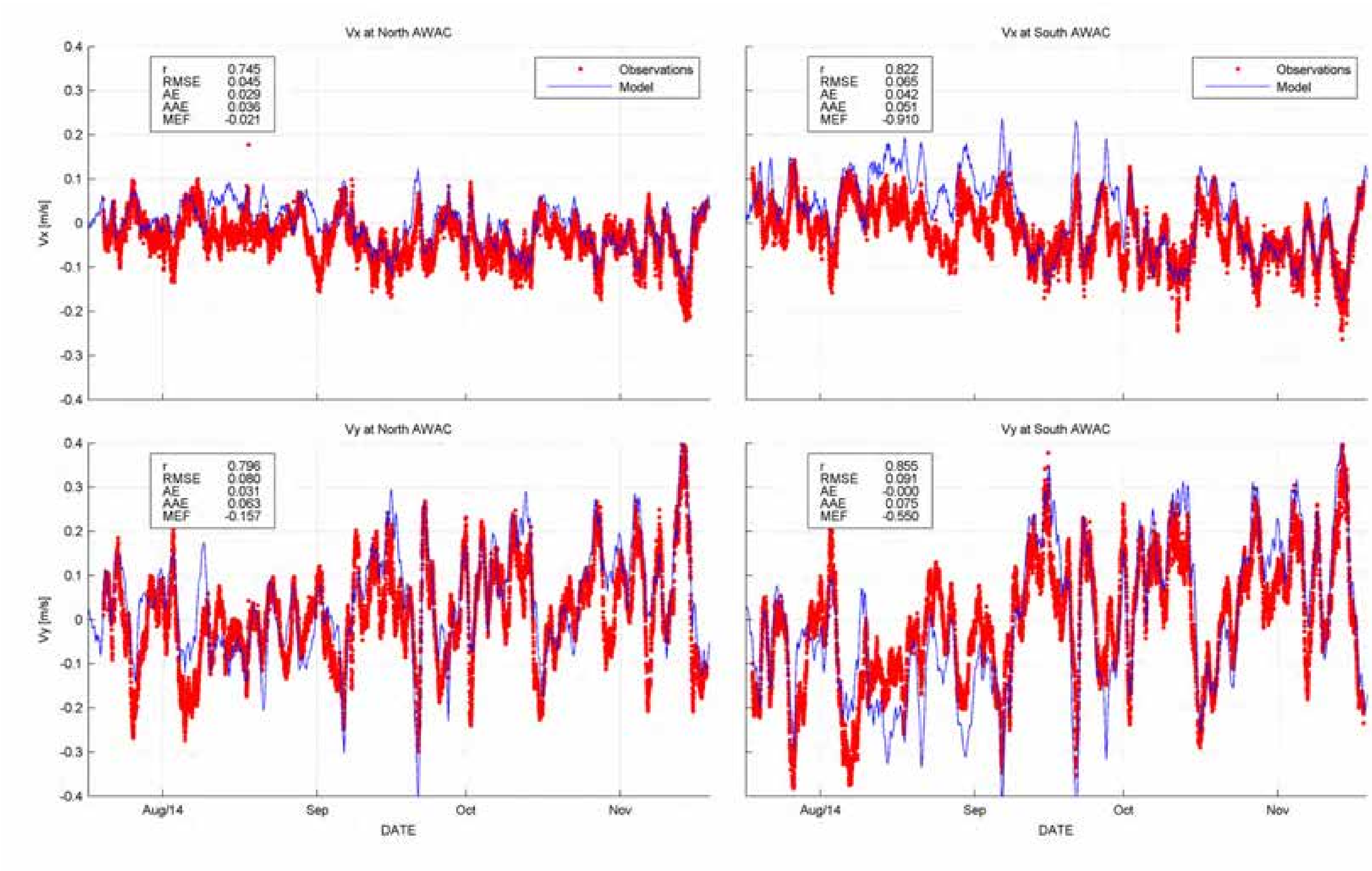


Figure 4-11 Depth-averaged velocity at sites outside of the proposed lease areas – Jul 2014 to Nov 2014 deployment

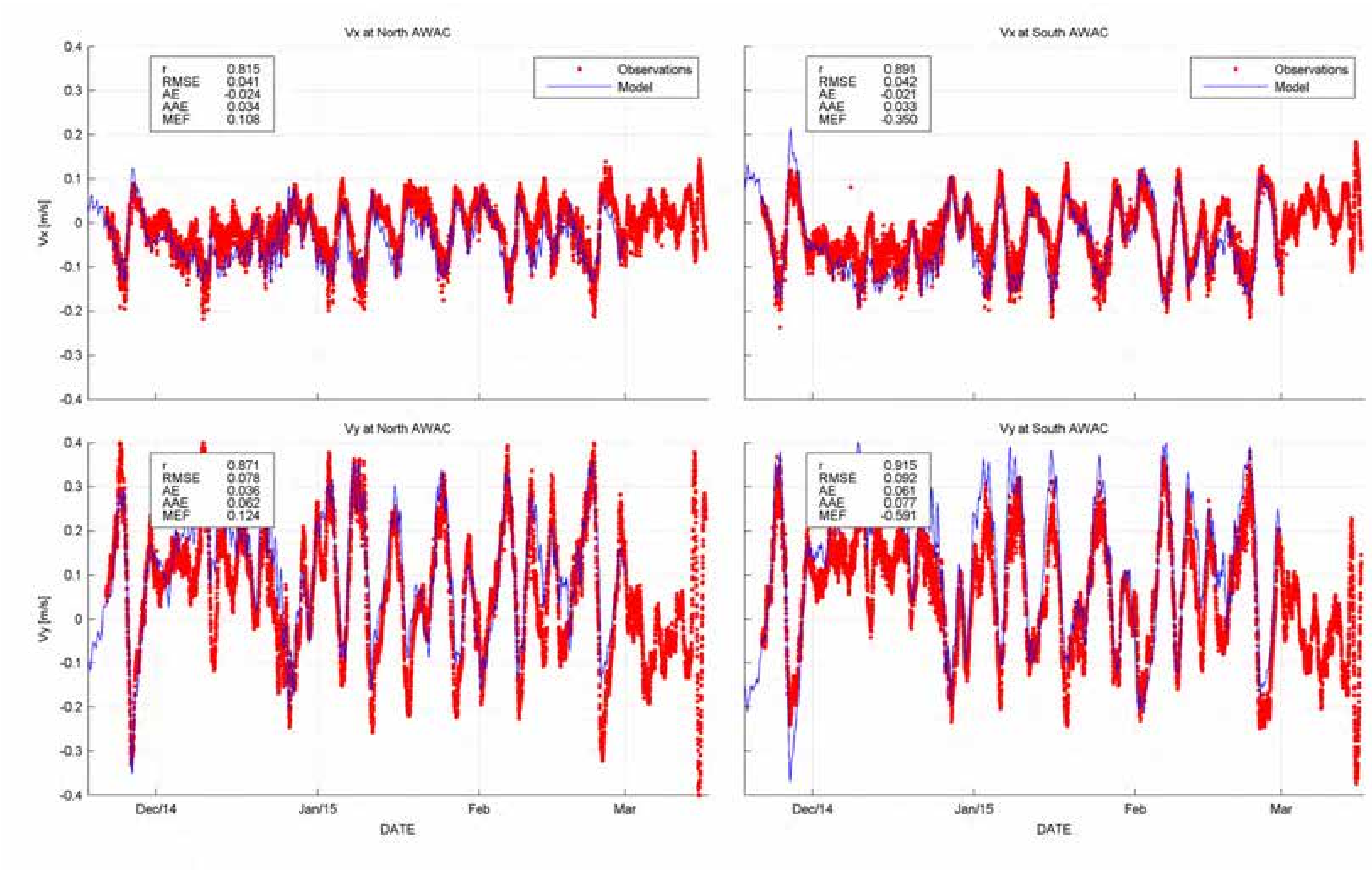


Figure 4-12 Depth-averaged velocity at sites outside of the proposed lease areas –Nov 2014 to Mar 2015 deployment

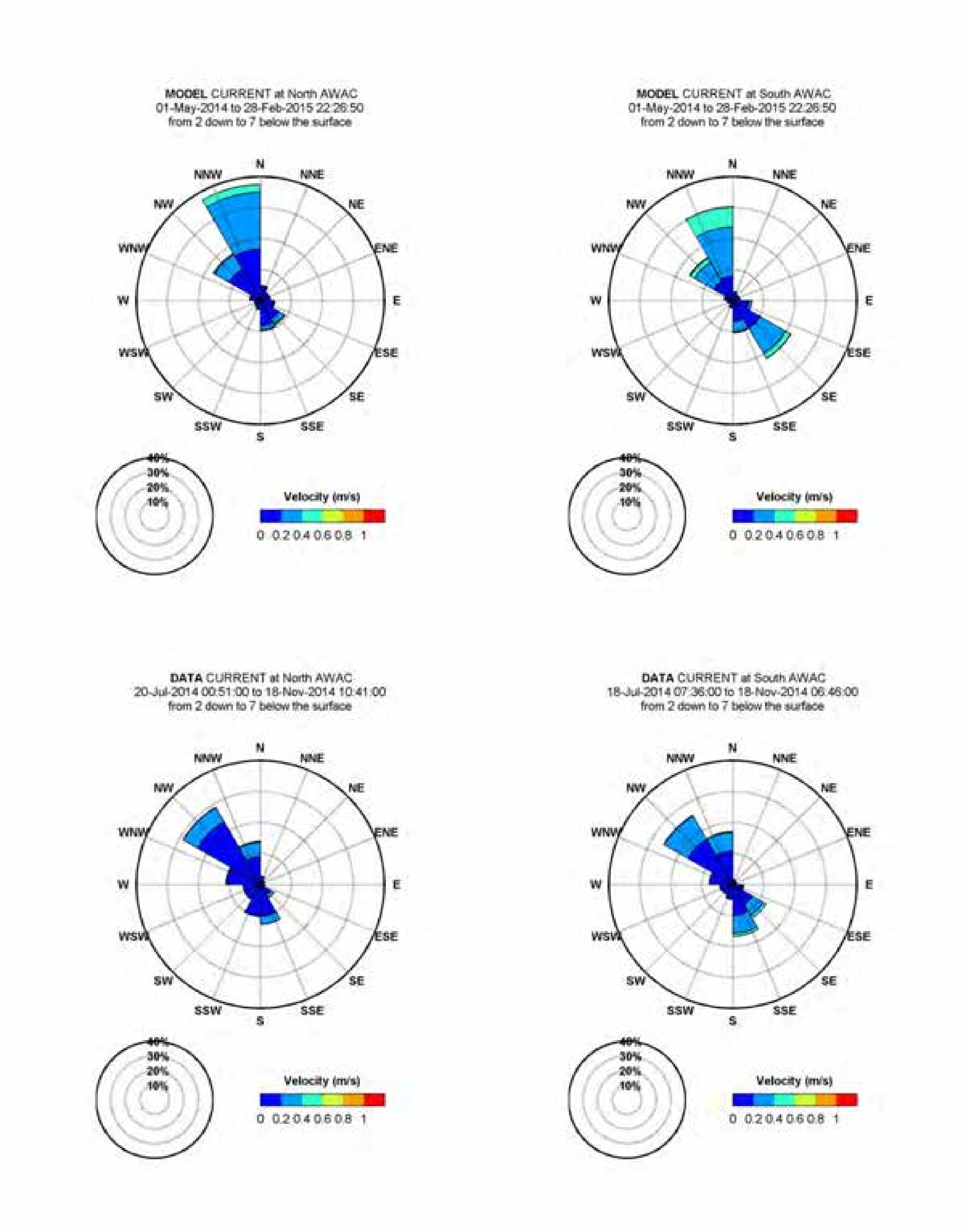


Figure 4-13 Rose plot of surface (2m to 7m depth) velocity – Jul 2014 to Nov 2014 deployment

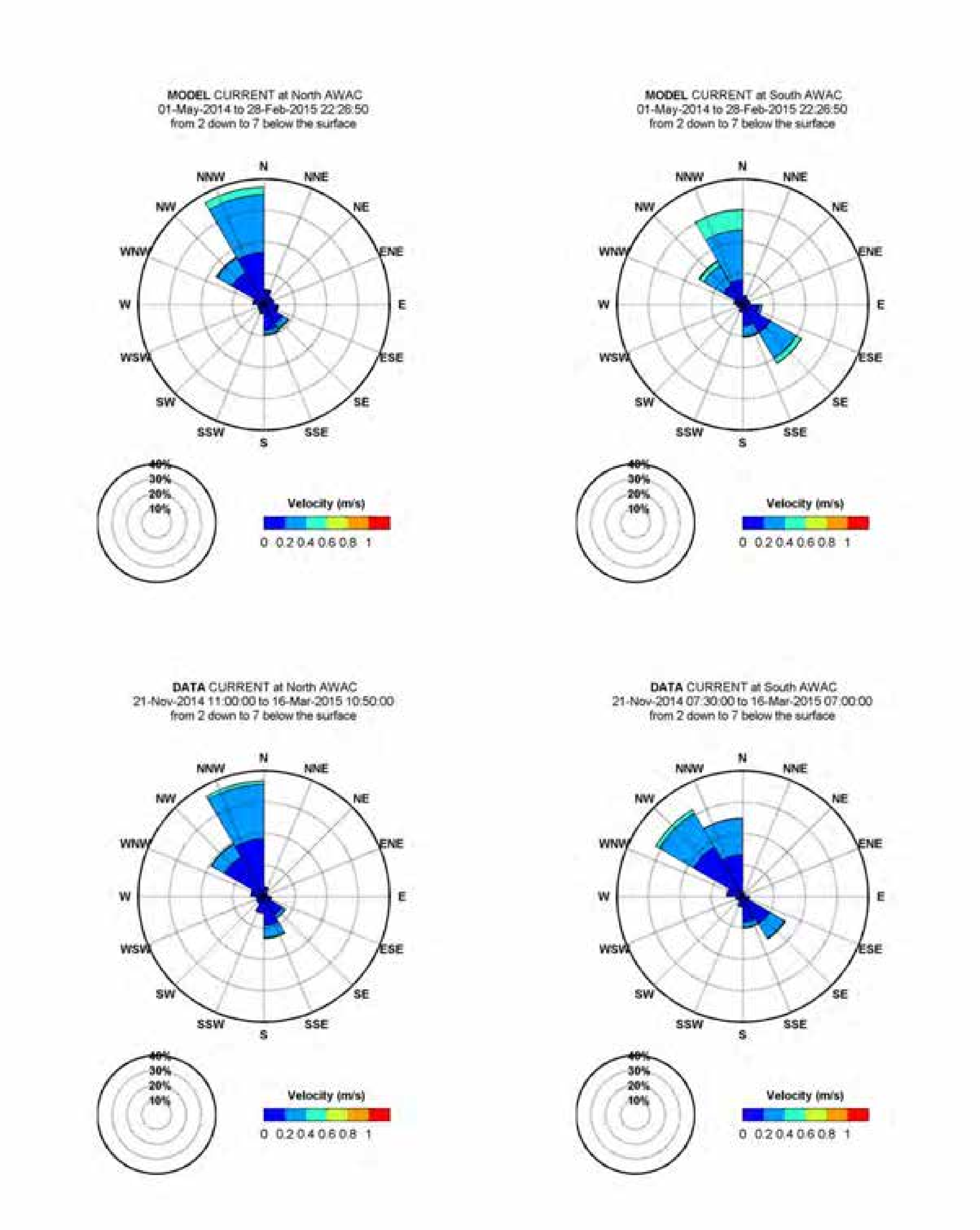


Figure 4-14 Rose plot of surface (2m to 7m depth) velocity – Nov 2014 to Mar 2015 deployment

Depth-averaged velocity comparisons for sites within the lease areas are presented in Figure 4-16 to Figure 4-19. In comparison to the open-ocean sites, this region poses a greater challenge to the model in that regional currents interact with islands and other bathymetric features to create a dynamic environment. Depending on the corresponding regional eddy field, the prevailing currents can rapidly switch from an east-to-west flow through the Zeewijk Channel, to flow in the opposite direction (e.g. during late November at site ADCP L1, Figure 4-18). Despite the difficulties of modelling such an environment, the model does an excellent job of recreating the observed velocities, albeit with slightly lower statistical scores than at the open-ocean sites. During some periods (e.g. May 2014) the model does not always match the variability of the measured velocity fields, which, as noted above, is likely due to errors in the boundary forcing data as it is not a consistent feature throughout. There are other periods (e.g. November 2014) in which the model follows observations very closely. This variability results in a range of r values from -0.072 (Y component at ADCP L2 during May/June 2014) to 0.815 (X component at ADCP L1 during February/March 2015). The Y component of velocity at site ADCP L2 typically has the lowest r values, which is likely due to the island chain south of this point curtailing north-south flows, making local effects rather than regional currents the dominant factor.

Currents at both the regional and lease-area sites are primarily driven by the residual currents provided by HYCOM (mesoscale eddies and regional currents such as the Leeuwin Current). A fast Fourier transform (FFT; Figure 4-15) of velocities identifies peaks at 12.5 and 24 hours, suggesting there are tidal influences, but velocity time-series suggest these are minor in comparison to those of regional currents. Furthermore, a test was carried out to examine the impact of wave action on velocities within the lease areas, which found that waves had a negligible impact on velocities, but were an important contributor to bed shear stress (Section 4.1.3).

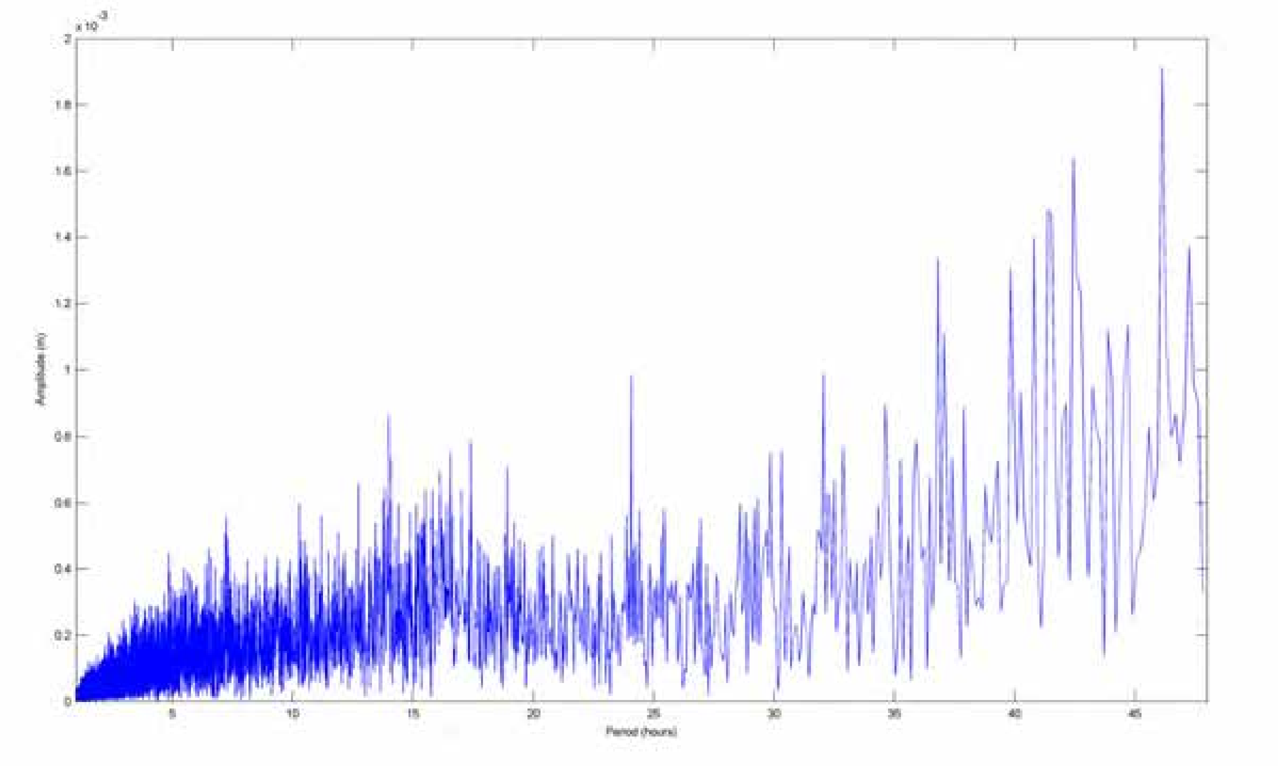


Figure 4-15 Periods from fast Fourier transform of velocity at the northern regional site during the July to November 2014 deployment.

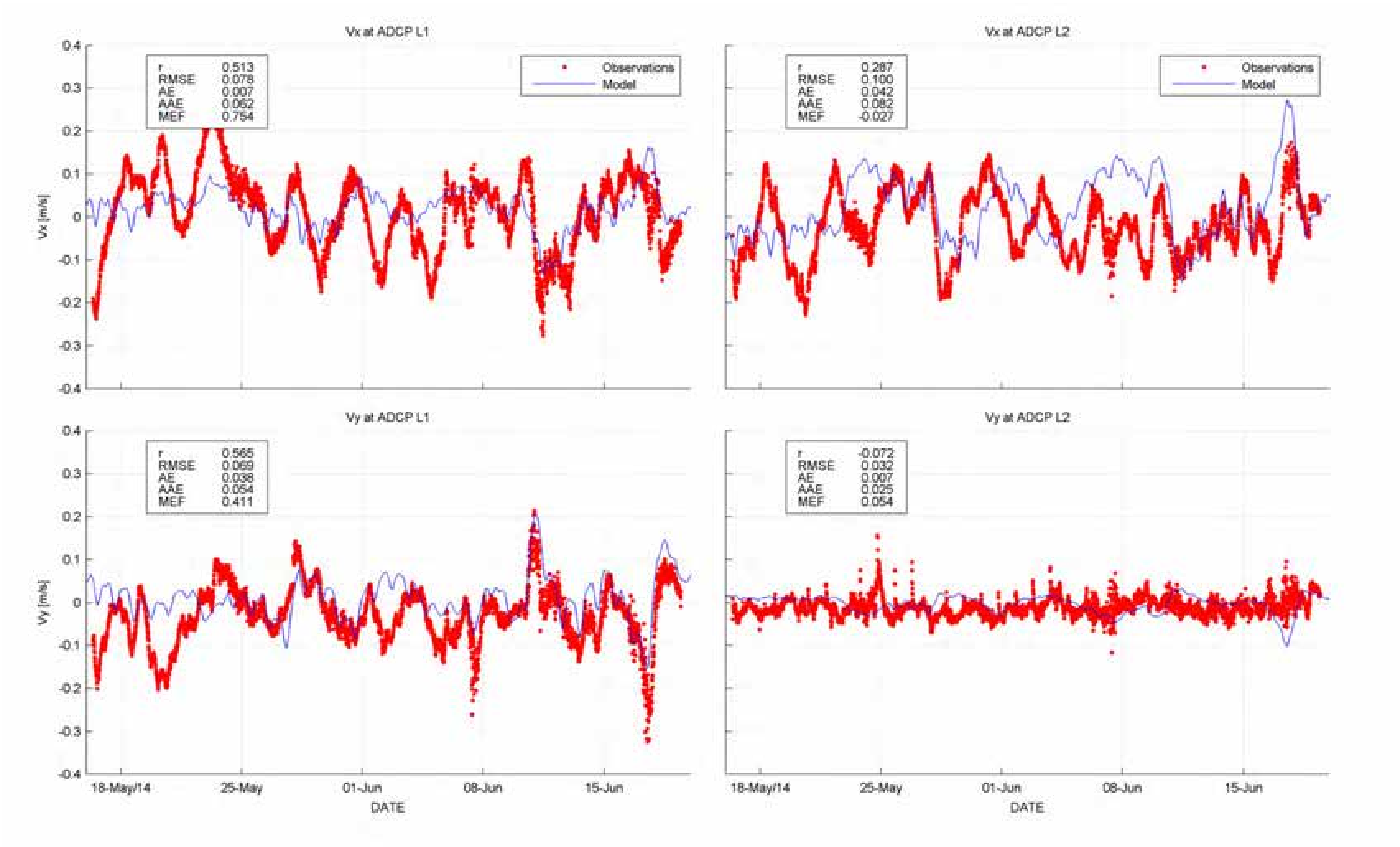


Figure 4-16 Depth-averaged velocity at sites within the proposed lease areas – May 2014 to Jun 2014 deployment

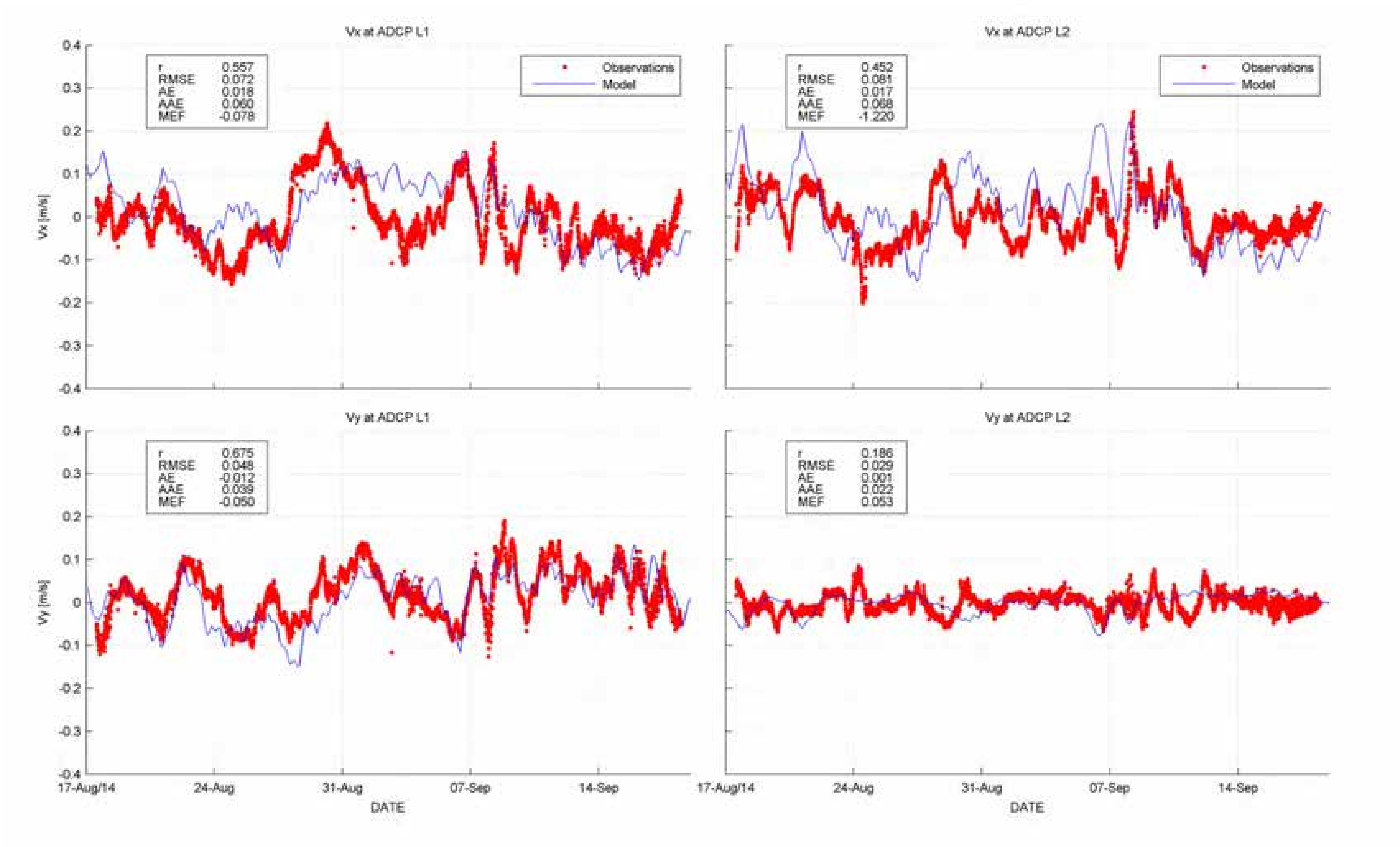


Figure 4-17 Depth-averaged velocity at sites within the proposed lease areas – Aug 2014 to Sep 2014 deployment

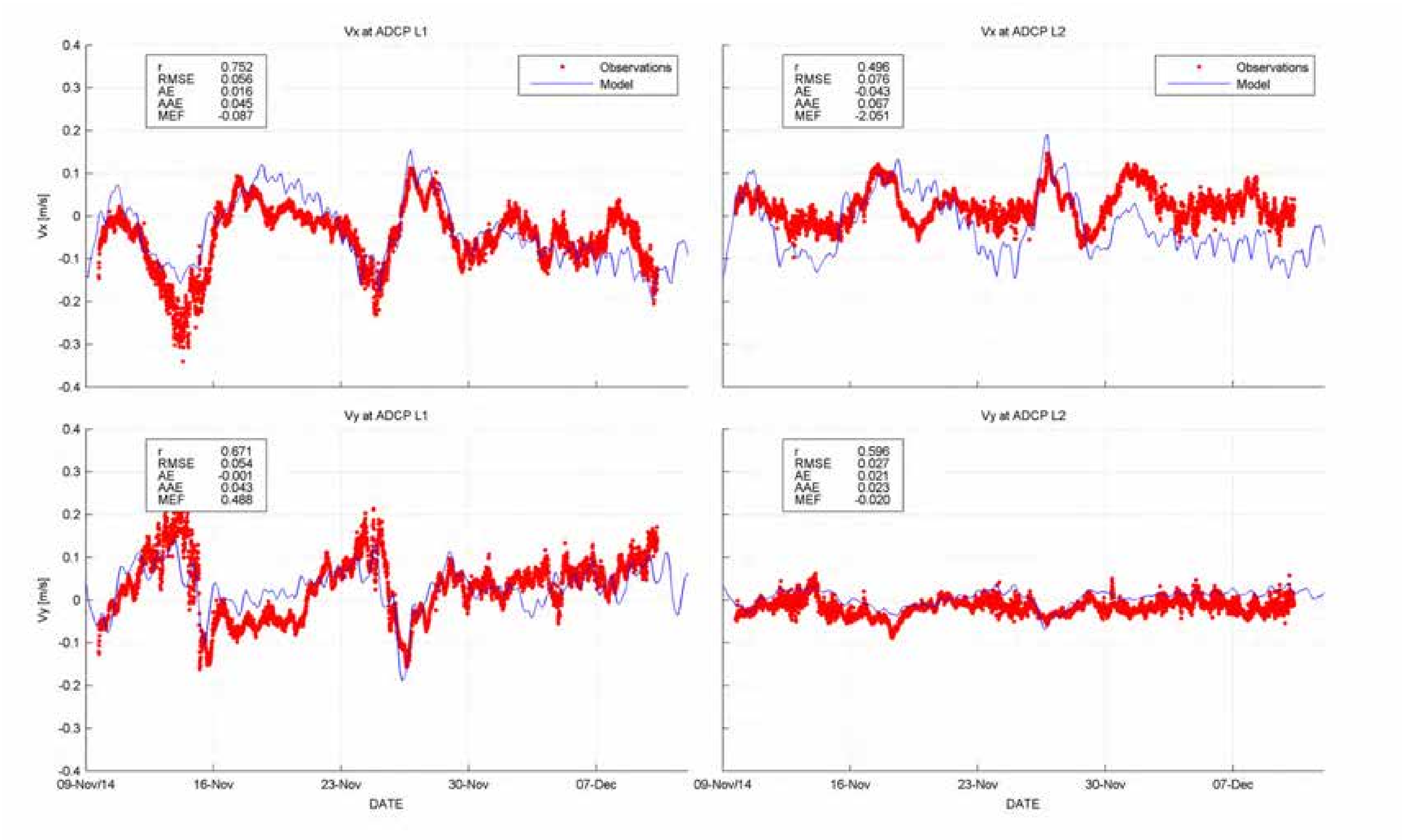


Figure 4-18 **Depth-averaged velocity at sites within the proposed lease areas –Nov 2014 to Dec 2014 deployment**

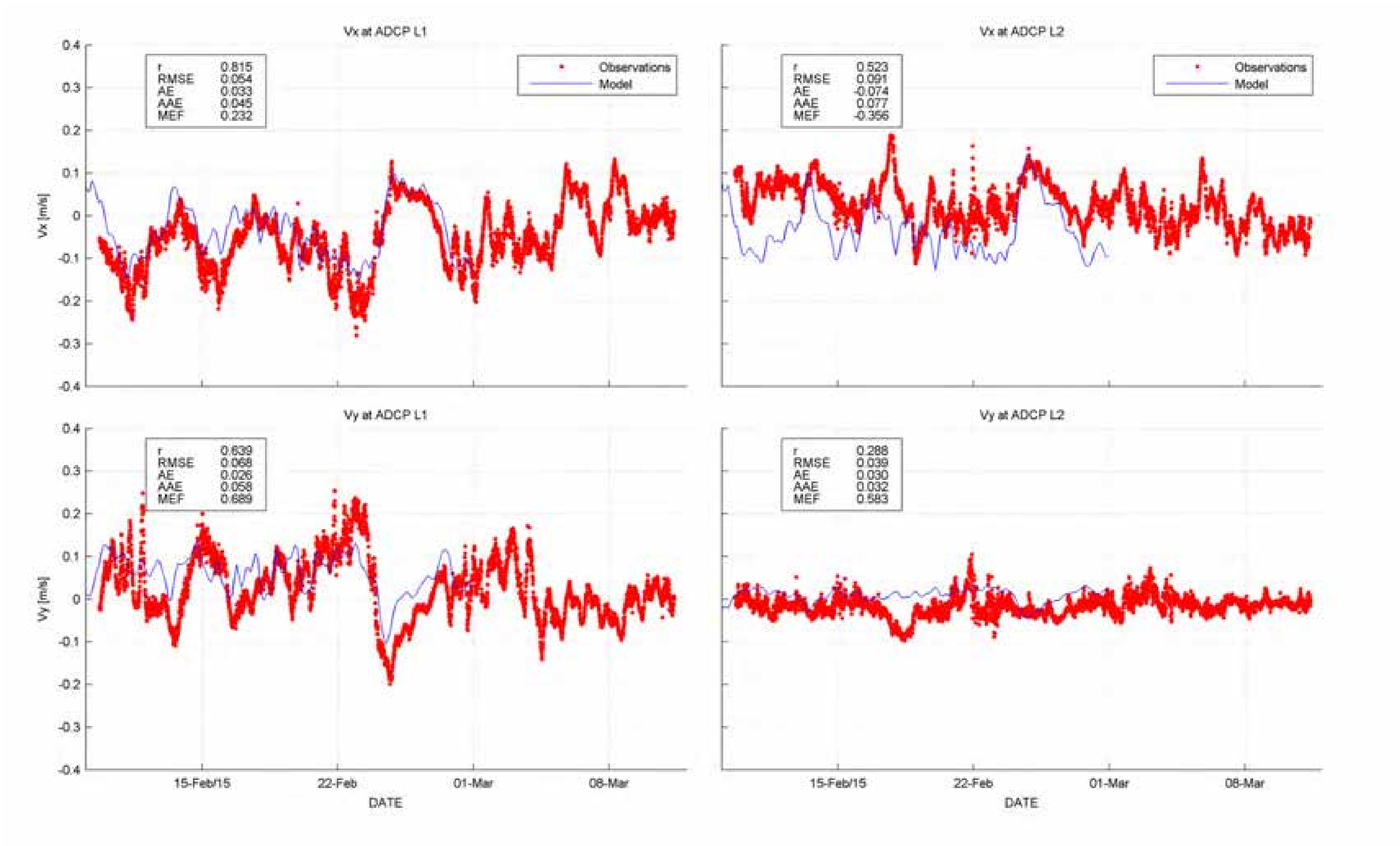


Figure 4-19 Depth-averaged velocity at the lease-area sites – Feb 2015 to Mar 2015 deployment

4.1.3 Waves

4.1.3.1 Summary

Along with current velocities, wave dynamics are of key importance to this study, due to their influence on resuspension and deposition of food and faecal particles arising from aquaculture activities. As illustrated below, the model does an excellent job of capturing both the magnitude and variability of peak wave period at both the regional and lease-area sites, which is a key parameter affecting the resuspension of particles on the seabed. Peak wave direction is also successfully reproduced, while significant wave height is typically over-estimated at both regional and lease-area sites, although the model captures the variability of wave height extremely well ($r > 0.84$ for all sites). The over-prediction in the SWAN model is likely due to over-predictions of swell from the Wavewatch III model, which is used as a forcing boundary condition.

To investigate the impact of significant wave height on particle distribution, a sensitivity test was run with significant wave height reduced by 20% when applied to the TUFLOWFV model. The sensitivity test indicated that the reduced wave height did not have a notable impact on the distribution of particles released from fish cages. Nevertheless the original forcing will be used for scenario runs as this represents the conservative approach.

4.1.3.2 Additional detail

Comparisons of SWAN wave model output against observations at the regional and lease-area sites are presented in Figure 4-20 to Figure 4-25 below for significant wave height, peak wave period and peak wave direction. Additional plots for the period of the second, regional-site deployment are also included in Appendix B.4, although these only cover the period to 1st January 2015 as boundary conditions from the global Wavewatch III swell model were not available for later dates at the time the model was run.

As can be seen in the time-series plots of Figure 4-22 to Figure 4-25, the model does an excellent job of capturing both peak wave period and peak wave direction at both lease-area and regional sites. Within the lease areas, peak wave direction is constrained by topography, which typically results in waves coming from the west through the Zeewijk Channel, or from the southeast, having refracted around the Pelsaert group and leading to the binary behaviour illustrated in Figure 4-25.

As noted in Section 4.1.3.1 above, however, significant wave height is over-predicted by the model. As the model is approximately 40m deep at both regional and lease-area sites, it is thought that bed friction is not an important component of the wave model and, therefore, that the likely cause of the over-prediction is excessive wave heights at the model boundary. To overcome this issue, a sensitivity test was run with significant wave height reduced by 20% when applied to the TUFLOWFV model (Figure 4-26). The test included the TUFLOWFV particle tracking module, which was run with particle parameters similar to the finest particles arising from aquaculture activities, as follows:

- Critical erosion shear stress of 0.15 N/m^2
- Erosion rate of 0.02 $g/m^2/s$.

The criteria for the environmental impact assessment relate to the area surrounding fish cages, which is affected by the deposition of organic material. The area over which particles are deposited to the seabed for both model runs is included in Figure 4-27. As can be seen, the over-predicted wave height has a limited impact on the area upon which particles are deposited, with similarly-sized footprints for both model runs. Nevertheless, the original, over-predicted wave forcing will be included in scenarios for this assessment, as this represents the conservative approach in determining the upper limit of stocking densities which can be sustained.

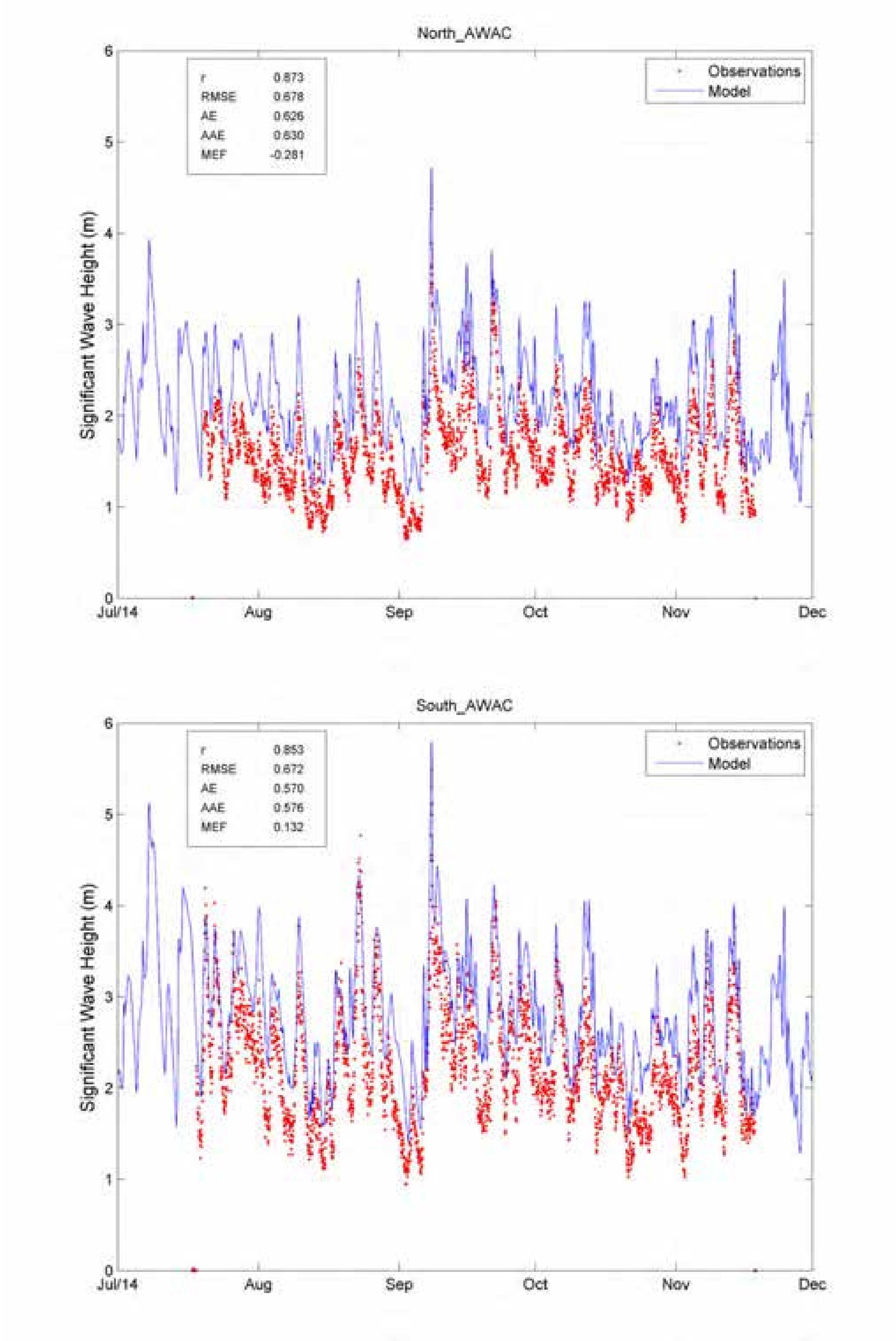
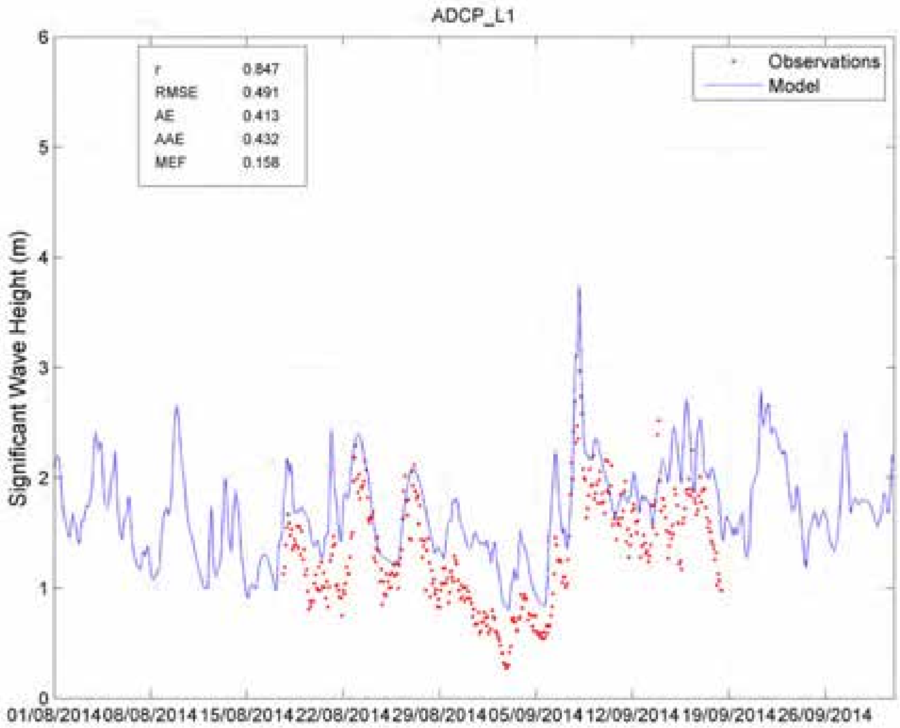


Figure 4-20 Significant wave height at regional sites



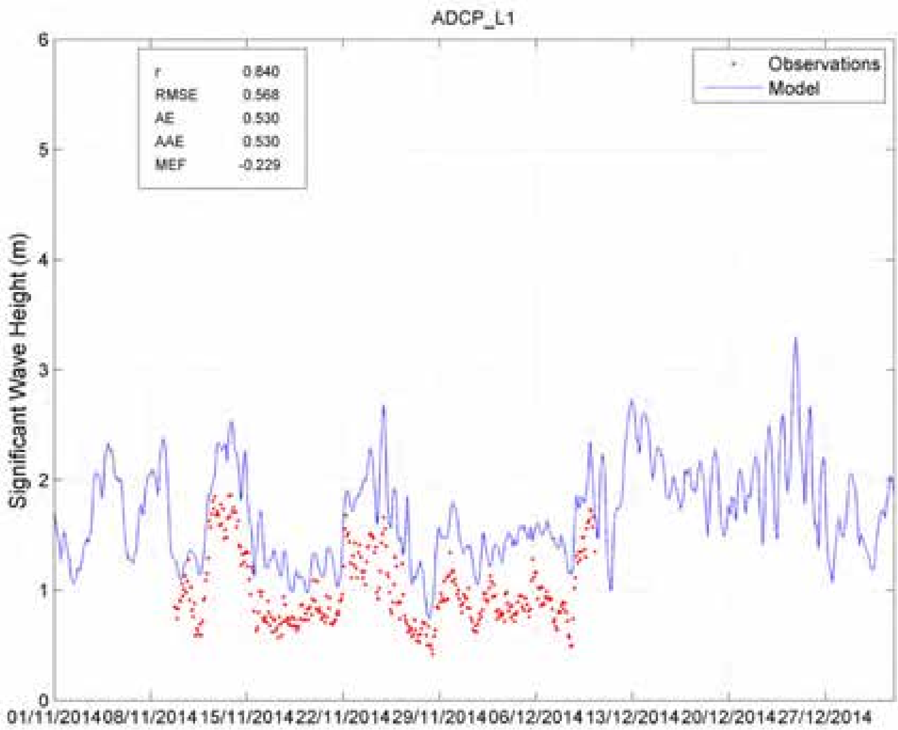


Figure 4-21 Significant wave height at northern lease-area site

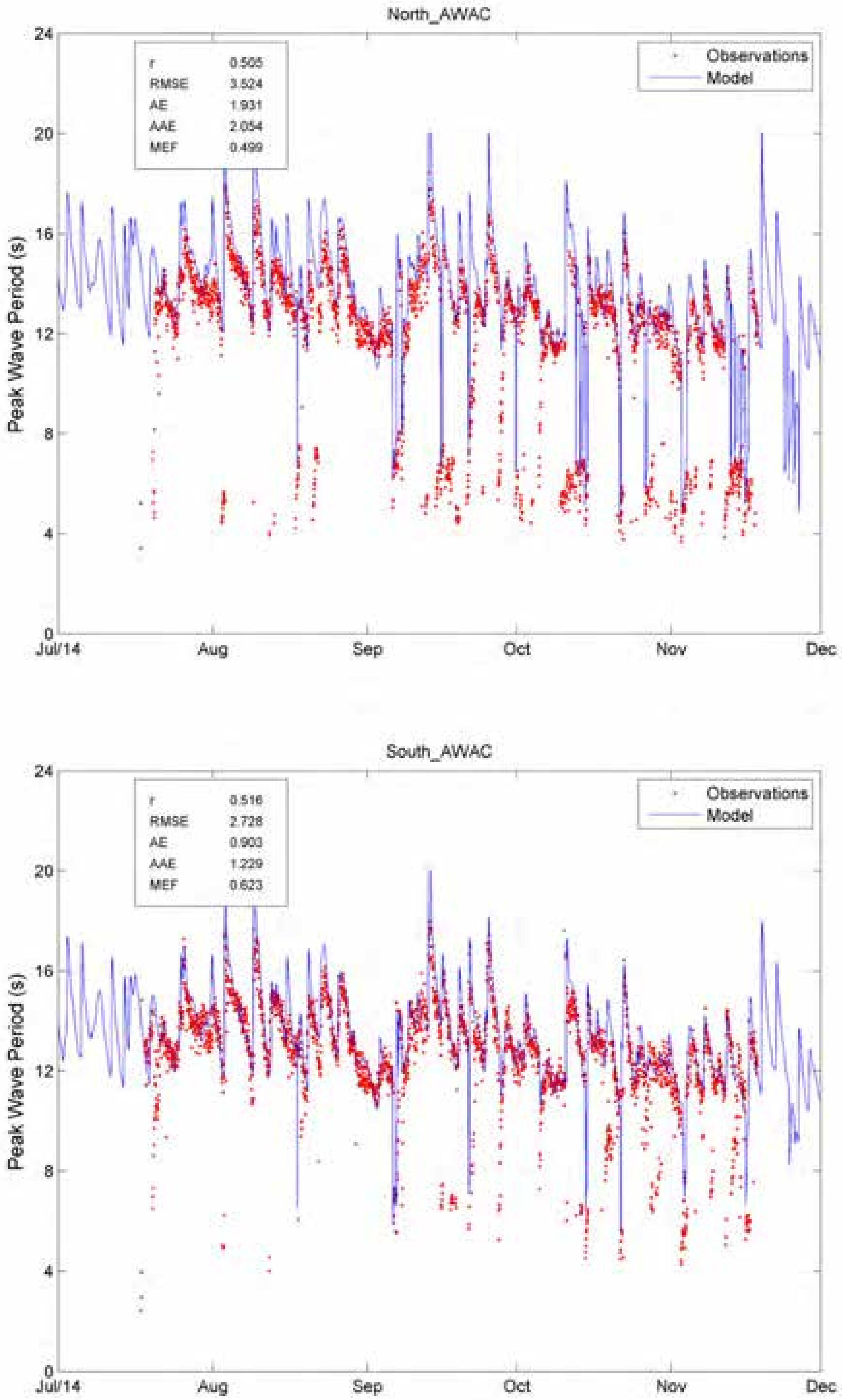


Figure 4-22 Peak wave period at regional sites

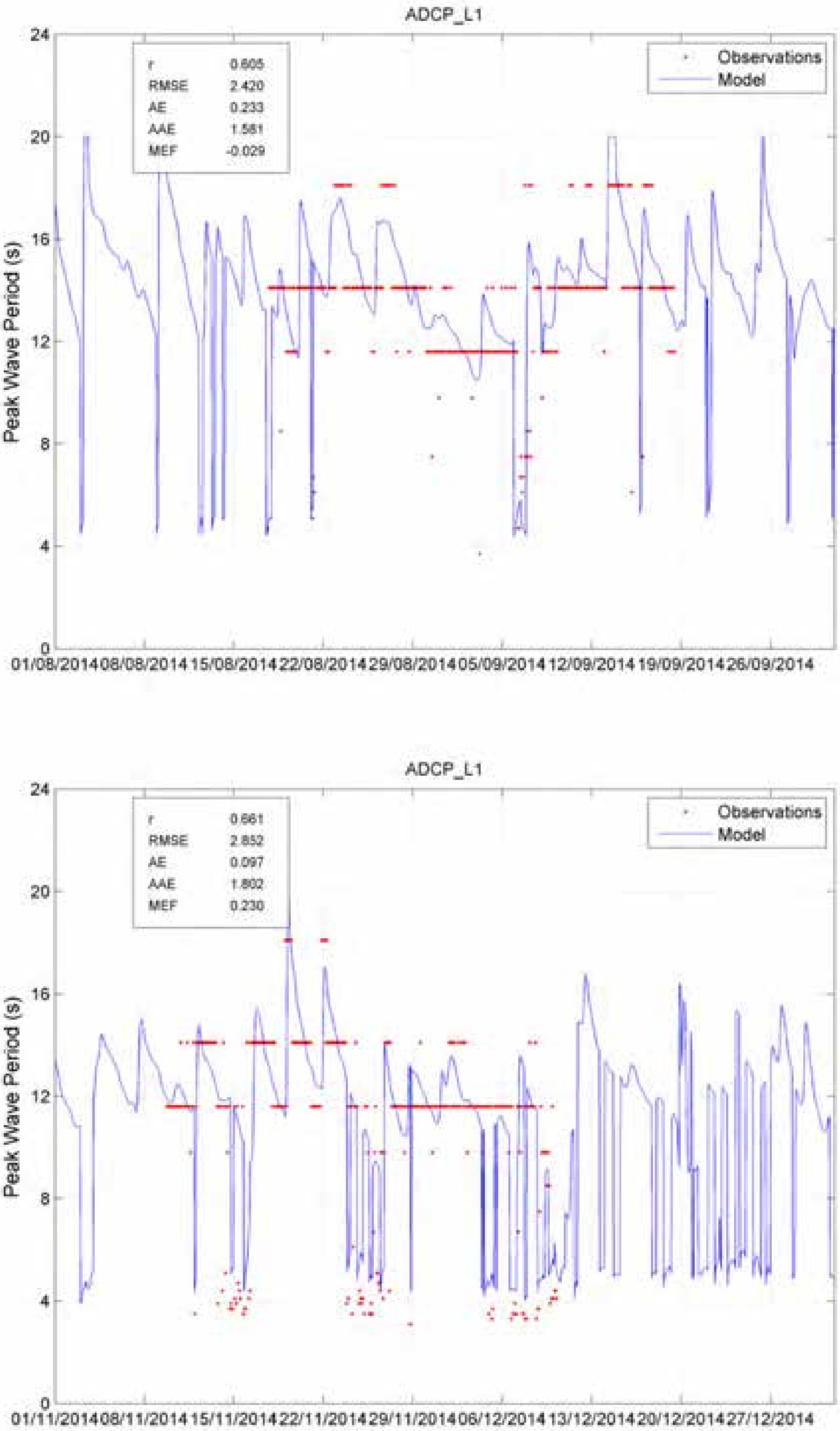


Figure 4-23 Peak wave period at northern lease-area site. Observation data is presented as it was provided by DoF, which appears to bin data into particular bands.

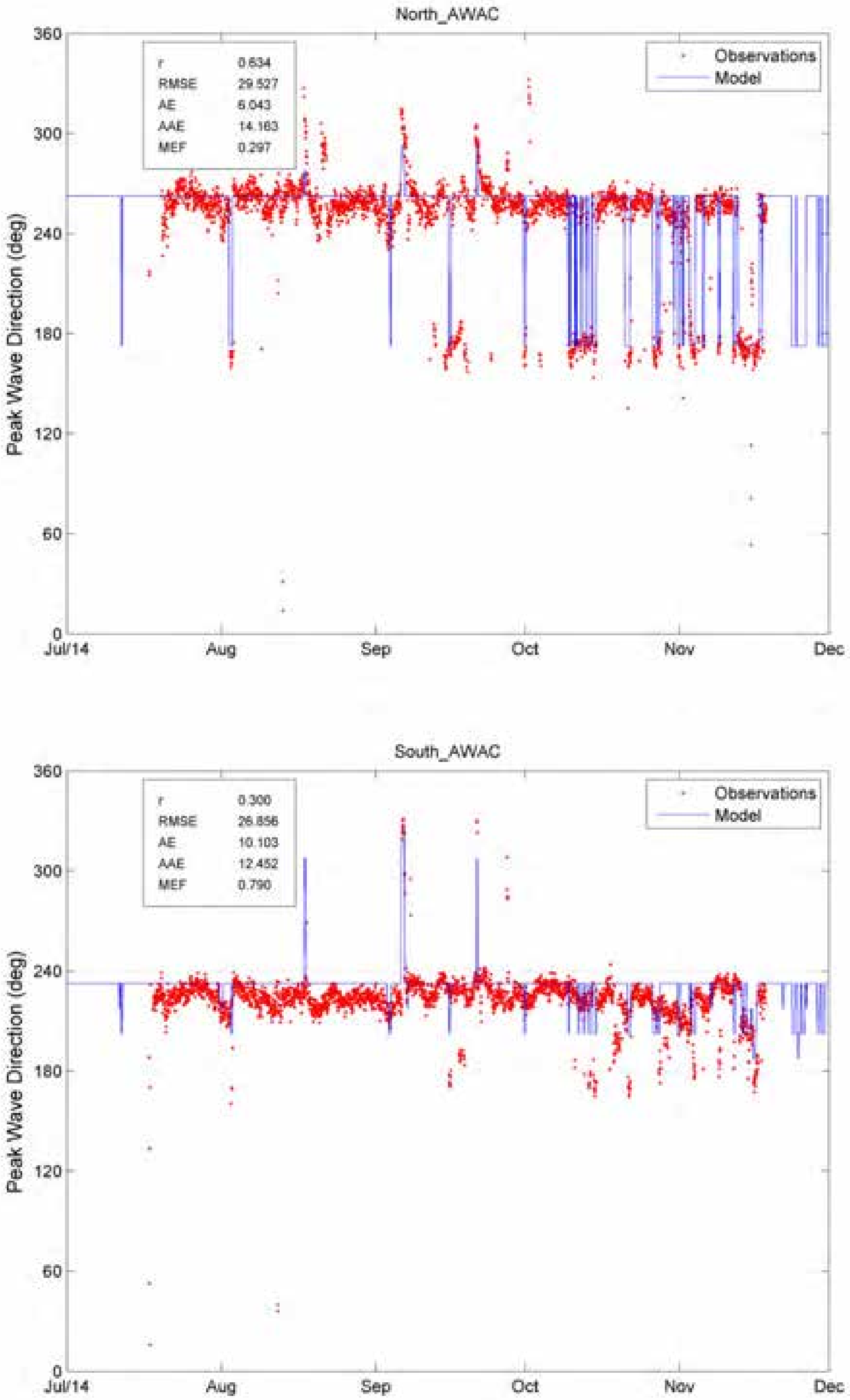


Figure 4-24 Wave direction at regional sites

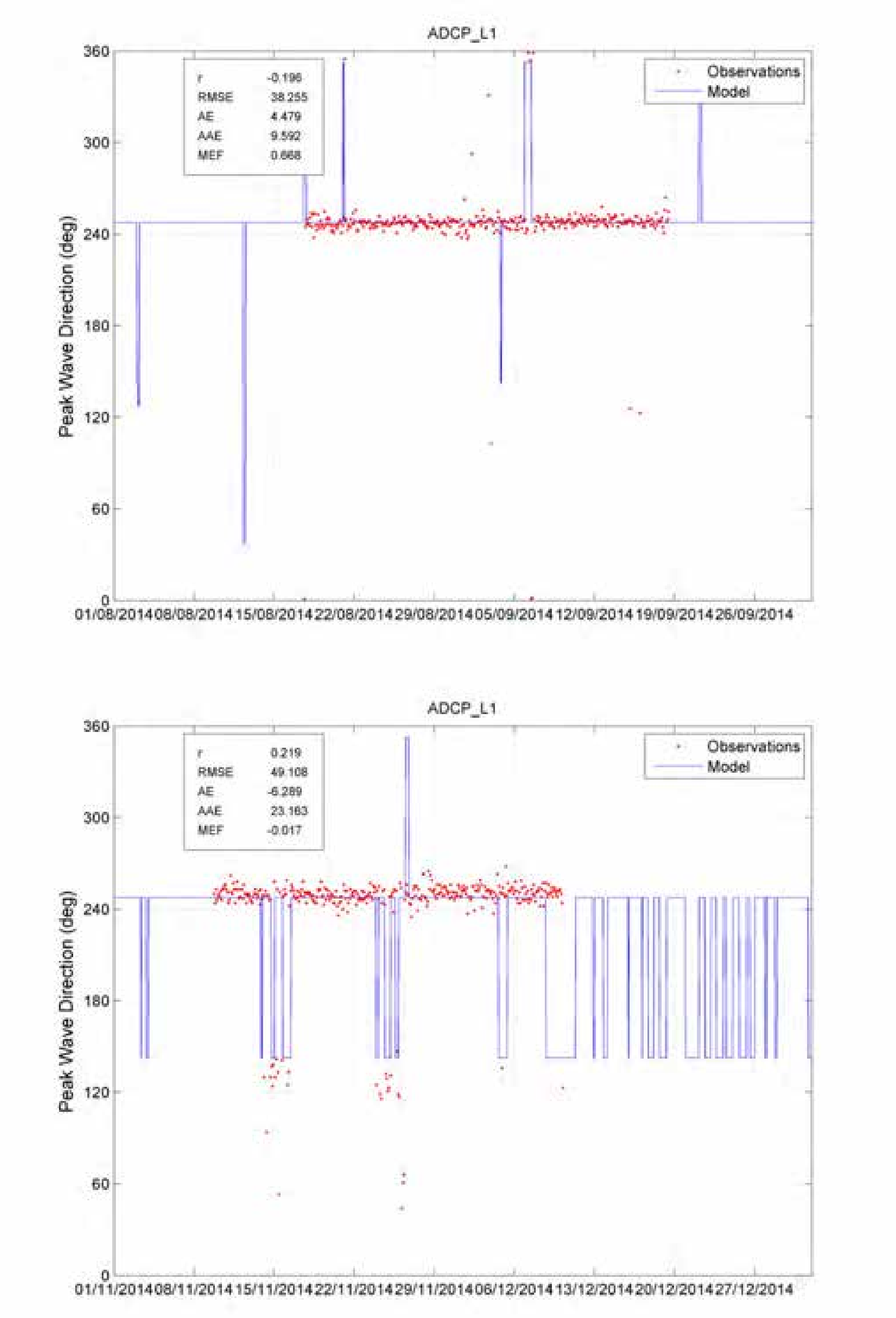


Figure 4-25 Wave direction at northern lease-area site.

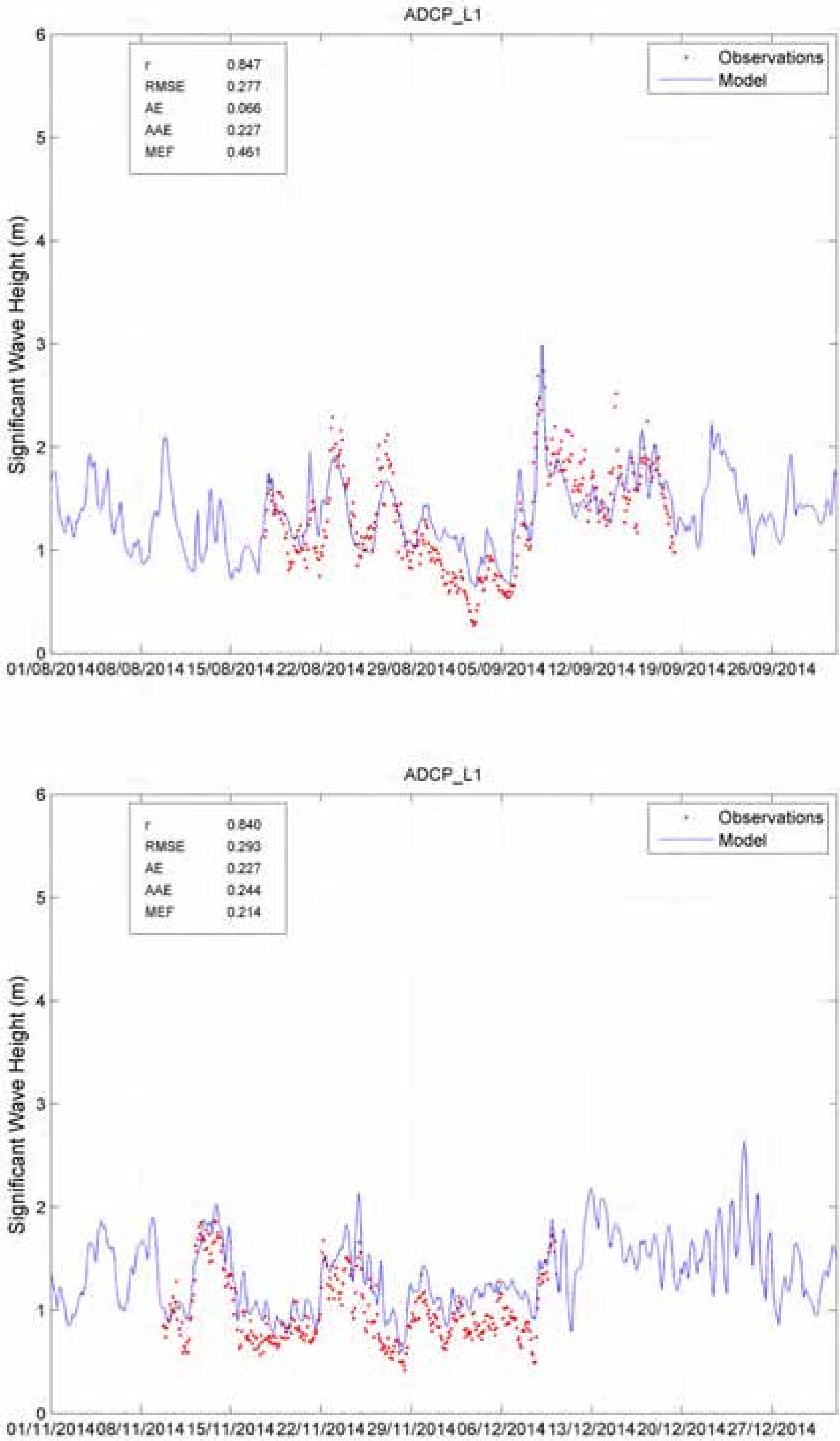


Figure 4-26 Comparison against observations if significant wave height were reduced by 20%

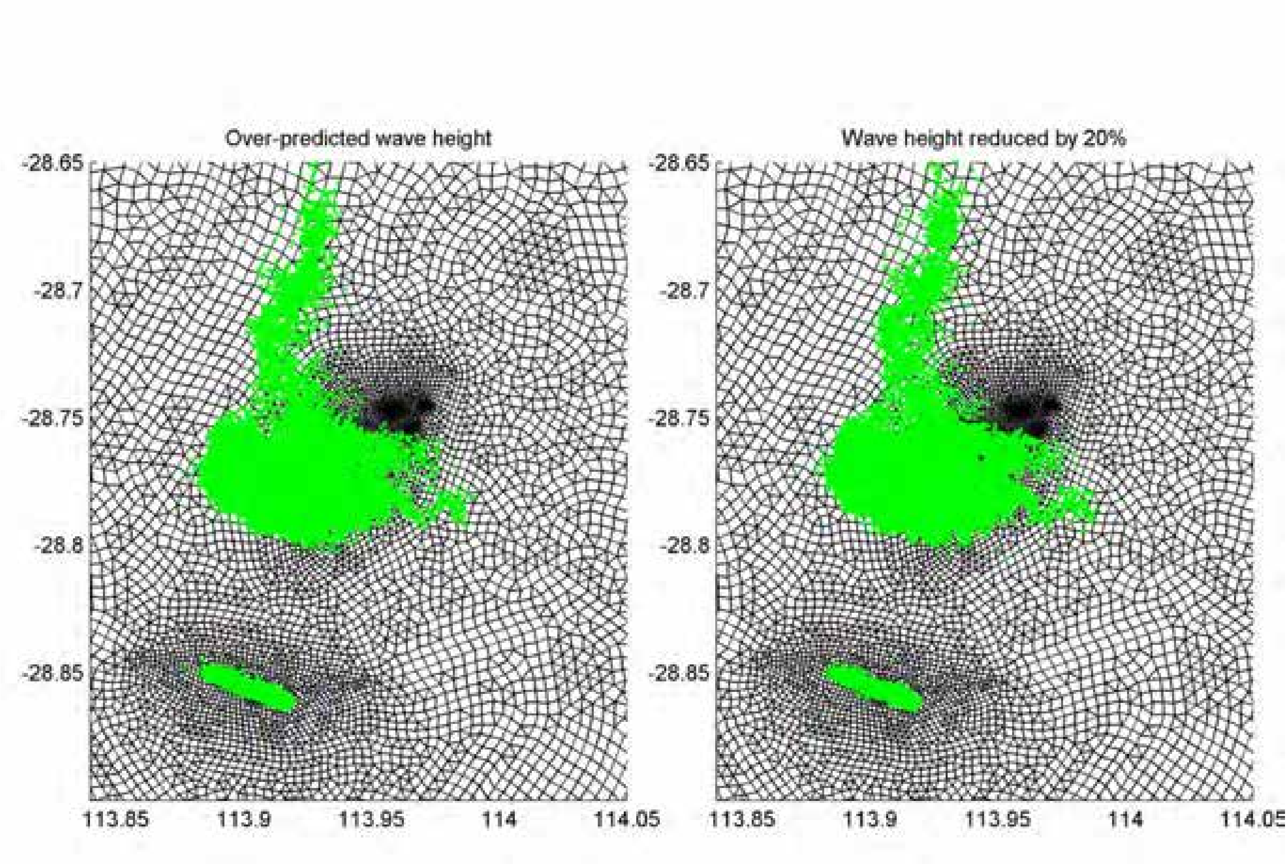


Figure 4-27 Comparison of depositional area under the original wave forcing (left plot) and the wave forcing with reduced significant wave height (right plot)

4.1.4 Temperature

4.1.4.1 Summary

A good temperature calibration is of primary importance to the water quality model, as temperature has a controlling effect on the rate of key biogeochemical processes. It is particularly important to recreate the variability of temperature with depth to ensure that stratification processes are captured.

The model does a good job of recreating observed temperature at both the regional and lease-area sites. Seasonal dynamics are well captured, with particularly good r values for the second four-month deployment. Short-term dynamics are also recreated, with the model capturing the passage of regional eddies through the system (e.g. during late December at the southern regional site), albeit occasionally simulating a warm-core eddy rather than a cold-core eddy (e.g. during August 2014 at the northern regional site). The model does miss some short-term events but overall the comparison of temperature time-series is very good. An example of such an event is the temperature drop around 15th November 2014 at the southern lease-area site, which the model does not capture. A temperature over-prediction of approximately 1 °C, such as that observed here, would cause some water quality processes to progress more quickly than they otherwise would through an Arrhenius factor. However, there is no consistent departure from observations of this magnitude and average errors tend to be much smaller over time (AE < 0.5 °C typically).

Depth profiles taken at multiple sites around the lease areas illustrate that there is no significant stratification in the region most of the time, although there are occasional, isolated stratification events (e.g. at the L2D and L2E sites during June, Figure 4-37). Importantly, the model recreates these isolated stratification events, and subsequent dismantling, indicating that the processes driving the events are well captured. Site R2C (Figure 4-38) provides a good example of a stratification event (or events) beginning in May 2014, strengthening in June 2014 and entirely dismantled during subsequent sampling periods.

4.1.4.2 Additional Details

Comparisons of temperature at the regional sites are presented in Figure 4-28 and Figure 4-29, with figures of the same time-series broken down into calendar months included in Appendix B.3. Comparisons of temperature at the lease-area sites are presented in Figure 4-31 to Figure 4-34. Additionally, depth profiles of temperature at each location are presented in Figure 4-35 to Figure 4-39, which illustrate a short-lived stratification event simulated in February 2015. This event was driven by both HYCOM boundary conditions and meteorological data, but wasn't sampled by depth profiles taken at this time. It is possible that the event may have been mis-timed by the model, or that those features that dismantle stratification (wind, swell, etc.) were under-predicted at this time.

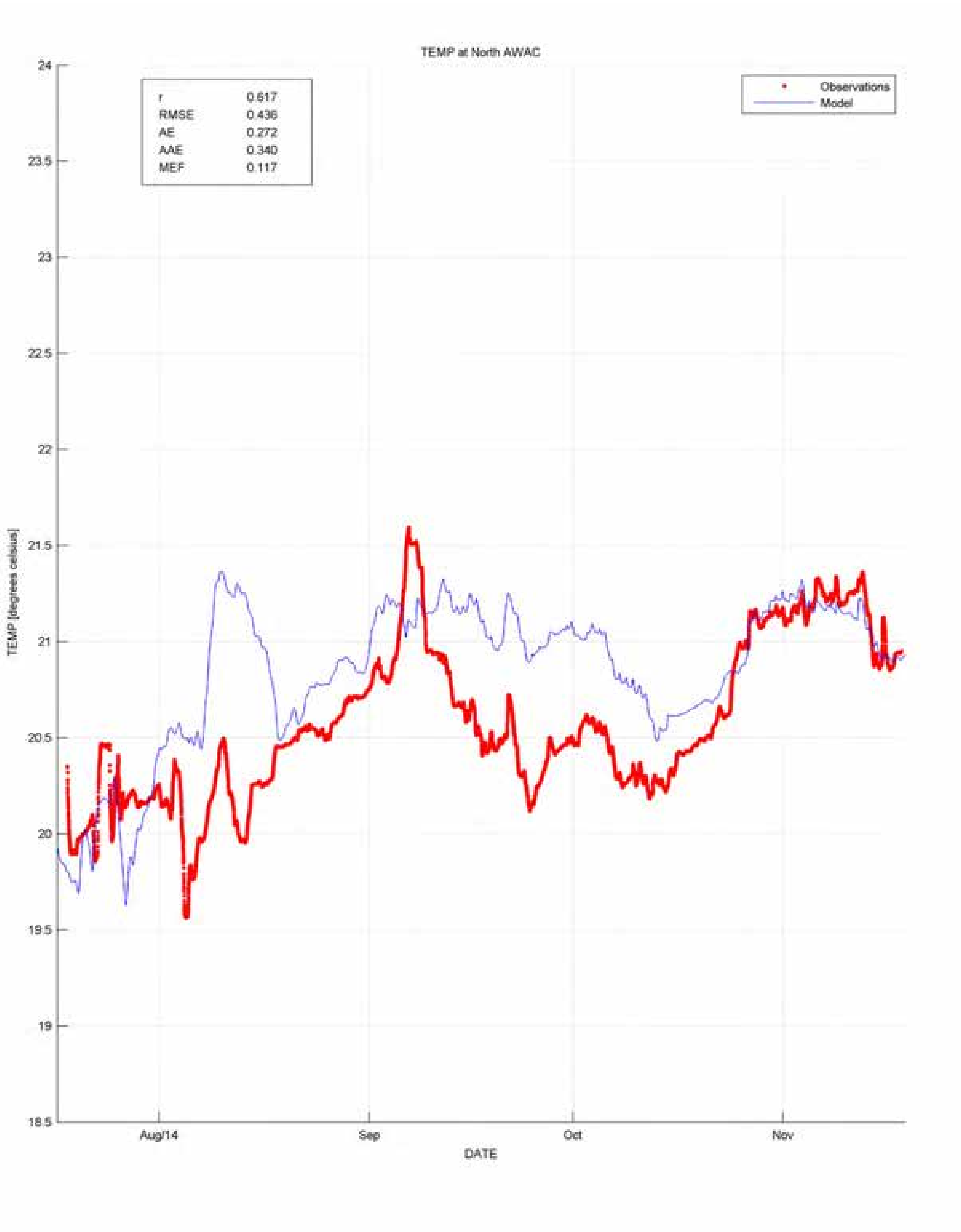


Figure 4-28 Seabed temperature at the northern regional site – Jul 2014 to Nov 2014 deployment

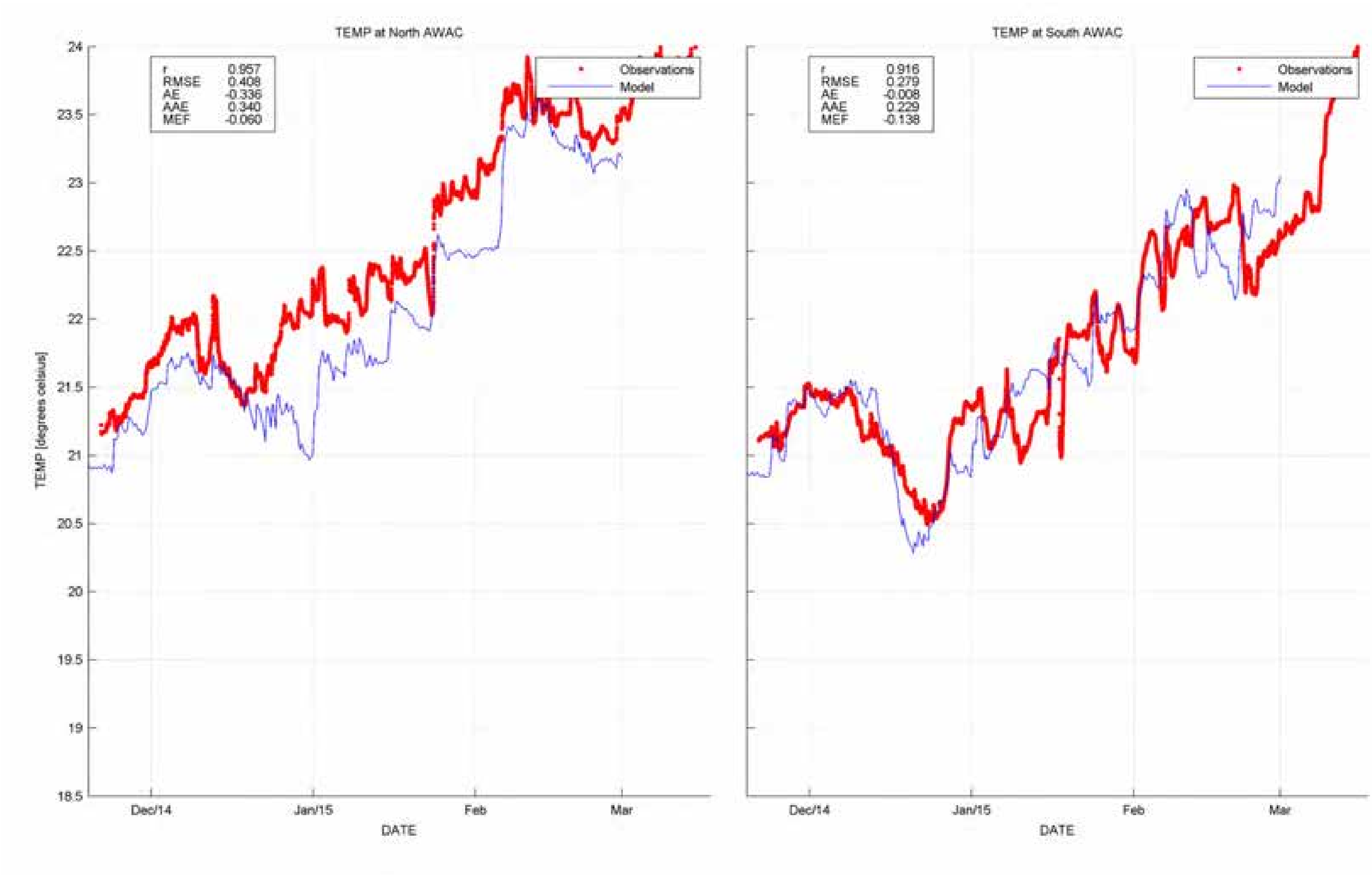


Figure 4-29 Seabed temperature at the regional sites –Nov 2014 to Mar 2015 deployment

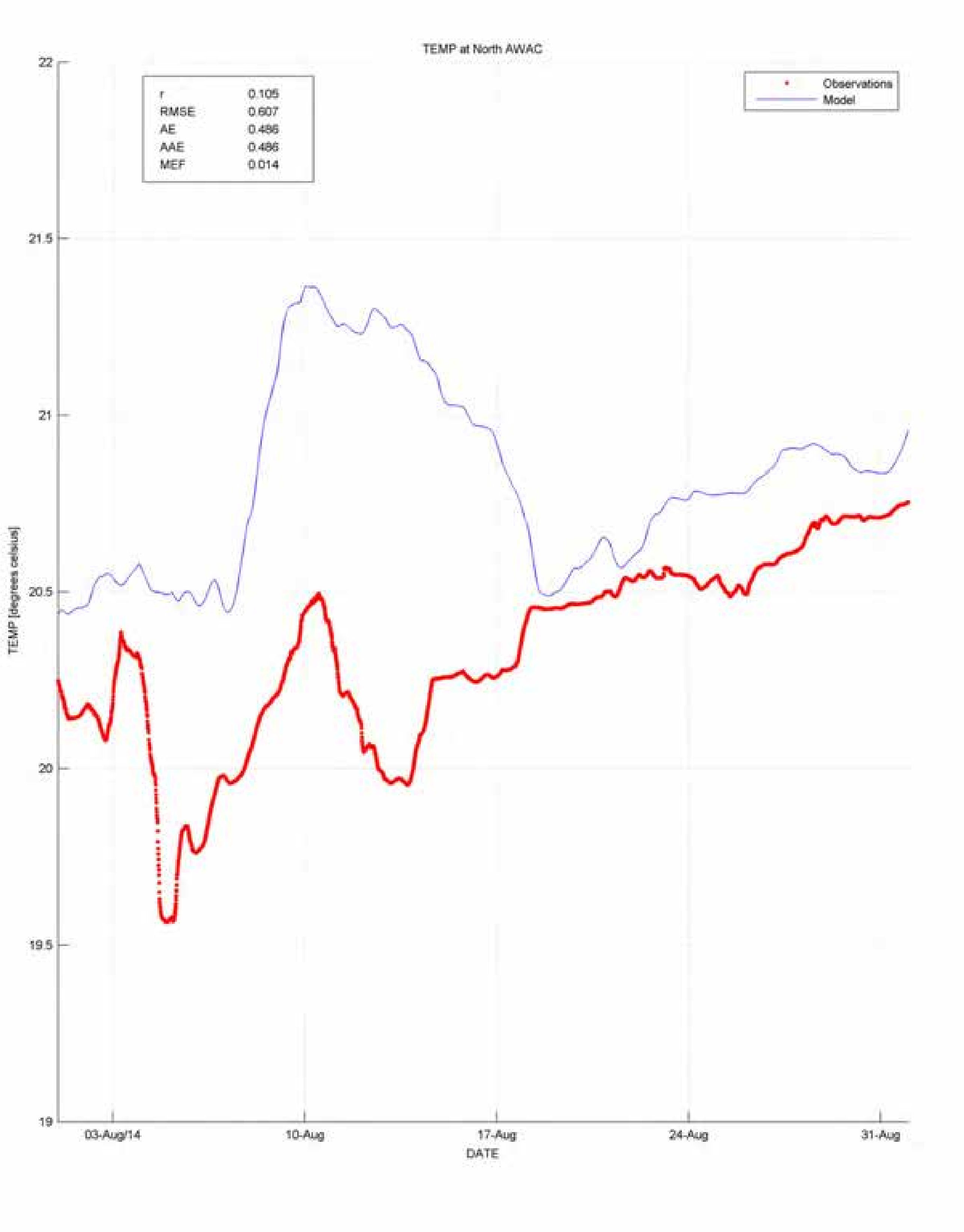


Figure 4-30 Seabed temperature at northern regional site during Aug 2014

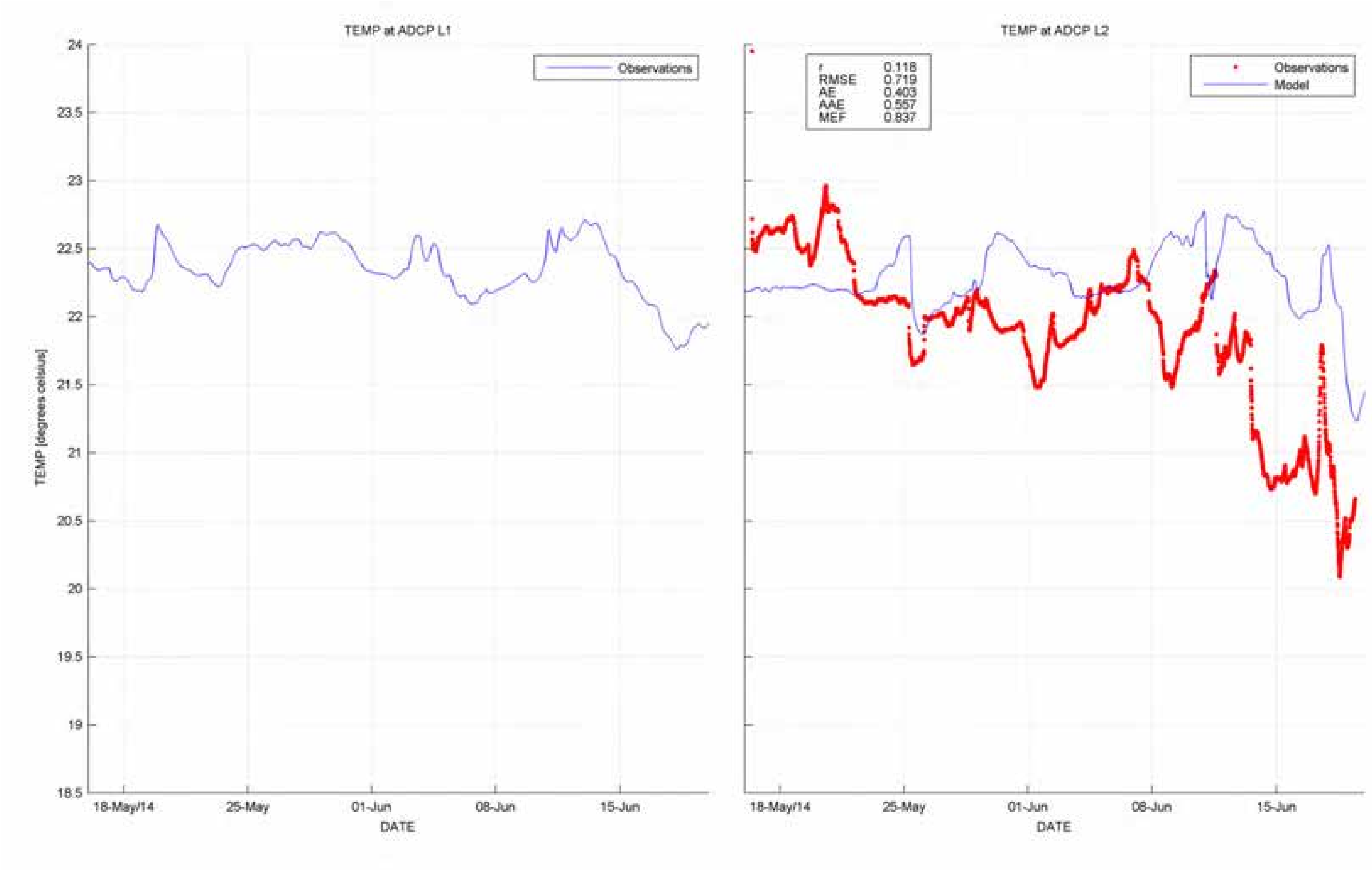


Figure 4-31 Seabed temperature at lease-area sites – May 2014 to Jun 2014 deployment

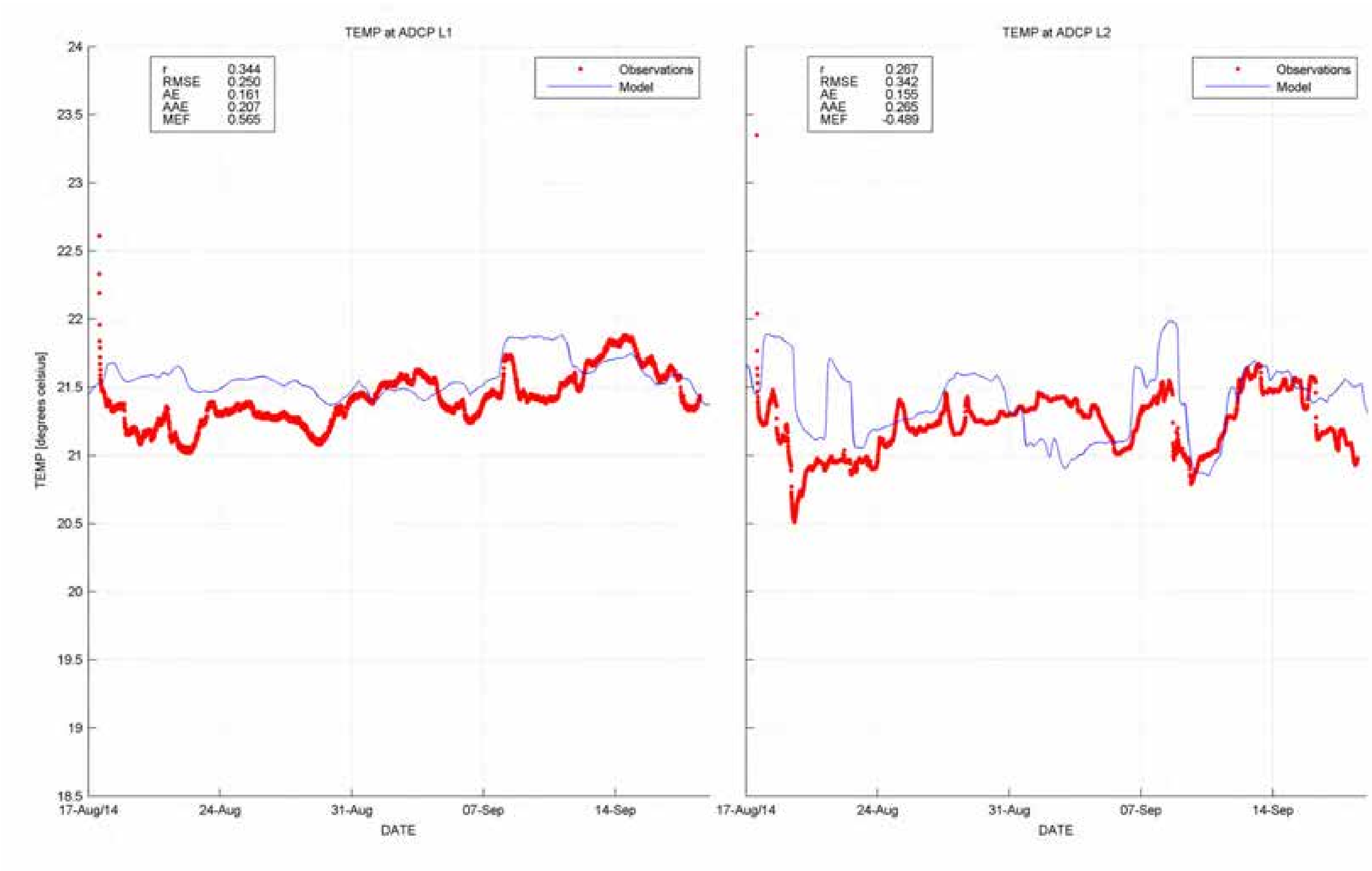


Figure 4-32 Seabed temperature at lease-area sites – Aug 2014 to Sep 2014 deployment

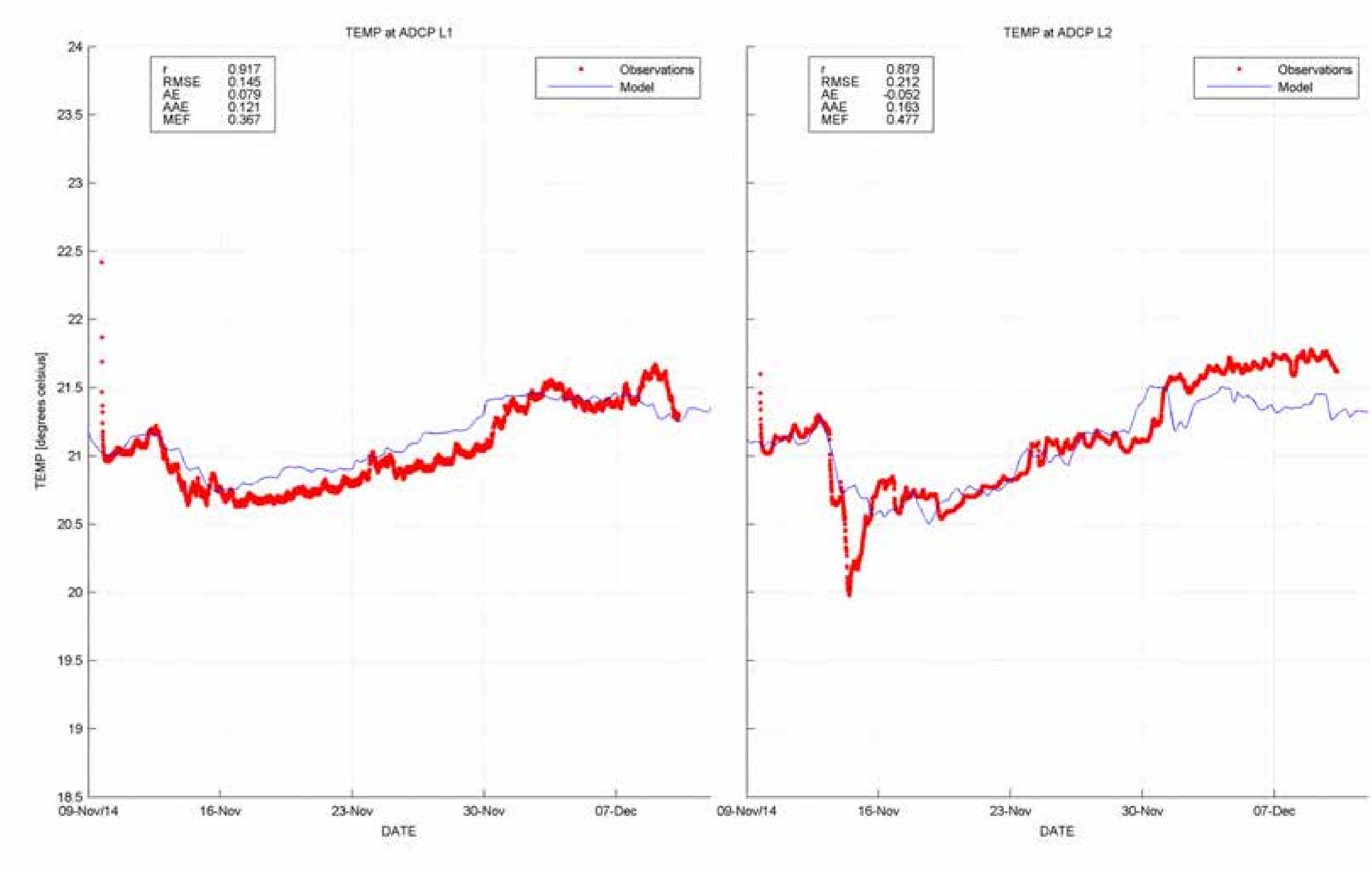


Figure 4-33 Seabed temperature at lease-area sites – Nov 2014 to Dec 2014 deployment

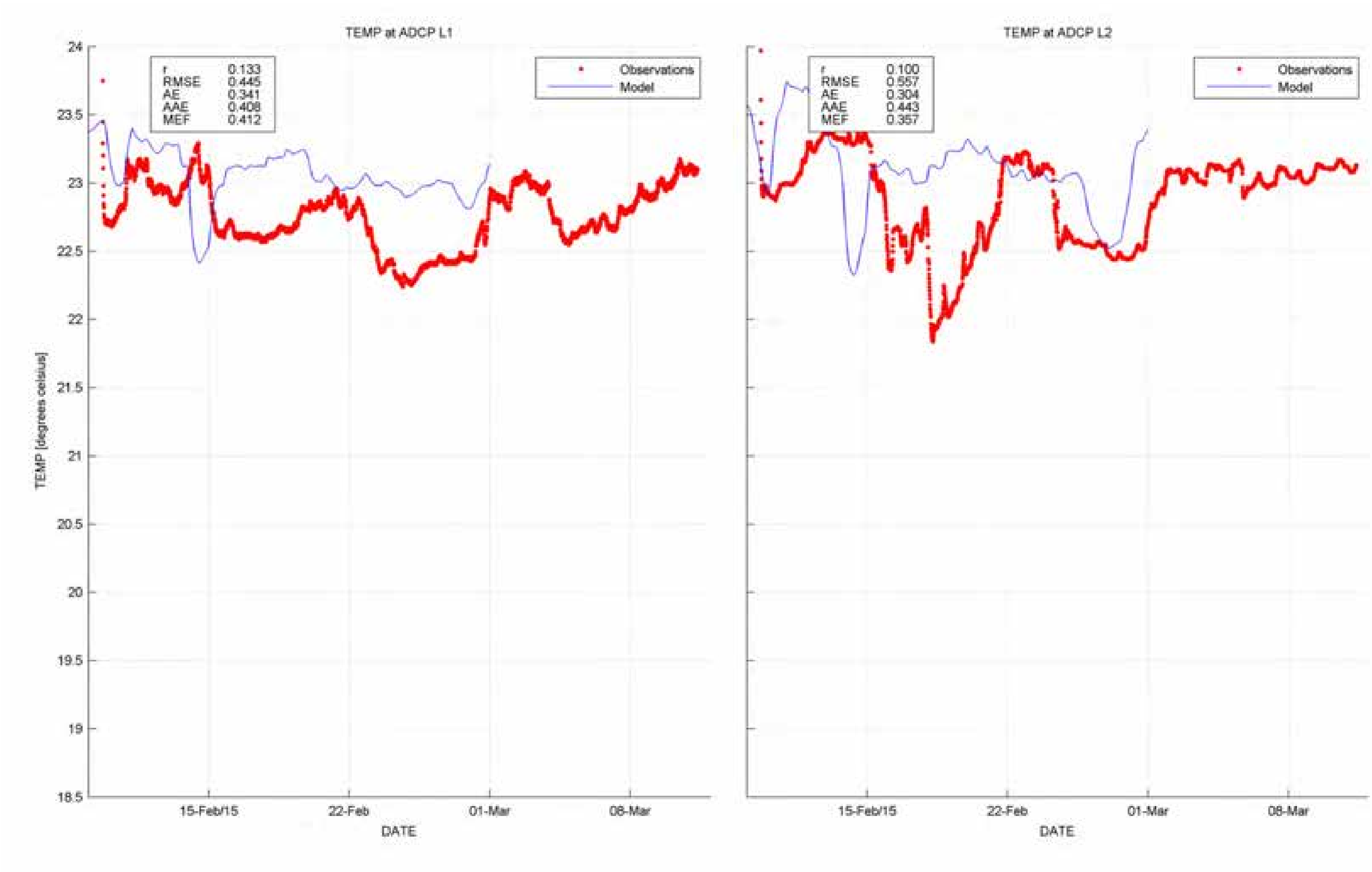


Figure 4-34 Seabed temperature at lease-area sites – Feb 2014 to Mar 2014 deployment

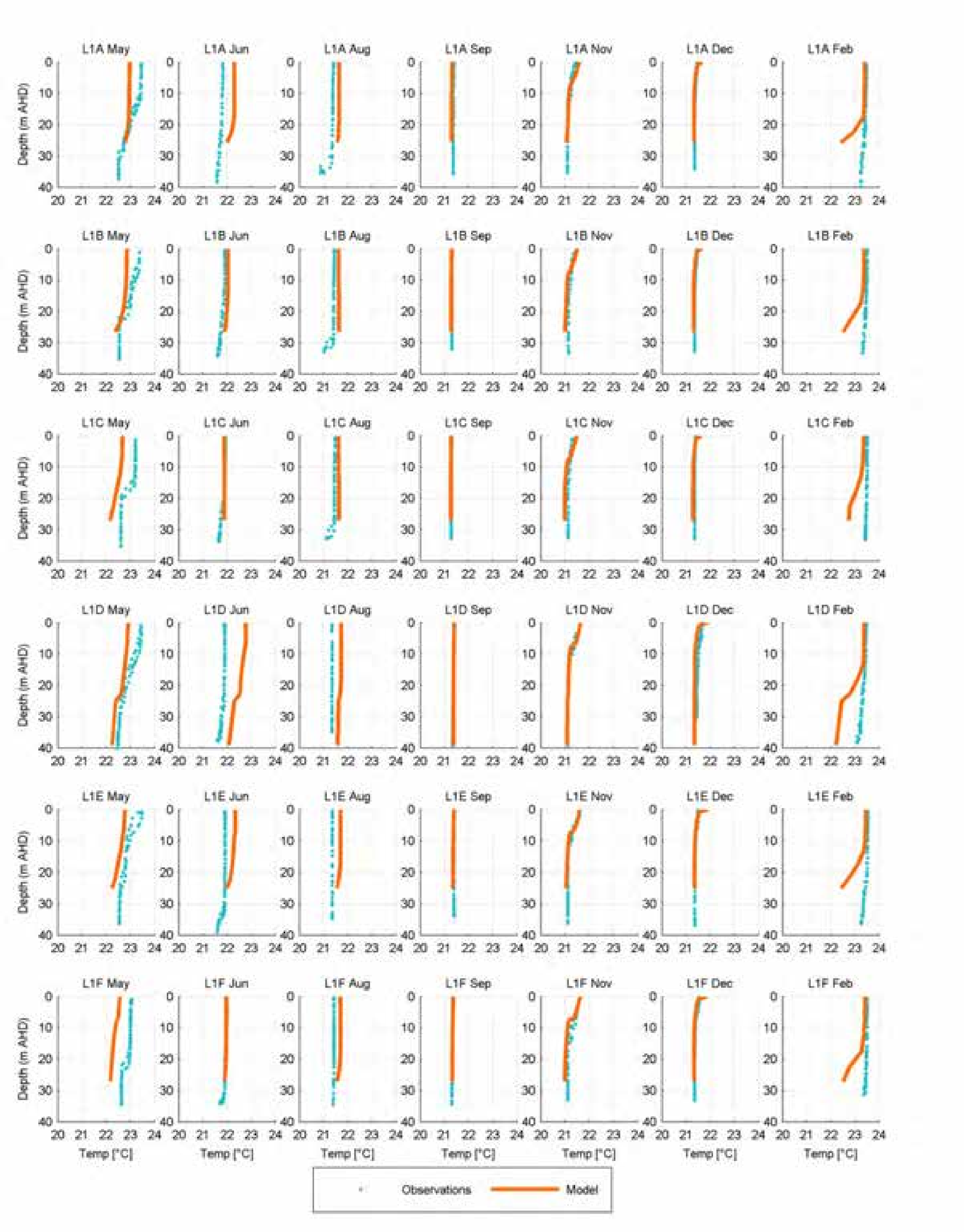


Figure 4-35 Depth profiles of temperature at lease-area sites – 1 of 5

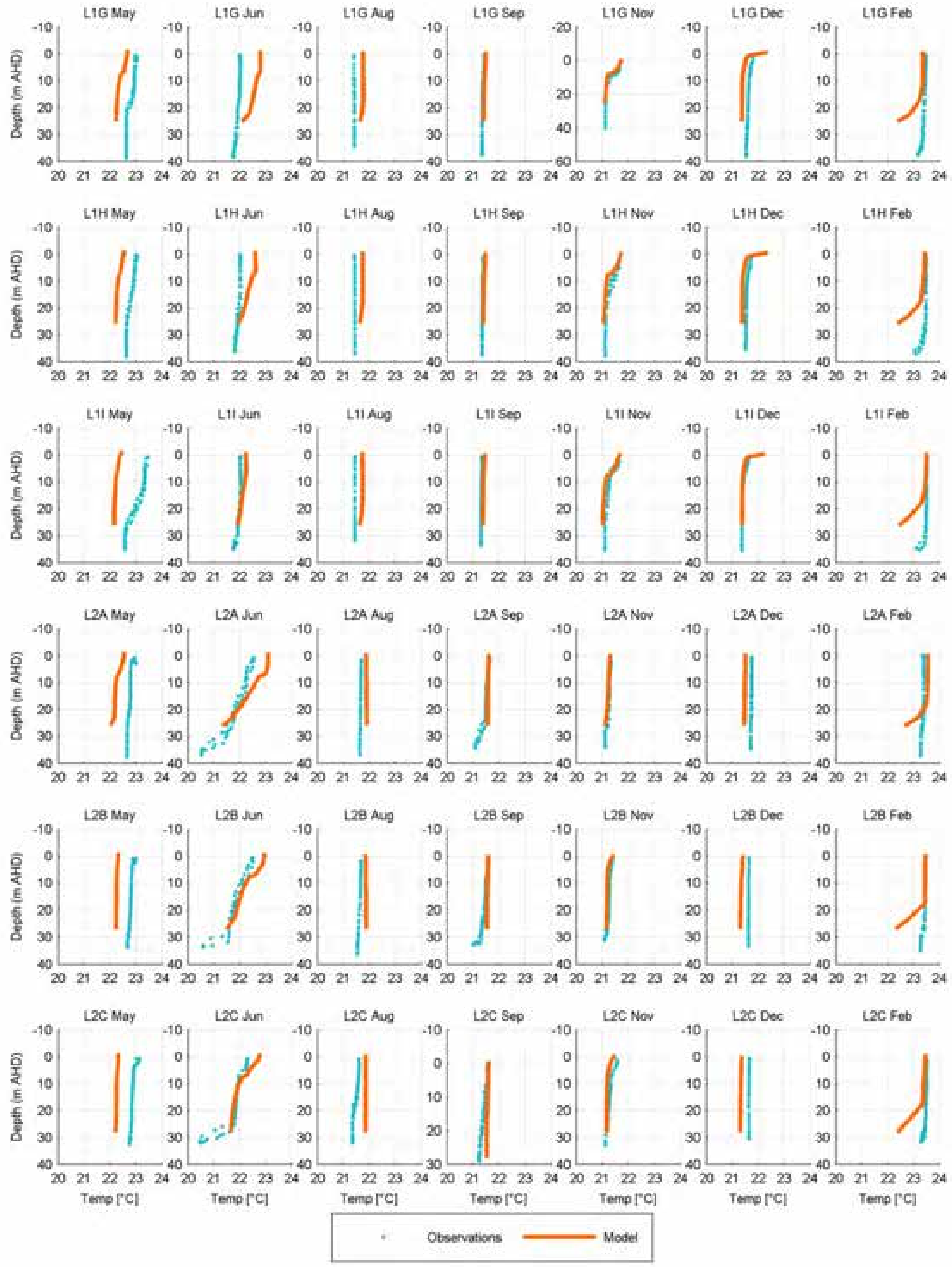


Figure 4-36 Depth profiles of temperature at lease-area sites – 2 of 5

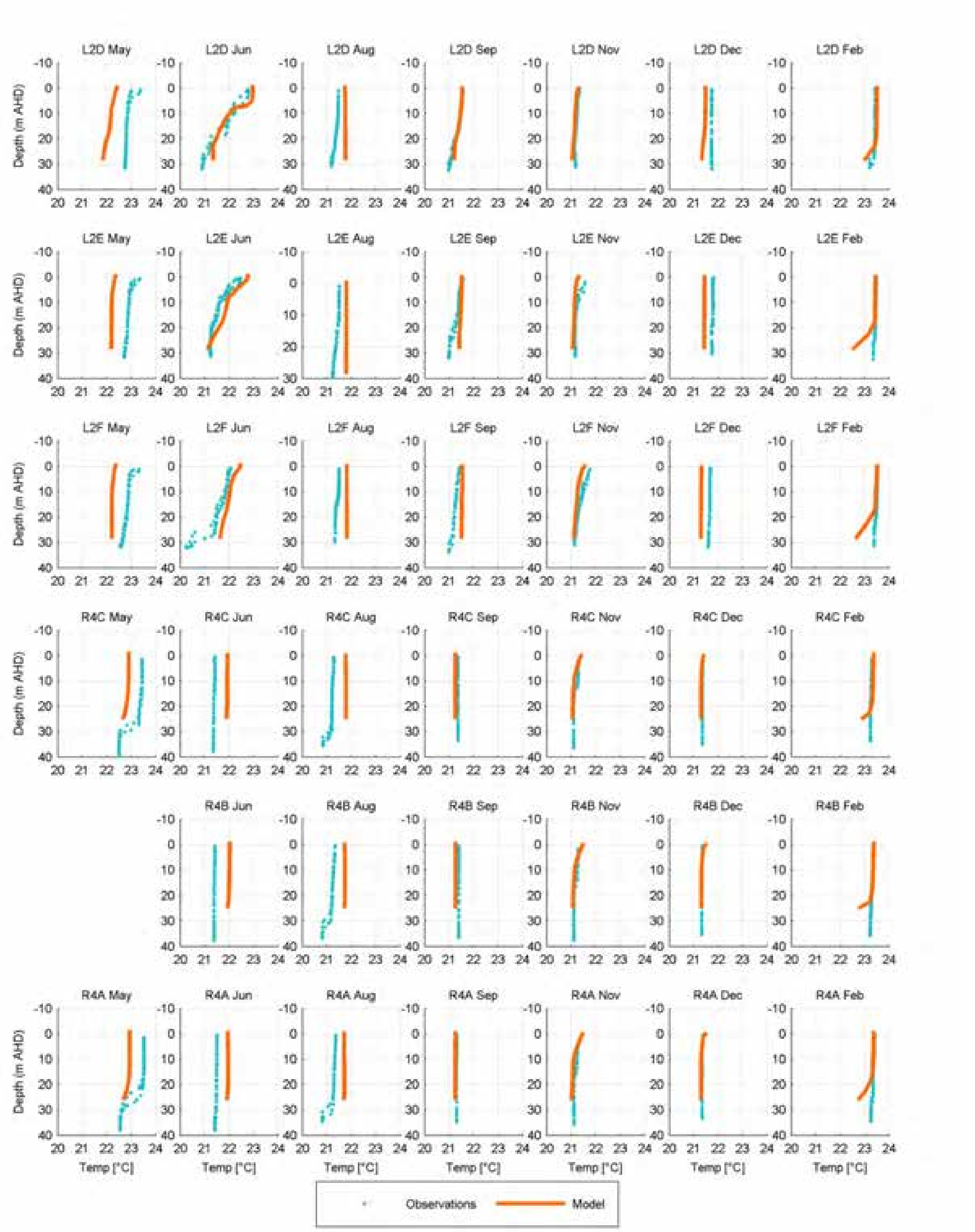


Figure 4-37 Depth profiles of temperature at lease-area sites – 3 of 5

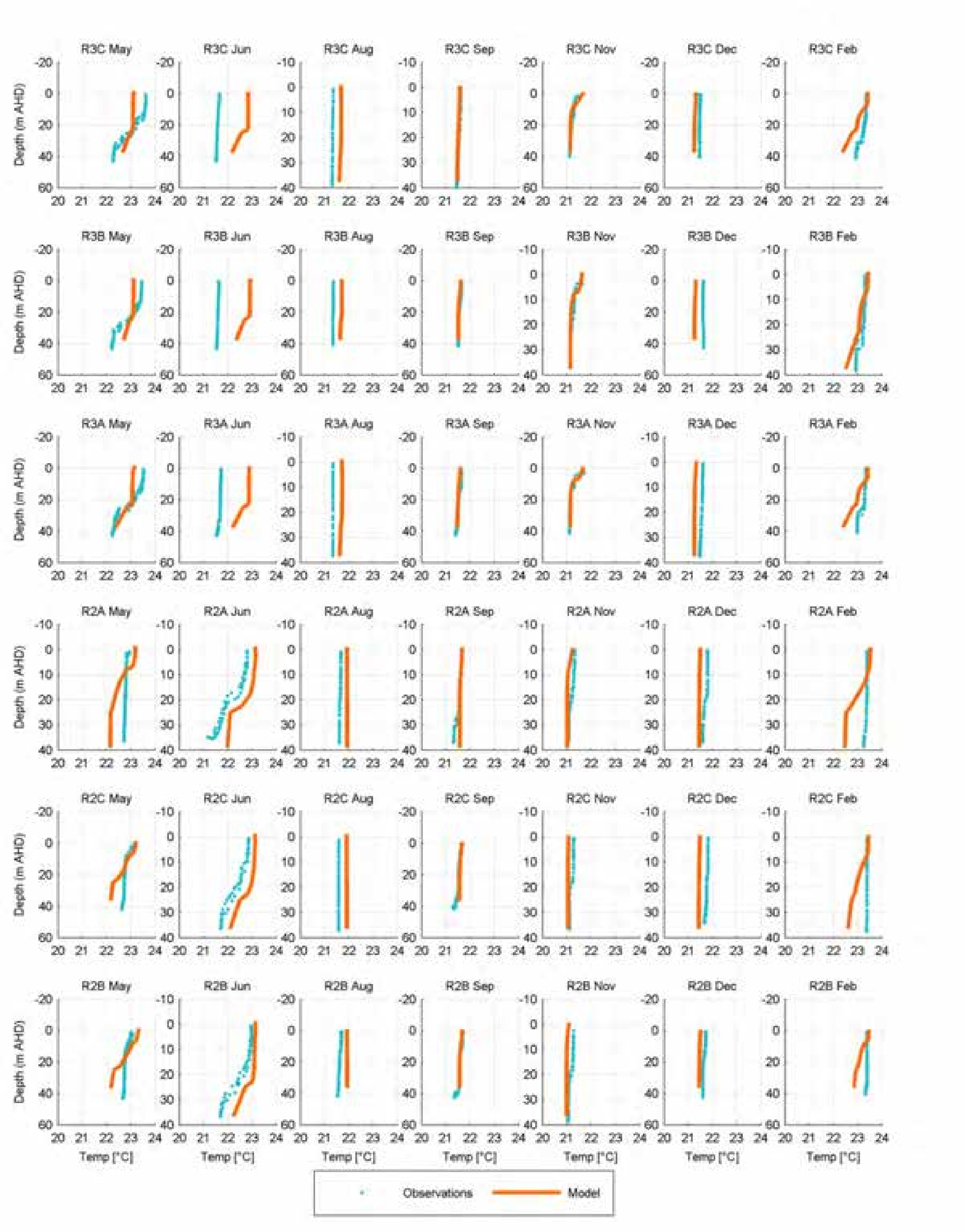


Figure 4-38 Depth profiles of temperature at lease-area sites – 4 of 5

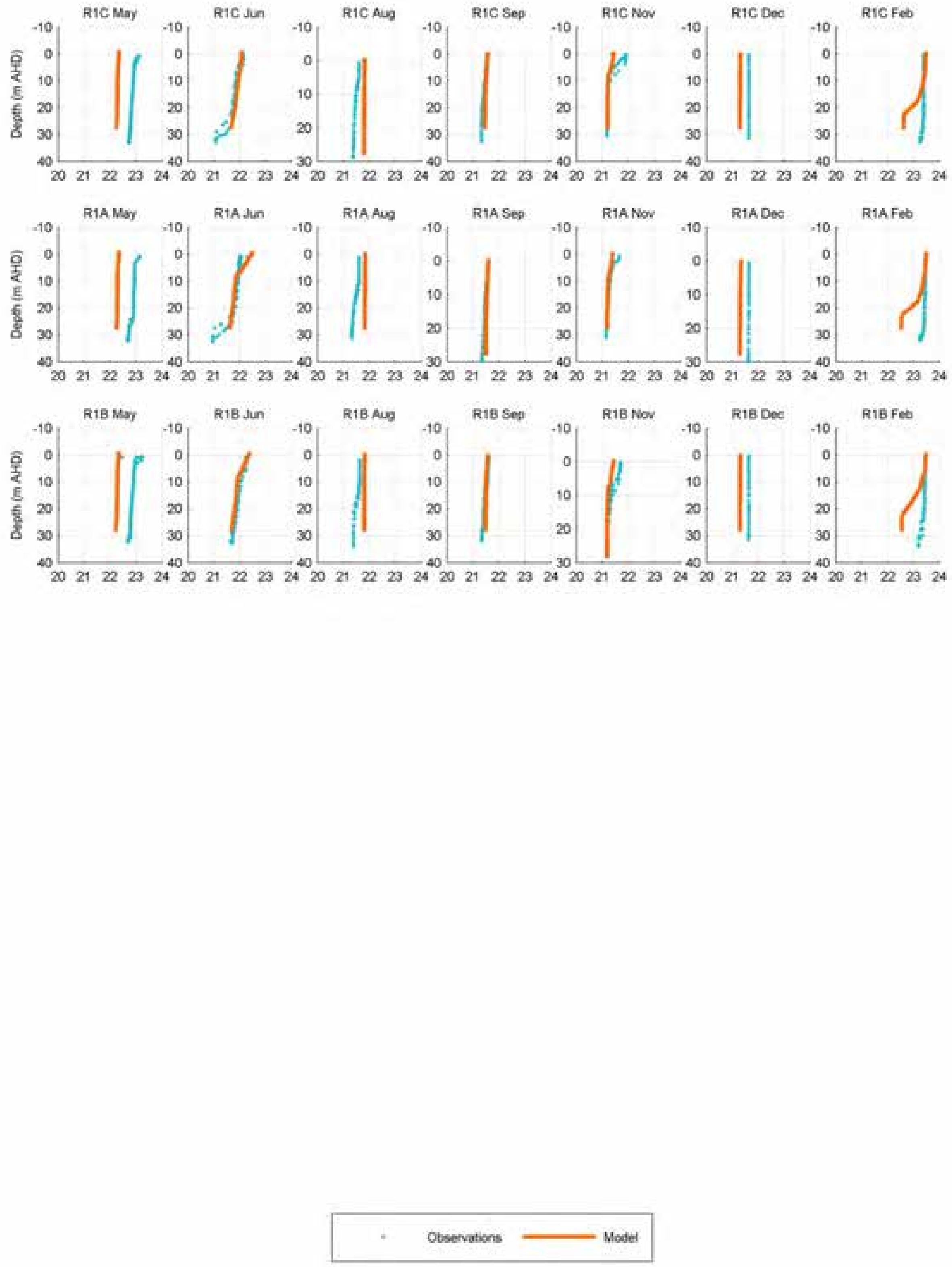


Figure 4-39 Depth profiles of temperature at lease-area sites – 5 of 5

4.1.5 Salinity

Comparisons of salinity at the regional sites are presented in Figure 4-40. Note that a decrease in salinity is apparent in the observations beginning in February 2015, which is likely the result of bio-fouling (apparent measured salinity decreases are often a signature of bio-fouling). This is particularly clear at the northern site (‘North AWAC’). Initial calibration runs indicated a consistent bias of approximately 0.3 PSU at regional sites (Figure 4-41) so an offset of 0.3 PSU was applied to the HYCOM boundary forcing to mitigate the bias, which improved the results.

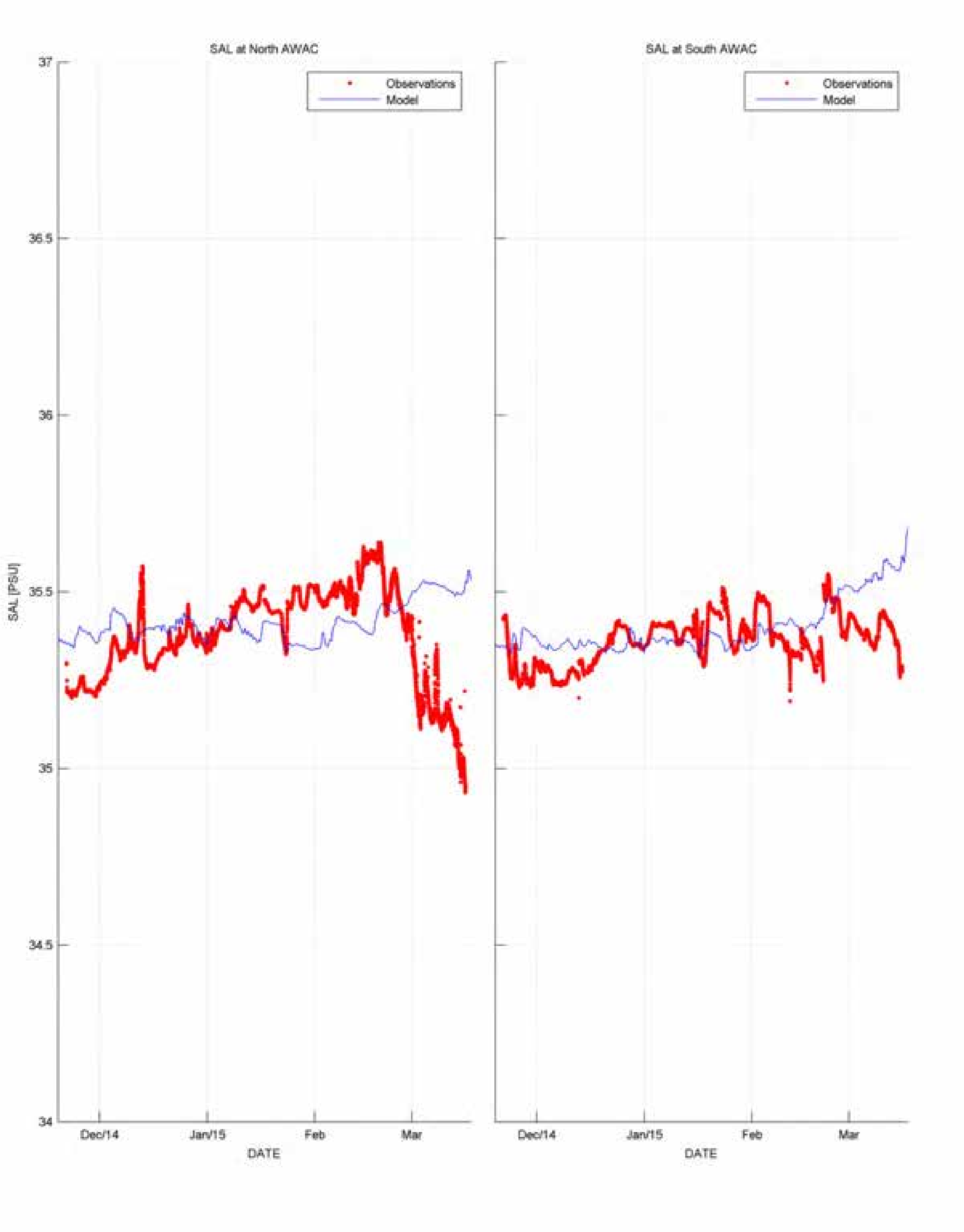


Figure 4-40 Seabed salinity at regional sites – Nov 2014 to Mar 2015 deployment

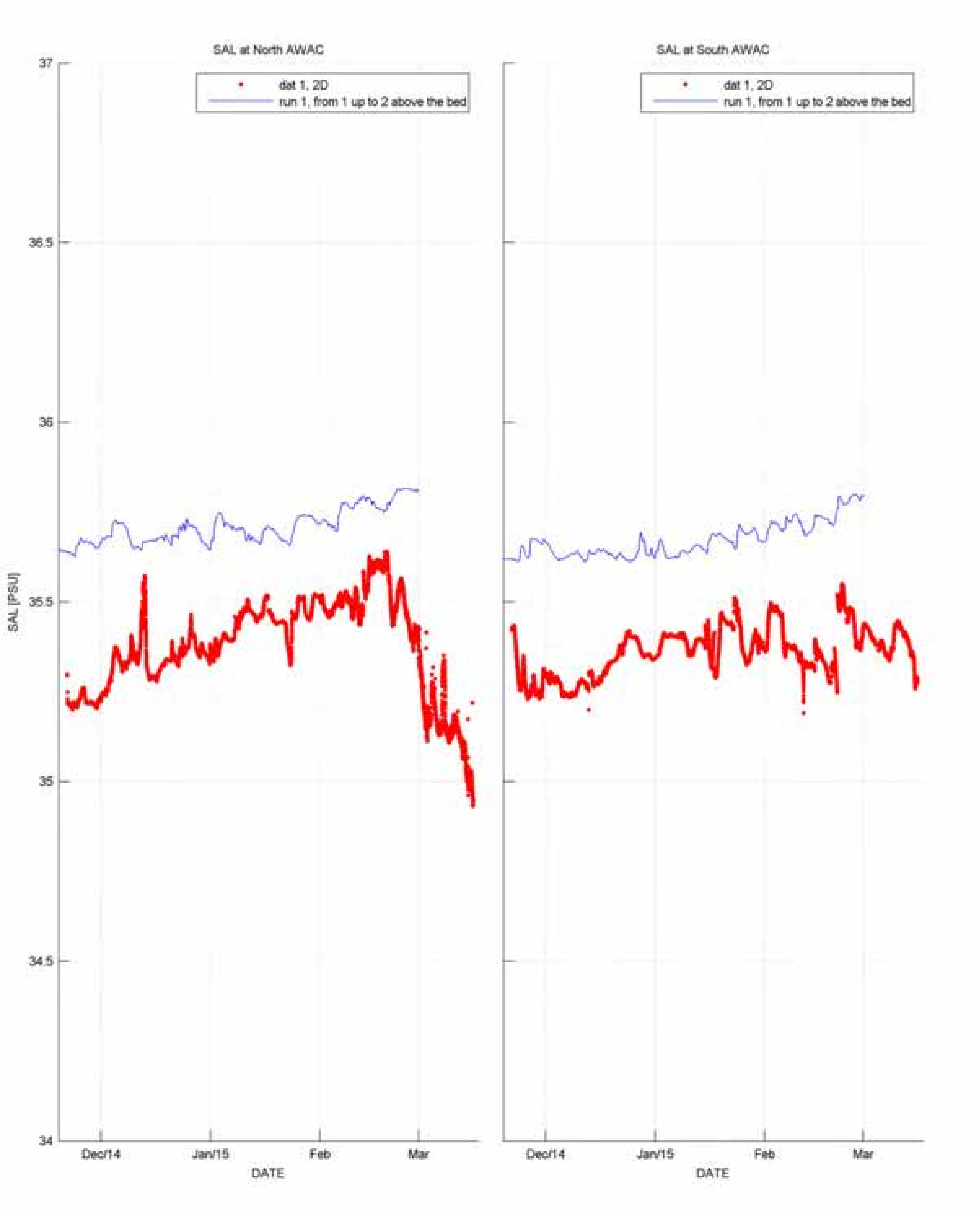


Figure 4-41 Initial salinity comparison indicating bias of 0.3 PSU

4.2 Water quality calibration

The water quality samples taken during the monitoring program indicate that the MWADZ study area is oligotrophic, with low nutrient and chlorophyll concentrations that are often below the limits of detection. As noted in Section 3.2, there is also little in the way of temporal variability and, therefore, no clear system dynamics to calibrate the model to. As such, the calibration process was reduced to one of 'verification', which simply compared simulated water quality concentrations to observations, without the need for changes to water quality parameter sets. This section provides those comparisons for the following key variables:

- Dissolved oxygen saturation
- Total nitrogen
- Ammonium
- Oxidised inorganic nitrogen (nitrate plus nitrite)
- Total phosphorus
- Phosphate
- Chlorophyll a.

Note that suspended sediment was not included in the calibration process, as observations indicated that turbidity is routinely very low, with low ambient suspended sediment concentrations. Two-thirds of all TSS measurements were at or below the detection limit of 1 mg/L, while the median of the remaining one-third was 2 mg/L. Introduction of aquaculture activities is expected to affect turbidity, so the suspended sediment module will be included when assessing the impact of those activities on water quality.

4.2.1 Dissolved oxygen

Time series of simulated DO are presented in Figure 4-42, with depth profiles of simulated and observed DO at the same sites presented in Figure 4-43 to Figure 4-47. There are no major sinks of DO in the model, resulting in values of close to 100% saturation at all times. Nevertheless there are occasionally very slight variations of DO with depth, which the model manages to successfully recreate (e.g. site L2A, L2B and L2C in June 2014; Figure 4-44).

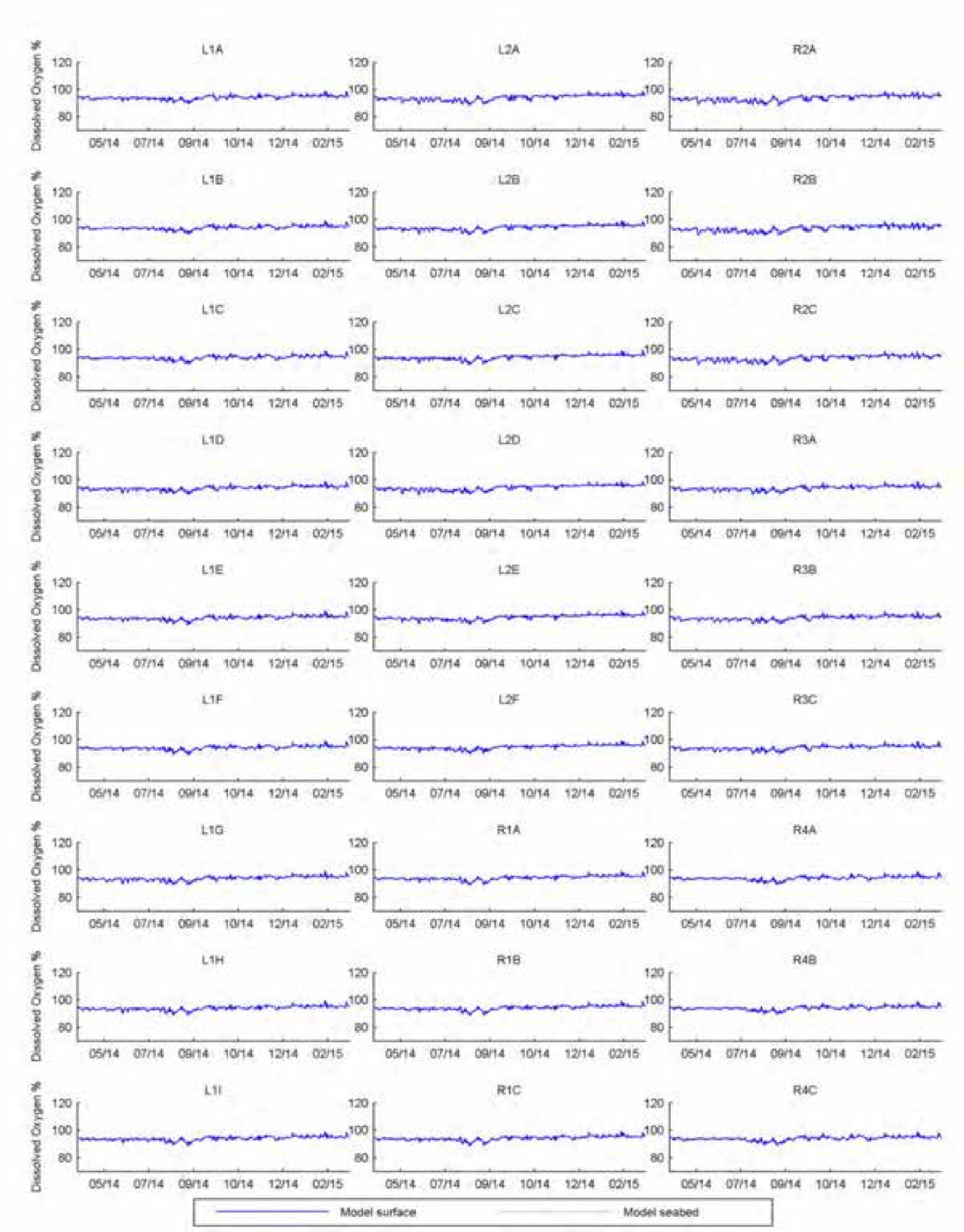


Figure 4-42 Time series of simulated percent DO saturation at lease-area sites

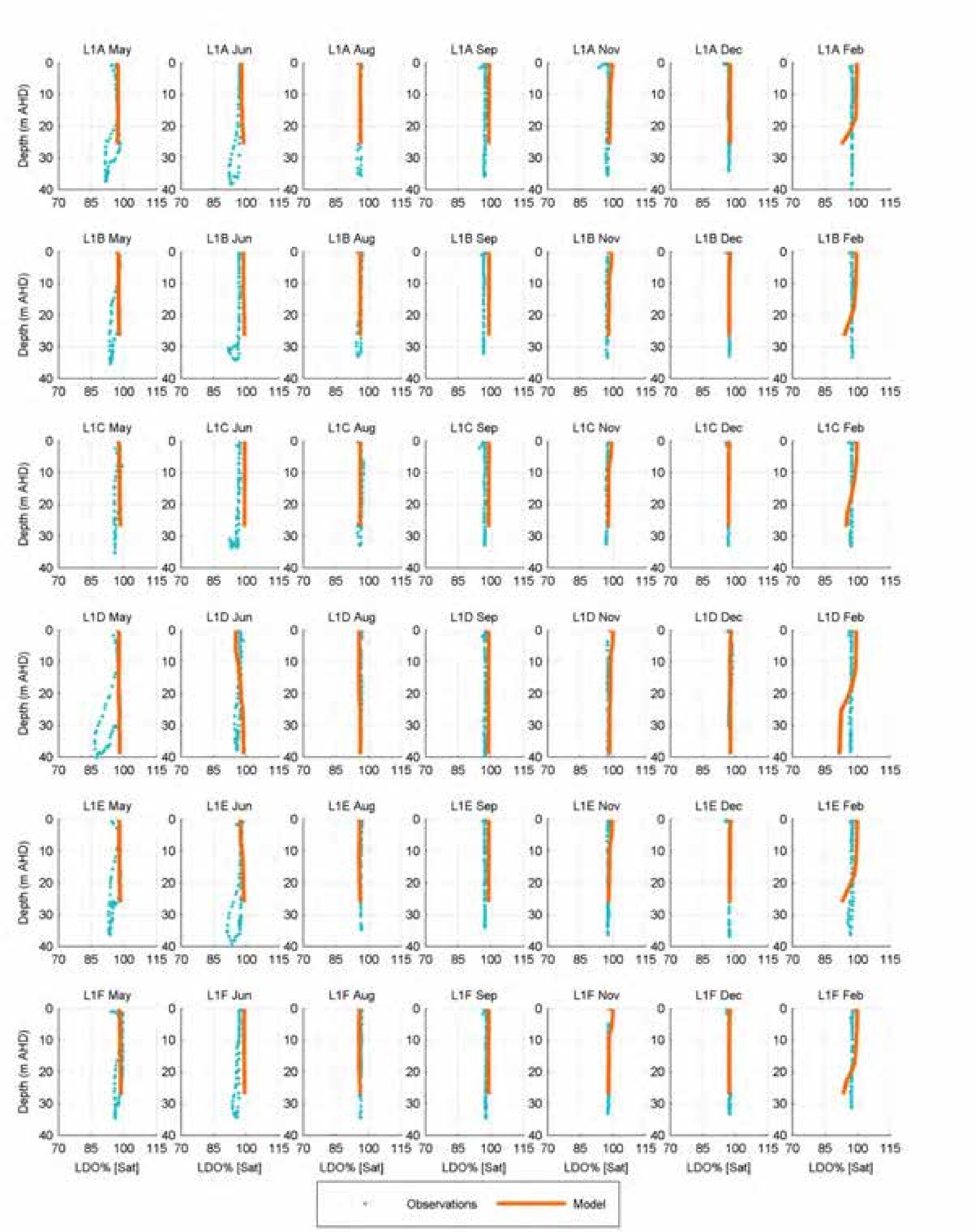


Figure 4-43 Depth profiles of percent DO saturation at lease-area sites – 1 of 5

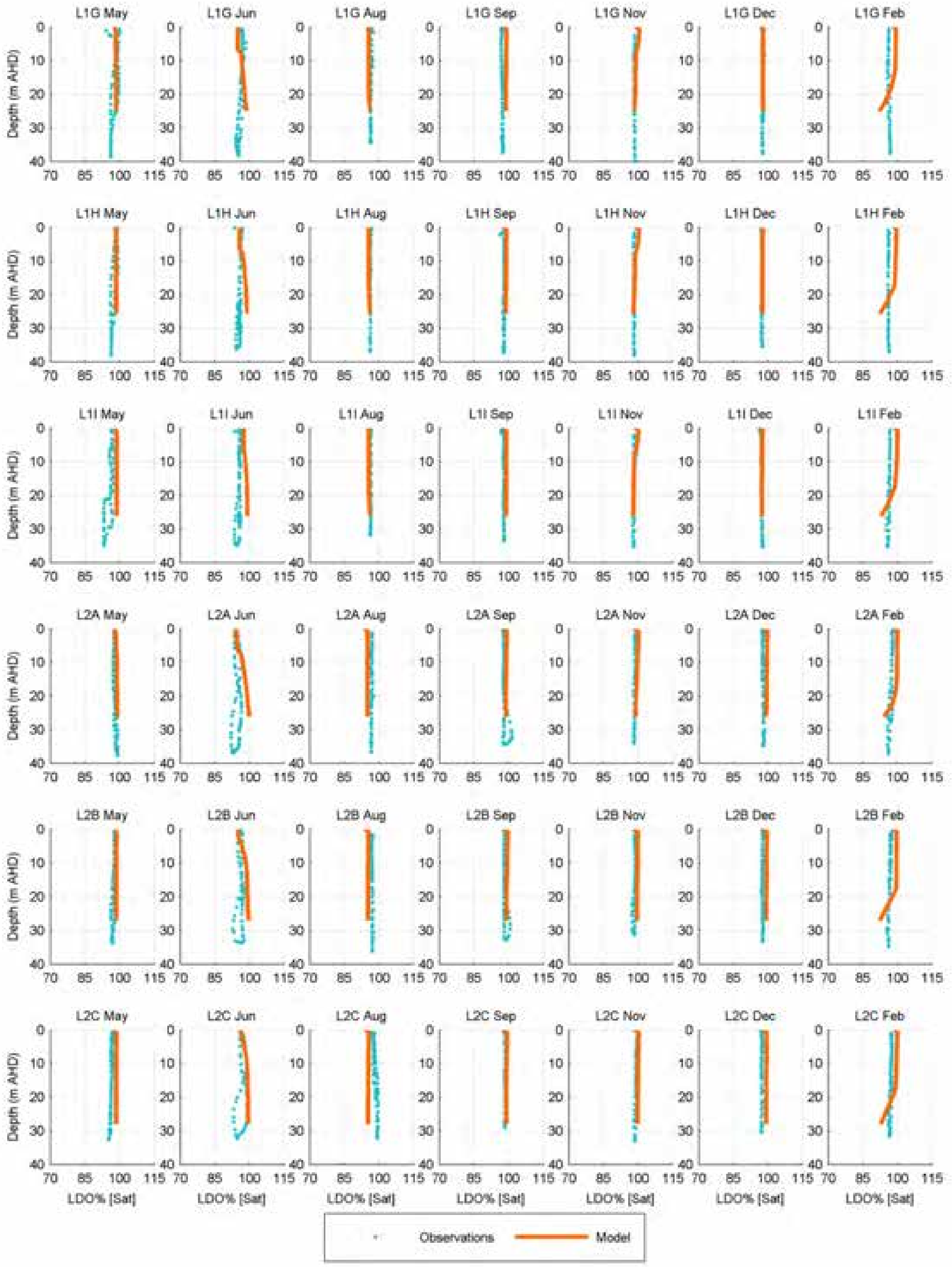


Figure 4-44 Depth profiles of percent DO saturation at lease-area sites – 2 of 5

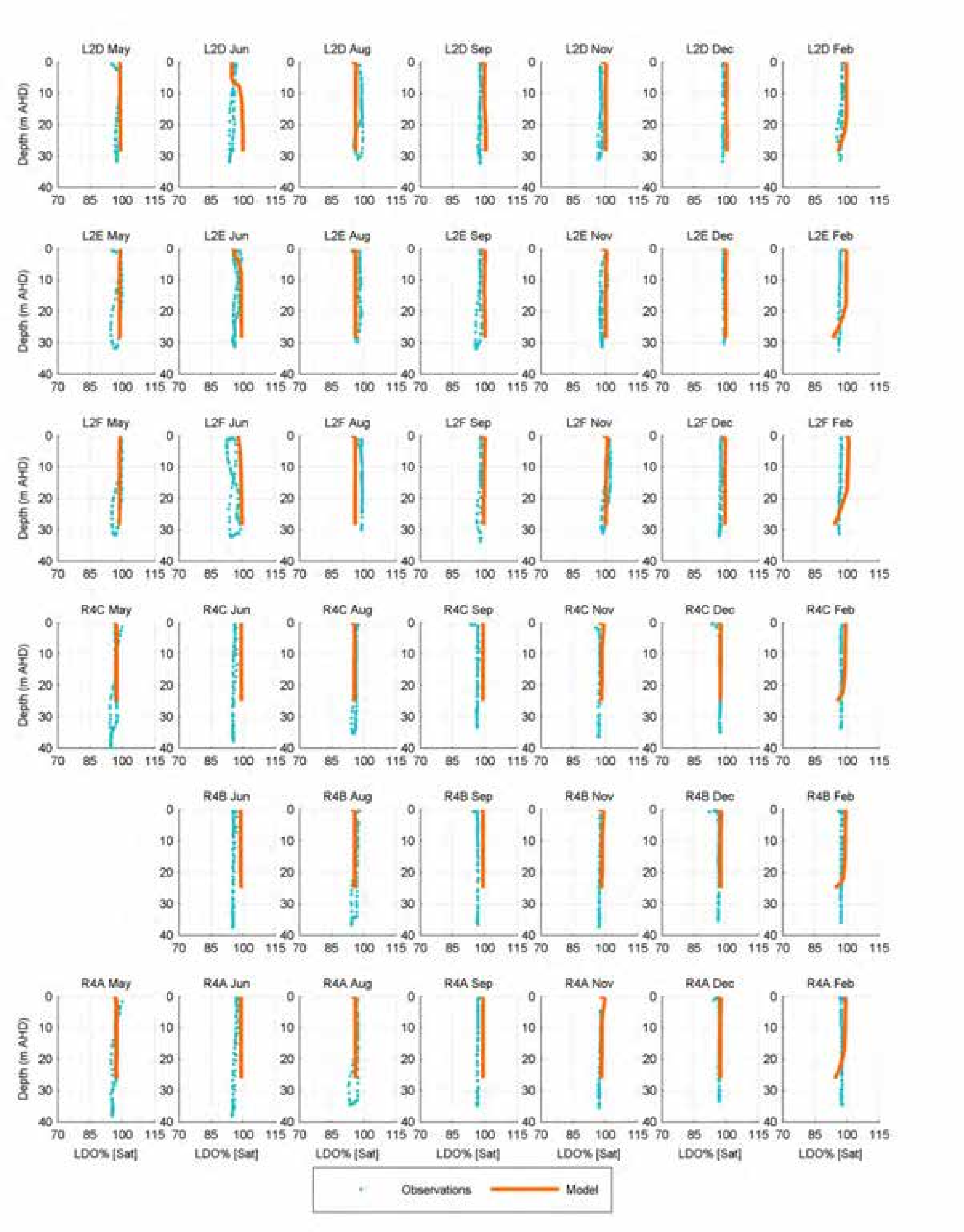


Figure 4-45 Depth profiles of percent DO saturation at lease-area sites – 3 of 5

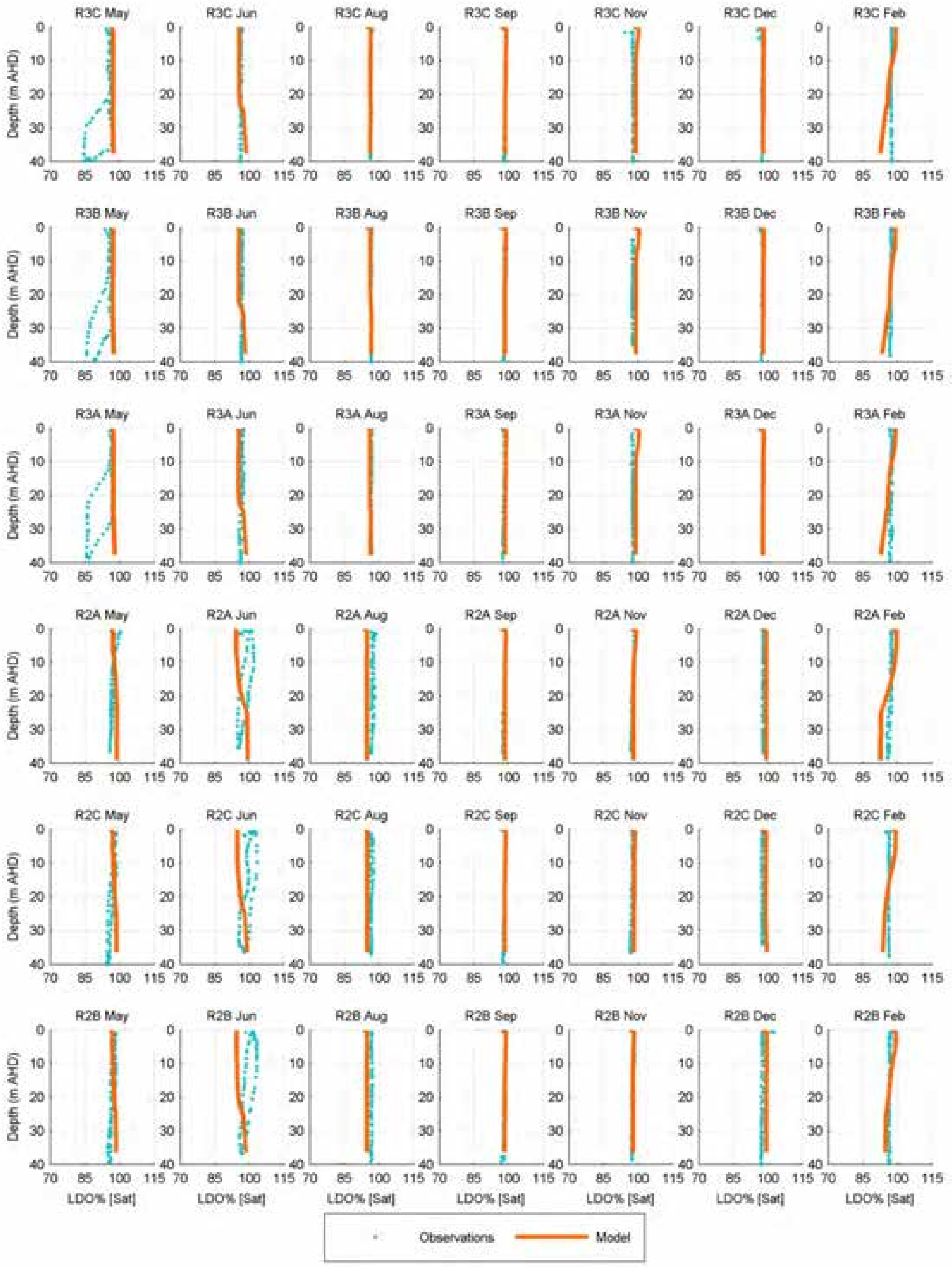


Figure 4-46 Depth profiles of percent DO saturation at lease-area sites – 4 of 5

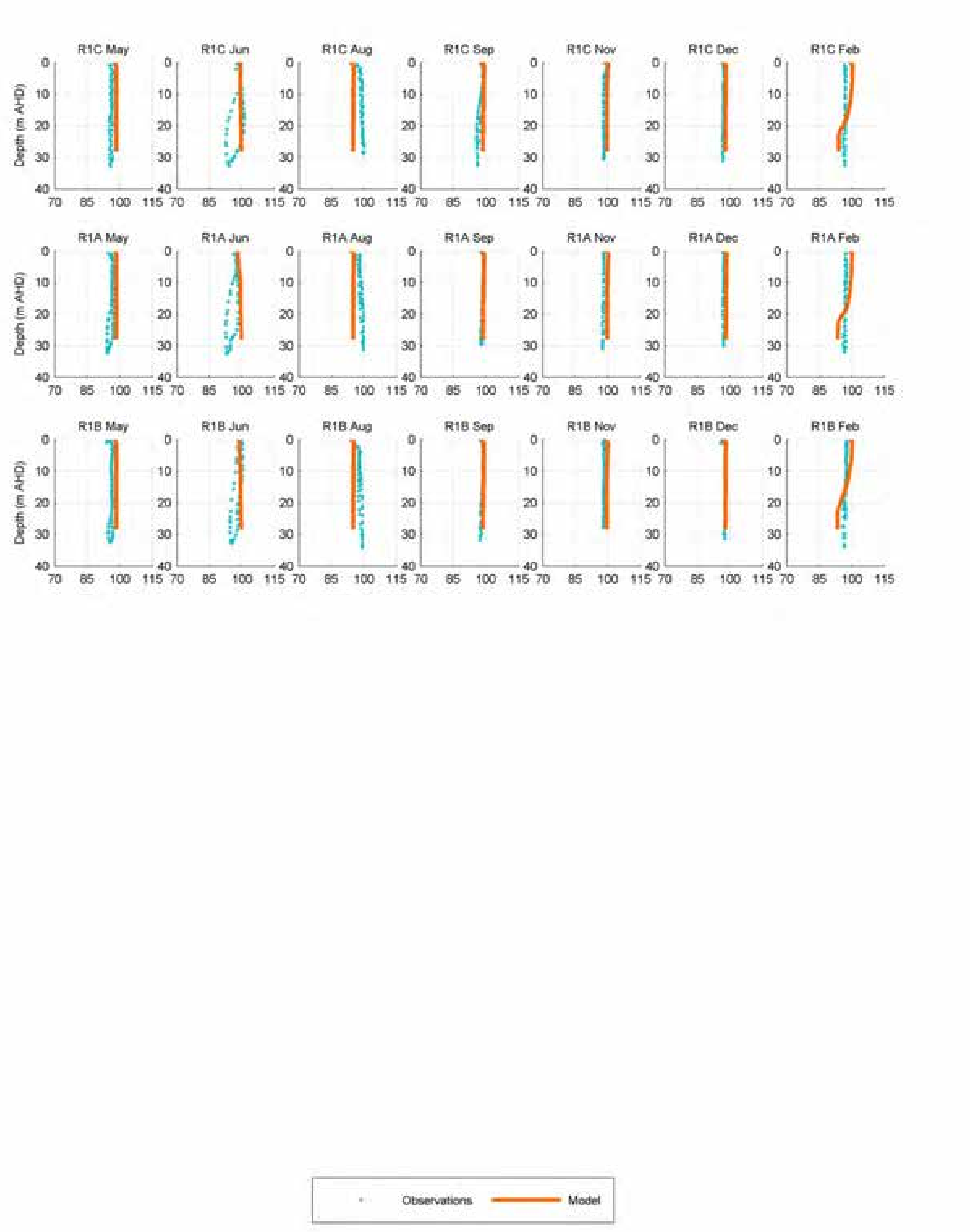


Figure 4-47 **Depth profiles of percent DO saturation at lease-area sites – 5 of 5**

4.2.2 Nitrogen

Time-series comparisons of simulated and observed TN, oxidised inorganic nitrogen and ammonium are presented in Figure 4-48, Figure 4-49 and Figure 4-50, respectively. Concentrations of TN are typically 0.2 mg/L or less, with similarly low values of speciated nitrogen, although there are some outliers (e.g. at L2A in August 2014). The model does not vary significantly during the calibration period, but agrees well with observations.

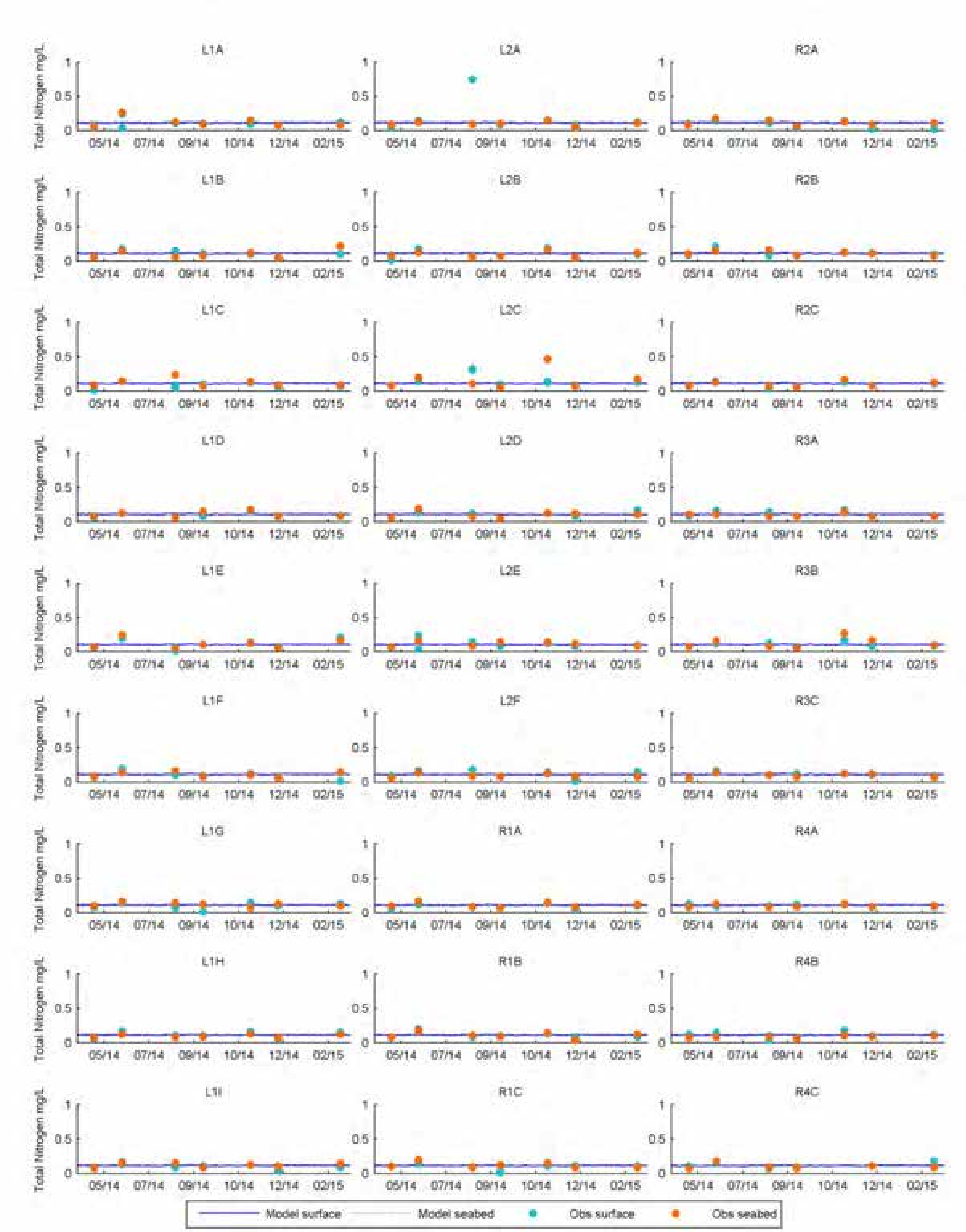


Figure 4-48 Time-series of total nitrogen at lease-area sites

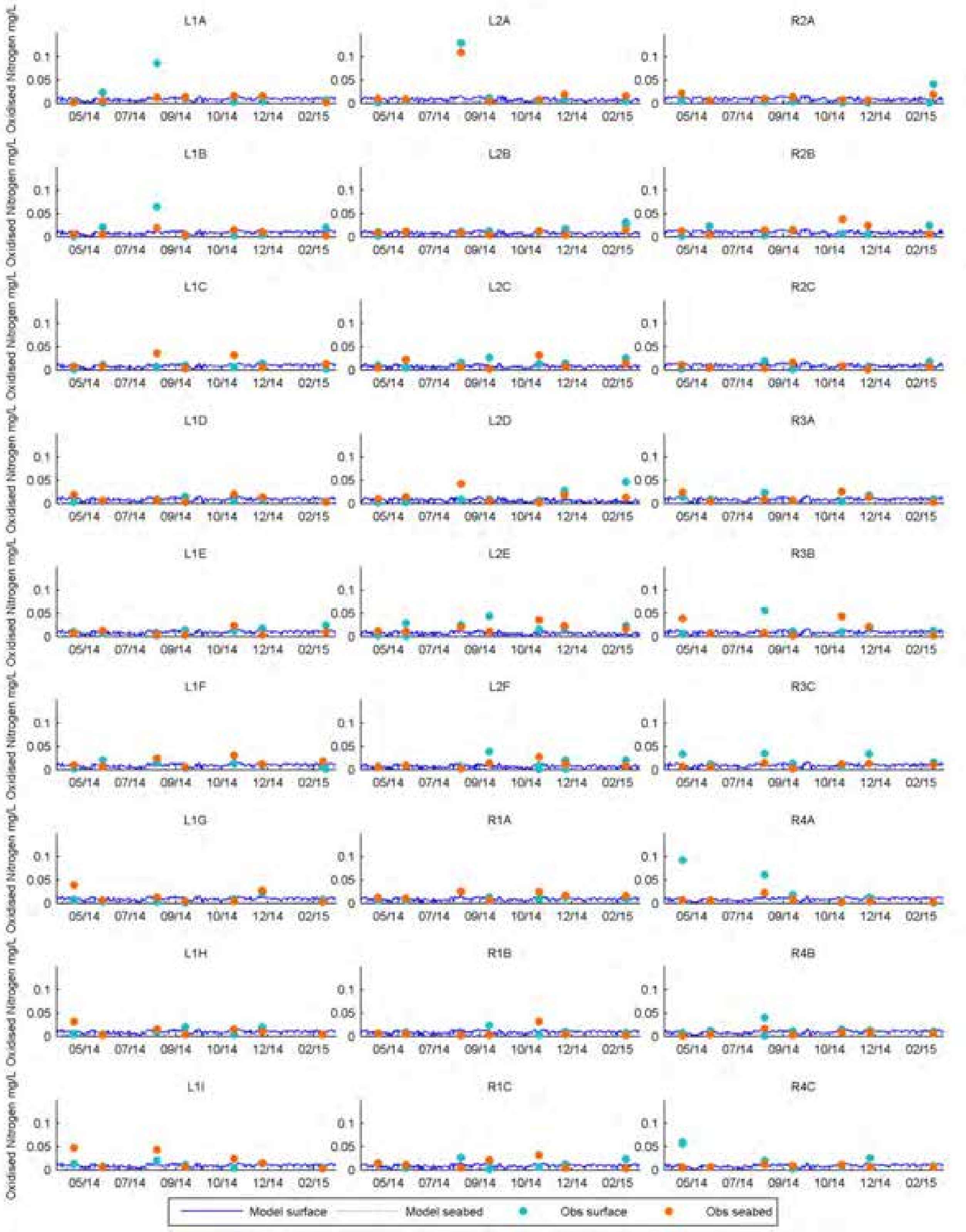


Figure 4-49 Time-series of oxidised inorganic nitrogen at lease-area sites

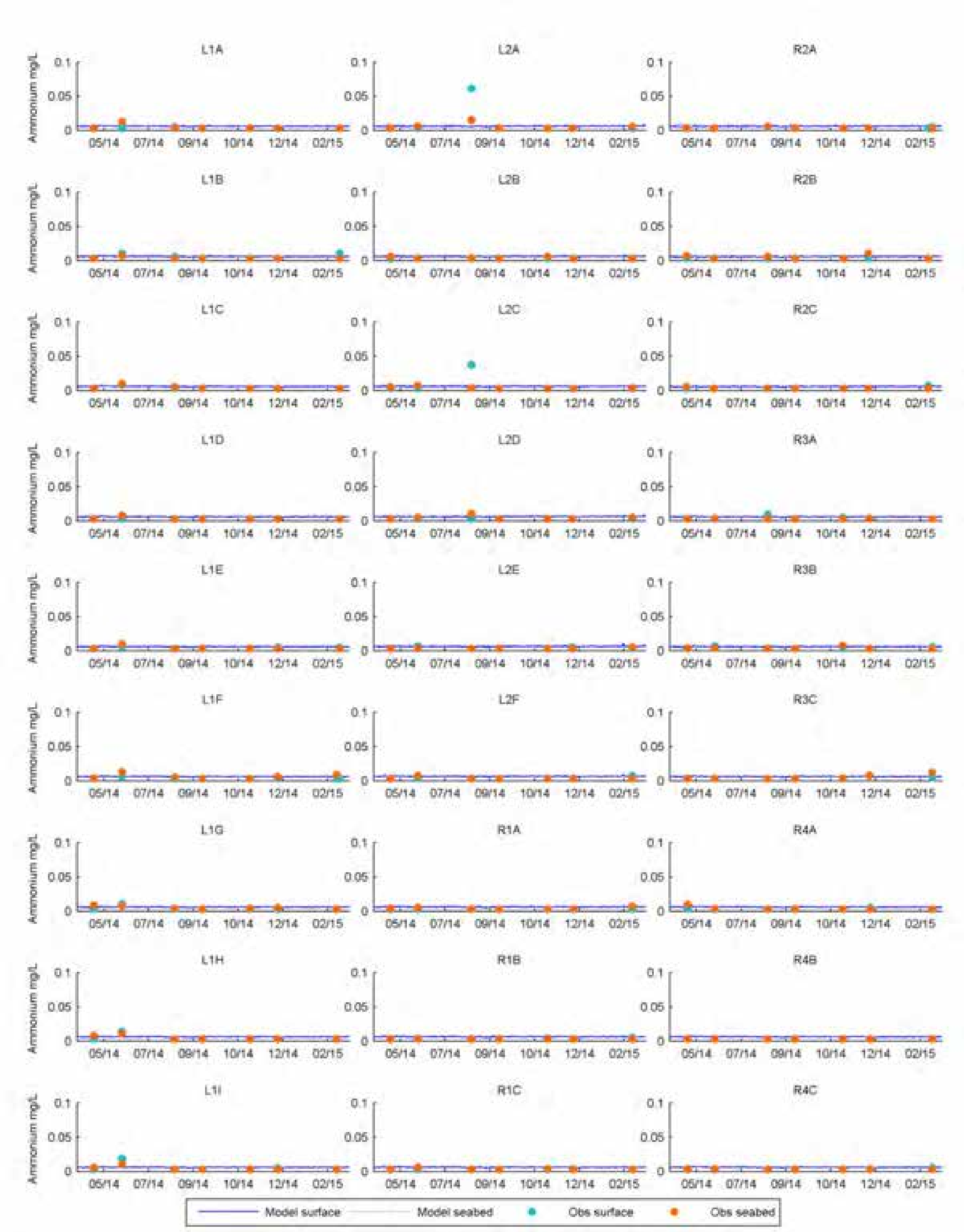


Figure 4-50 Time-series of ammonium at lease-area sites

4.2.3 Phosphorus

Comparisons of simulated and observed TP and FRP are presented in Figure 4-51 and Figure 4-52, respectively. Similarly to nitrogen, concentrations of TP and FRP are low, with occasional outliers. Neither model nor measured concentrations vary substantially during the calibration period.

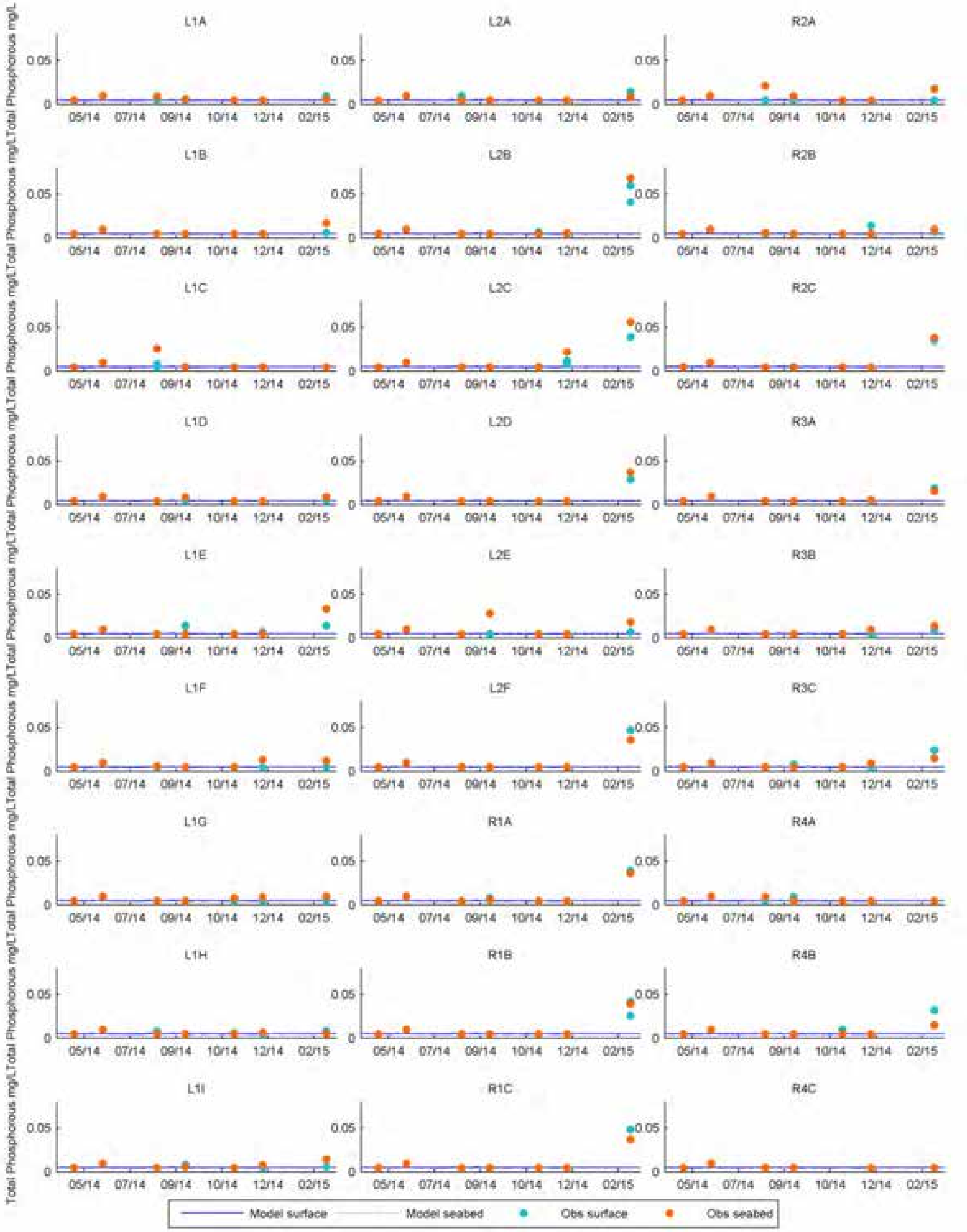


Figure 4-51 Time-series of total phosphorus at lease-area sites

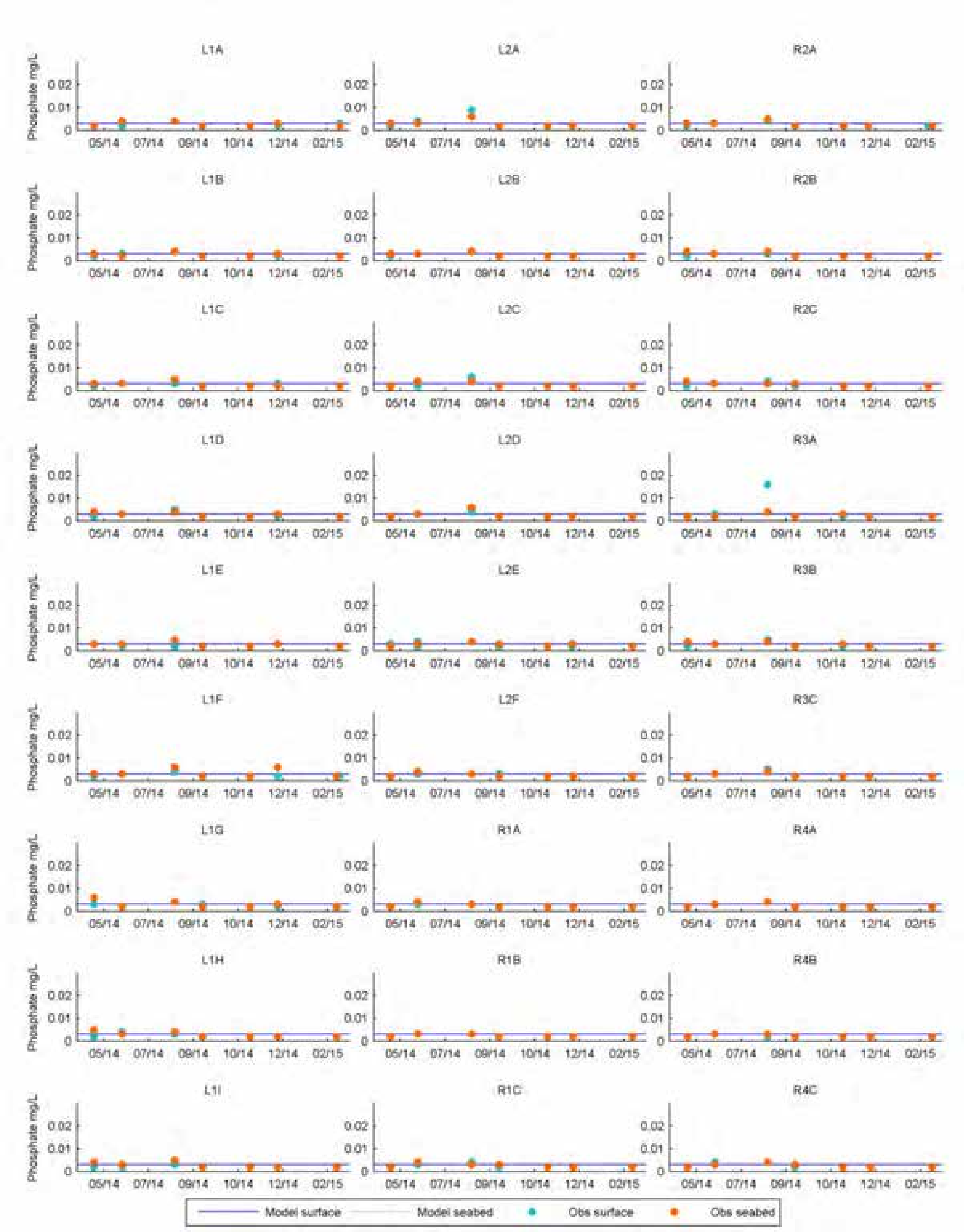


Figure 4-52 Time-series of FRP at lease-area sites

4.2.4 Chlorophyll a

Comparisons of simulated and observed chlorophyll *a* concentrations are presented in Figure 4-53. Similarly to nutrients, chlorophyll *a* concentrations are low and do not vary substantially. Observed concentrations are often at or below the detection limit of 2 µg/L and the model also simulates chlorophyll *a* concentrations around this level.

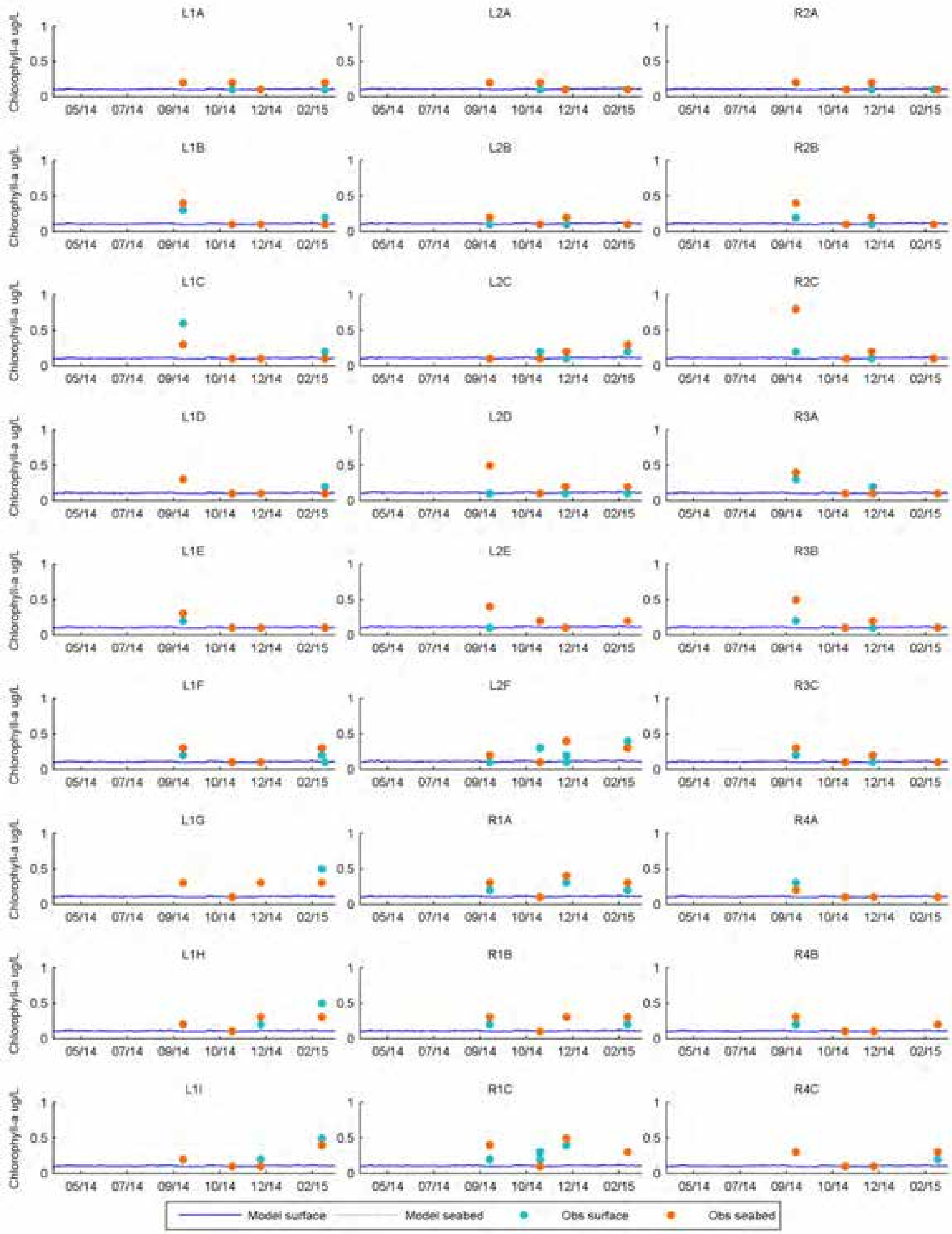


Figure 4-53 Time-series of chlorophyll *a* at lease-area sites

5 Discussion

As noted in the introduction, the region surrounding the Abrolhos Islands is challenging from a modelling perspective, as it requires the successful resolution of processes on a range of spatial scales from regional (e.g. Leeuwin Current) to local (e.g. local bathymetric features). The model described in this report achieves this by including the following:

- Global, assimilative models as boundary forcing to capture regional effects (HYCOM, TPX, CFSR)
- Kilometre-scale resolution outside of the area of interest to capture eddy dynamics
- Horizontal spatial scales down to approximately 40m to resolve local effects in the vicinity of the proposed cage locations
- Vertical spatial scales of 1 m or less to simulate stratification and other density-driven processes
- Hourly meteorological data to provide fine-scale resolution of key weather-driven processes (e.g. wave dynamics, radiative processes).

By including the above features, the model does an excellent job of replicating the hydrodynamic environment in the area of interest and is fit for the purposes of simulating the fate of particles released from aquaculture activities and providing a realistic hydrodynamic regime to the water quality module. Additionally, the water quality model recreated the oligotrophic conditions at the site, and therefore is ‘fit-for-purpose’ in assessing the effects of aquaculture activities on water quality concentrations within the area of interest.

Current velocities and wave dynamics are particularly well represented, with the model capturing both short-term and long-term variability. This is key to a successful study as these processes are vital in accurately simulating particle distribution, which, in turn, is crucial in determining the impact of food and faecal particles on the environment surrounding fish cages. Tidal range is slightly under-predicted but a sensitivity test indicated that changing the model to address this was detrimental to the velocity calibration, which is more important. Significant wave height also has a slight bias but this was shown to have a limited effect on the ‘footprint’ of particles released from fish cages. While wave height magnitude was slightly over-predicted, the simulated *variability* of wave height matched observations very well, with r values greater than 0.84 at all sites. The other wave parameters of peak wave direction and peak wave period compared very favourably in both magnitude and variability.

The model captured seasonal and short-term temperature dynamics very well, including a number of localised and short-term thermal stratification events, as demonstrated by comparisons against 188 depth profiles taken during the study. The ability to recreate these events indicates that the model’s representation of bathymetric features around the Abrolhos Islands is good, and it captures the interaction between these and the important large-scale currents in the region. Arguably, it is more important to capture the seasonal dynamics as the impact of aquaculture activities will be assessed over the long-term. The model illustrated its capability in this regard by successfully recreating the onset of summer temperatures, with r values of 0.916 and 0.957 during the

November 2014 to Mar 2015 deployment. Furthermore, the model matched salinity observations well once a constant offset of 0.3 PSU was applied to the HYCOM boundary forcing.

The water quality model compared well with observations, but no significant water quality dynamics were observed during the sampling period. Most samples were at or below the detection limit and, as such, the calibration was more of a ‘verification’ that the model would also recreate the oligotrophic conditions apparent in the region.

6 References

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Appendix A Methodology Letter – March 2015

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Our Ref: L.B20639.005.Methodology.docx

15 September 2015

Cardno
Level 9 The Forum
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St Leonards
NSW 2077

Attention: Dr. Doug Treloar

Dear Doug,

RE: MIDWEST ZONE AQUACULTURE MODELLING PROPOSED METHODOLOGY

Thank you for your comments reviewing our proposed methodology for this study, provided during the meeting at BMT WBM's office on 5th March 2015 and based on the latest revision of our methodology document (L.B20639.004.Methodology.pdf; minutes of meeting outlined in M.20639.001.MethodsReviewMeetingMinutes.pdf).

A finalised methodology document, addressing each of the comments, is included below for your records.

Yours Faithfully
BMT WBM

Michael Barry

1 Introduction and Background

The Department of Fisheries, Western Australia (DoF), on behalf of the Minister for Fisheries proposes to create an ‘Aquaculture Development Zone’ to provide a management precinct for prospective aquaculture proposals within the State Waters, off the Houtman Abrolhos Islands (HAI) Fish Habitat Protection Area (FHPA), which is approximately 75 kilometres west of Geraldton. The Mid-West Aquaculture Development Zone (MWADZ) has been selected by DoF to maximise suitability for marine finfish aquaculture, and minimise potential impacts on existing marine communities and human use.

The MWADZ is proposed to encompass an area of 8041.83 hectares (ha) across two development areas (Figure 1). The study sites are located within the two MWADZ areas:

- A 3000 ha area located in Zeewijk Channel, between the Pelsaert and Easter Groups; and
- A 1740 ha study area located north of Murray Island in the Pelsaert Group

Under the Environmental Scoping Document (ESD) associated with the proposed MWADZ, DoF is required to prepare a Public Environmental Review (PER) document in accordance with the Western Australian Environmental Protection Act 1986 (EP Act). The objectives of this assessment are to identify an environmentally acceptable location for the MWADZ and to identify the operational limits and objectives to apply to future proposals in the MWADZ to manage the cumulative impacts of multiple sea cage operations. To fulfil the requirements of the ESD and the preparation of the PER, DoF has engaged BMT Oceanica to undertake the technical studies for the environmental impact assessment (EIA) associated with operations within the proposed MWADZ. This involves investigating the influence of various factors such as nutrient and contaminant input, establishment of infrastructure, management practices, and the hydrodynamics of the surrounding marine environment.

BMT Oceanica, alongside its sub-consultants BMT WBM and the University of Western Australia (UWA) (hereafter, ‘We’), will develop environmental models to assess the potential impact of finfish aquaculture on marine flora and fauna in the area, including significant marine fauna of the region. This document contains a description of the modelling sampling program that will be undertaken, the modelling methodology that will be employed, and the pressure-response analysis strategy that will be used to address the regulatory requirements. It is intended that this document be reviewed on technical grounds by the team’s peer reviewer, with a view to refining/modifying the proposed methods to the satisfaction of the reviewer.

2 Pressure-Response Analysis Strategy

2.1 Pressure-response relationships and trigger parameters

Pressure-response relationships and the environmental trigger parameters (thresholds) relating to aquaculture in tropical and subtropical environments are well known to BMT Oceanica. BMT Oceanica has 20+ years of experience of pressure-response relationships associated with sewage outfalls (which impart similar pressures to aquaculture), and recently played a key role in the development of an EIA for the Kimberley Aquaculture Development Zone (KADZ). A review of literature undertaken for the KADZ project (encompassing over 100 peer reviewed articles and reports), for example, identified critical threshold values for a number of key receptors (e.g. corals, sessile filter feeders and infauna) that could reasonably be applied across tropical and sub-tropical marine environments generally. The receptors and the critical thresholds for the Mid-West assessment are expected to be near identical to those identified in the KADZ project and for this reason will be used as the starting point in this project. Groundtruthing of thresholds will be undertaken using Mid-West specific data collected during the baseline assessment between May 2014 and February 2015. Ultimately, all thresholds will be set conservatively in line with approach of the EPA (2000), where 'safety factors' are applied to mitigate against uncertainty. The term ‘safety factor’ is used by the EPA to ensure modelling scenarios are conservative. Safety factors will be applied by (1) overestimating the stocking densities/standing biomass of fish stocks, (2) by using upper-end estimates for faecal-pellet sinking rate and the carbon content of faecal matter, and (3) by using appropriately conservative values for model parameters (e.g. sediment mineralisation rates). Outputs from the models will incorporate this uncertainty and use a conservative approach to ensure the cumulative impacts of proposed aquaculture operations are overestimated.

2.2 Developing and applying the trigger parameters

The EPA scoping guideline for this proposal requires the application of the impact categories outlined in EAG 7 (EPA 2011), which was originally designed to assess the impact of dredging activities and, hence, contains dredging terminology throughout. EAG 7 contains three predefined levels of impact: zone of high impact (ZoHI); zone of moderate impact (ZoMI) and the zone of influence (ZoI). The application of these categories is determined by ‘recovery time’: specifically, how long the impacted habitat will take to recover once the stressor(s) has/have been completely removed. Habitats requiring greater than five years to recover are designated zones of 'high' impact, and habitats requiring less than five years to recover are designated zones of 'moderate' impact. EAG 7 defines the ZoI as the area within which changes in environmental quality associated with dredge plumes are predicted and anticipated during the dredging operations (aquaculture operations in the case of this study), but where these changes would not result in detectable impacts on benthic biota.

While the EAG 7 approach is robust in theory, it is limited by local taxonomic information and a poor understanding of the response of organisms following different magnitudes of impact. This is exacerbated by the fact that, as EAG 7 was originally written to inform EIA processes associated with capital dredging works in the State’s north-west, much of the relevant literature focuses on inorganic suspended materials and its effect on corals. Hence, the effect of organic wastes and inorganic nutrients to other flora and fauna, and their recovery following removal of the ‘pressure’, has received relatively little attention.

2.3 Application of models to inform the EIA process

The EIA will proceed by investigating a number of cause-effect pathways and determining the likely impact of each pathway through the use of numerical models, where appropriate. A list of cause-effect pathways, and their receptors are included in Figure 1. Two distinct modelling approaches will be utilised:

- An integrated hydrodynamic, water quality and sediment-diagenesis model to investigate the potential environmental impacts of changes in water quality; and
- An integrated hydrodynamic, sediment particle transport and sediment-diagenesis model to investigate the potential environmental impacts of changes in sediment quality from aquaculture activities. This will include estimates of the time taken for sediments to recover to baseline conditions following removal of fish cages.

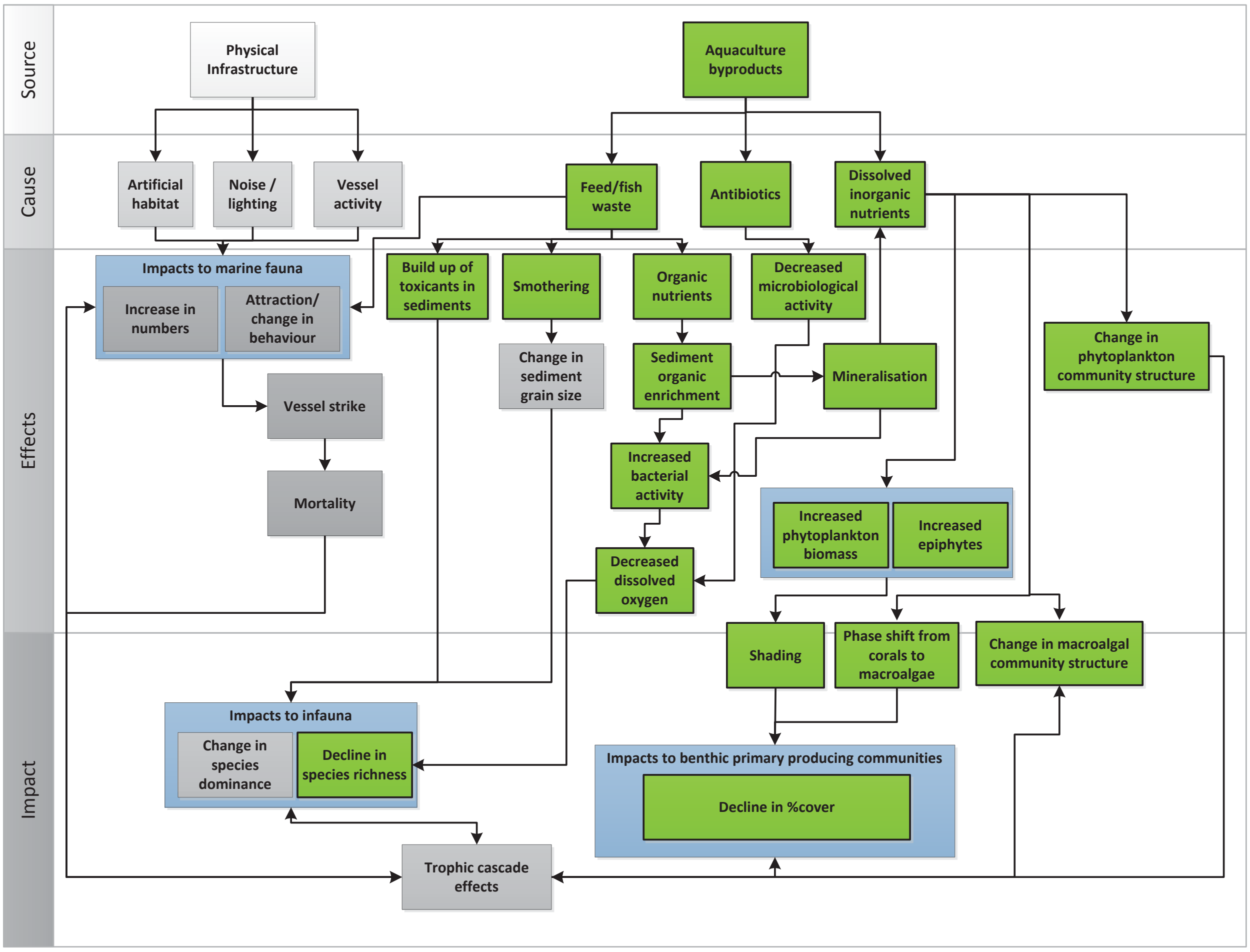


Figure 1 Cause-effect pathways to be investigated by modelling

As per EAG 7, the objective of the modelling is to determine the extent to which aquaculture will (1) impart 'high' and/or 'moderate' impacts to benthic habitats, and (2) impart an 'influence' on surrounding environmental quality without impacting benthic habitats. We propose to apply different approaches depending on two distinct receiving environments:

- Soft, sandy substrates, which are assumed to contain no significant flora or sessile benthic fauna.
- Hard substrates, with resident macroalgae, filter feeder or coral communities.

A habitat survey is planned to confirm the assumptions mentioned above (see Section 3.2.1) and, if possible, the cages will be preferentially placed such that hard-substrate habitats are avoided.

For soft substrates, the zones of impact will be modelled directly using the integrated hydrodynamic, particle transport and sediment-diagenesis models. Recovery times will be determined based on the time taken to achieve 'chemical' remediation. In this context, chemical remediation refers to the time taken for sediment conditions (e.g. nutrient, oxygen and chlorophyll concentrations) to return to their baseline condition. This is as opposed to 'biological' remediation, which refers to the time taken for sediment biological communities to return to their baseline state. Chemical remediation is a more reliable process with readily identifiable beginning and end points, while biological remediation, in contrast, may never occur completely, as guilds of infauna inhabiting similar ecological niches may replace each another, leading to subtle differences in post-remediation community structures–meaning the end point is difficult to quantify. In addition, chemical remediation may be modelled directly, whereas simulating biological remediation would require a model capable of resolving multiple species and successional processes at a number of trophic levels–which is unadvisable given its complexity, and presently impossible given the constraints of the model. For soft substrates, therefore, we believe the chemical-remediation approach is the most robust (a description of the relevant models is included in Section 4).

For hard substrates, the chemical remediation approach above will be followed but an additional step will be included to assess the impact on other receptors (corals, seagrasses and macroalgae). This additional assessment will proceed in two stages: (1) for each of the receptors, the critical thresholds at which high and moderate impacts are likely to occur will be determined and (2) these will then be cross-reference with the contaminant concentration gradients produced by the models, to spatially represent the zones of impact in two-dimensional space (aerial perspective). This is a complicated impact assessment because it has more assumptions than the soft sediment impact assessment. To mitigate the confounding effects of this complexity, the first step in the EIA process, where possible, will be to set up the model such that the sea-cage clusters (each consisting of 14 cages of approximately 38 m diameter) are positioned over soft sediment habitats and at least 100 m from the nearest hard substrate.

If the proposed MWADZ is positioned over hard substrate, it will be necessary to develop thresholds for a range of receptors. Hard substrates of the Abrolhos are sometimes inhabited by a combination of corals, macroalgae, seagrass and filter feeders. Because each has differing tolerances, it will not be possible to model recovery using a single time line, as some will recover faster than others. To overcome this, thresholds will be developed based on the most sensitive of receptors, or the most dominant of the receptors (whichever is more appropriate). Experience in the KADZ assessment suggests the thresholds will be based on corals (specifically *Acropora* spp).

For impacts associated with more diffuse (less direct) cause-effect pathways e.g. shading resulted from regional algal blooms, thresholds will be developed from known minimum light tolerances for benthic primary producing habitats, or the inorganic nutrient thresholds known to result in ecological phase shifts i.e. corals to macroalgal dominated reefs. Previous work undertaken as part of the KADZ assessment indentified thresholds based on both inorganic and organic stressors for a range of receptor organisms. Because some organisms were more sensitive than others, the complexity of the EIA was reduced by applying conservative thresholds based on the most sensitive species. Examples of the application of this process are provided below.

2.3.1 Suspended particles and sedimentation stressors

Thresholds for suspended particles were based on magnitude and duration of exposure (concentration [mg/L) by time [days]), and the thresholds for sedimentation were based on the depth of burial (mm). In terms of suspended particles, corals were found to be more sensitive (5-25 mg/L over a given percentage of time) than other types of filter feeders (10-1000 mg/L over 'X' number of days). Similar results were found in terms of sedimentation, with corals being more sensitive (with the lowest tolerance) (1.7-17.5 mm) than mobile invertebrates (20-30 mm) and bivalves (10-40 mm). It was also acknowledged through this process that the above thresholds were based on the effect of inorganic particles, and that the effect of organic particles, such as food or faecal particles, may differ. However, in the absence of comparative information relevant to organic particles, these thresholds were used as an estimate. It is also recognised that as much of the work associated with the KADZ assessment concentrated on the effects to resident corals and other filter feeders, further work will be required under the MWADZ assessment to determine the relative sensitivities of seagrasses and macroalgae to the effects of shading and sedimentation. Using the conservative approach advocated by the EPA (2000), and once armed with all relevant information, we will define the zones of impact using the known tolerances of the most sensitive microhabitats, and then derive recovery times based on the known biology of the constituent organisms, including times required for recolonisation and growth.

2.3.2 Inorganic-nutrient stressors

Aquaculture may contribute inorganic nutrients to the water column either directly through secretion of ammonia by fish, or indirectly through organic matter deposition and remineralisation. Inorganic nutrients in the form of ammonia, nitrite + nitrate and orthophosphate may lead to adverse environmental effects via a number of cause-effect pathways, all of which contain benthic, primary-producing organisms (BPPO) as key receptors (Figure 2).

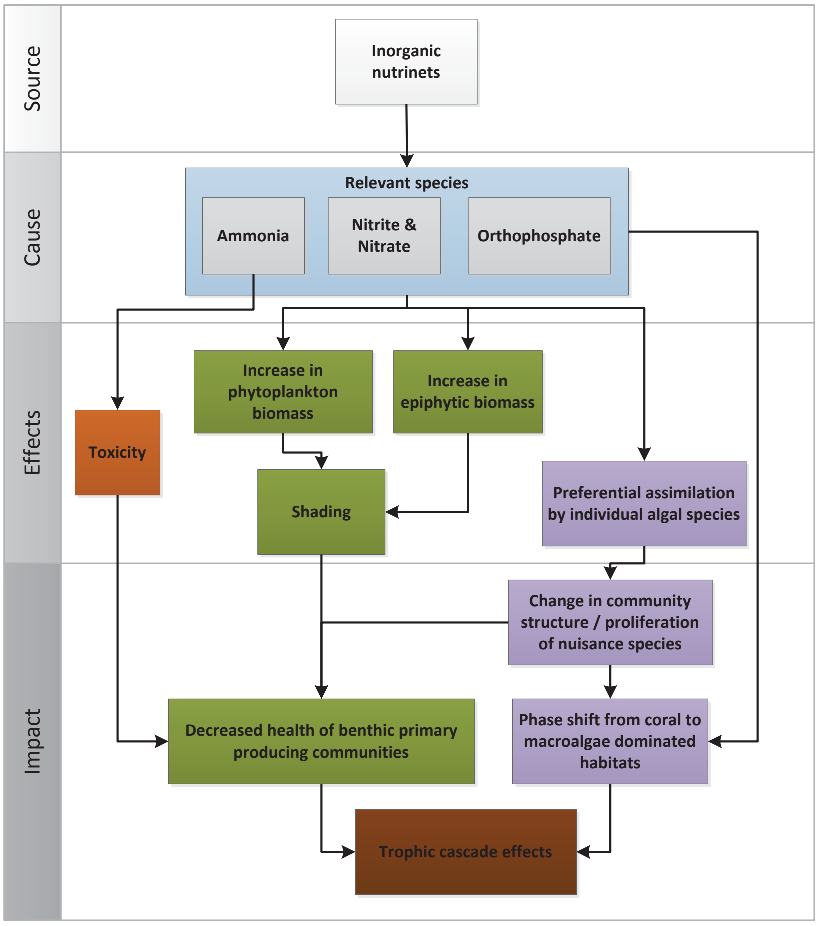


Figure 2 Relevant cause effect pathways relevant to inputs of dissolved inorganic nutrients

Adverse effects to corals have received particular attention in the literature. Prolonged exposure to nutrients may, under worst-case scenarios, lead to a phase shift, whereby healthy living corals are slowly replaced by macroalgae. The paradigm is that in the absence of herbivores, algae will proliferate at low dissolved inorganic nitrogen (DIN) concentrations of ~1 µmol/L. For the KADZ assessment, the threshold for inorganic nutrients was conservatively set based on this concentration, and specifically, whether or not local corals were exposed to this concentration for period greater than six months at a time. As the MWADZ assessment is likely to include other BPPO including seagrasses, the extent to which this threshold of ~1 µmol/L can be applied will be assessed. If necessary, a new threshold which takes into account the relative sensitivities of seagrasses will be built into the model. As with the assessment of the effects of organic stressors, the zones of impact will be determined based on the biology of the organisms and the timeframes required for recolonisation following complete removal of the pressure.

The thresholds for DIN are based on the paradigm established for corals in the 80's and 90's. The threshold of 1 uM/L is widely regarded to be highly conservative. Other studies report higher thresholds of between 1 and ~4 uM/L. The threshold is exclusively a concentration threshold, and no specific information is given in terms of duration (gain this varies from study to study). The 6 month duration used in the KADZ assessment was largely arbitrary and designed to cover (roughly) the duration of the wet different seasons (wet and dry). Given that our models will run over much longer periods (5-6 years), we will investigate whether it is defensible to extend the duration beyond 6 months.

2.3.3 Shading stressors

Light reduction at the benthic level may lead to sub-lethal or lethal effects on BPPO, including corals, seagrass and macroalgae. Light thresholds for the MWADZ assessment will be developed conservatively so that they are protective of the most sensitive of the BPPO, whether that be corals or other. By way of example, the light thresholds chosen for model interrogation in the KADZ were based on the triggers developed for the BHPB Outer Harbour Project. EAG 7 requires that thresholds are developed around the most sensitive organisms. The use of a sub-lethal threshold of a <60% reduction in SI is considered appropriate as the threshold for the ZoMI, because these levels of SI are known to cause sub-lethal stress in *Acropora* species. *Acropora* spp. are also likely to be common in the Houtman Abrolhos.

3 Sampling Program

The study area comprises two locations within the HAI FHPA in the Mid-West region of Western Australia. Location 1 is 3000 hectares located in Zeewijk Channel north of the Pelsaert Group, and Location 2 is 1740 hectares located immediately north of Sandy Island in the Pelsaert Group (Figure 3). Under the Environmental Scoping Document (ESD), EPA requires that the PER is supported by a comprehensive EIA including a comprehensive water, sediment and habitats survey to characterise baseline conditions. BMT Oceanica received a preliminary baseline survey design from DoF at the commencement of the project. Advice provided by BMT Oceanica resulted in changes to the program including the redistribution and expansion of sampling sites, and the recommendation that the study be supported by additional ADCP data.

DoF will collect the majority of the baseline datasets to support the EIA studies being undertaken and provide the raw data required for the modelling studies to the BMT Oceanica team. The baseline studies will be undertaken by DoF's Research Division through the Marine Ecology and Monitoring Section (MEMS).

BMT Oceanica's team is also collecting some additional (and complementary) hydrodynamic data in the region, in addition to DoF's data collection program. These data include 2 bed mounted Acoustic Doppler Current profiler (ADCP) instruments with supporting and co-located conductivity temperature depth (CTD) sensors. For simplicity, the DoF and BMT Oceanica's team deployments are presented and described together in this document.

For water quality, a total of 28 sites will be sampled comprising of 9 sites within Location 1 and 6 sites within Location 2, plus an additional 12 reference sites. All sites will be located within a similar depth contour (approximately 30-40m) (Figure 3). Sites have been positioned to allow for future Before-After-Control-Impact (BACI) style analyses and stratified to capture the presence of water quality gradients (if present at all). It should be noted that some sites are located within traditional trawl grounds for the Mid-West Trawl Fishery.

For sediment quality, a total of 33 sites will be sampled comprising of 12 sites within Location 1 and 9 sites within Location 2, plus an additional 12 reference sites. All sites will be located within a similar depth contour (approximately 30-40m). As with the water quality sites, sites have been positioned to allow for future BACI style analyses, and stratified to capture the presence of sediment quality gradients, if present (Figure 4).

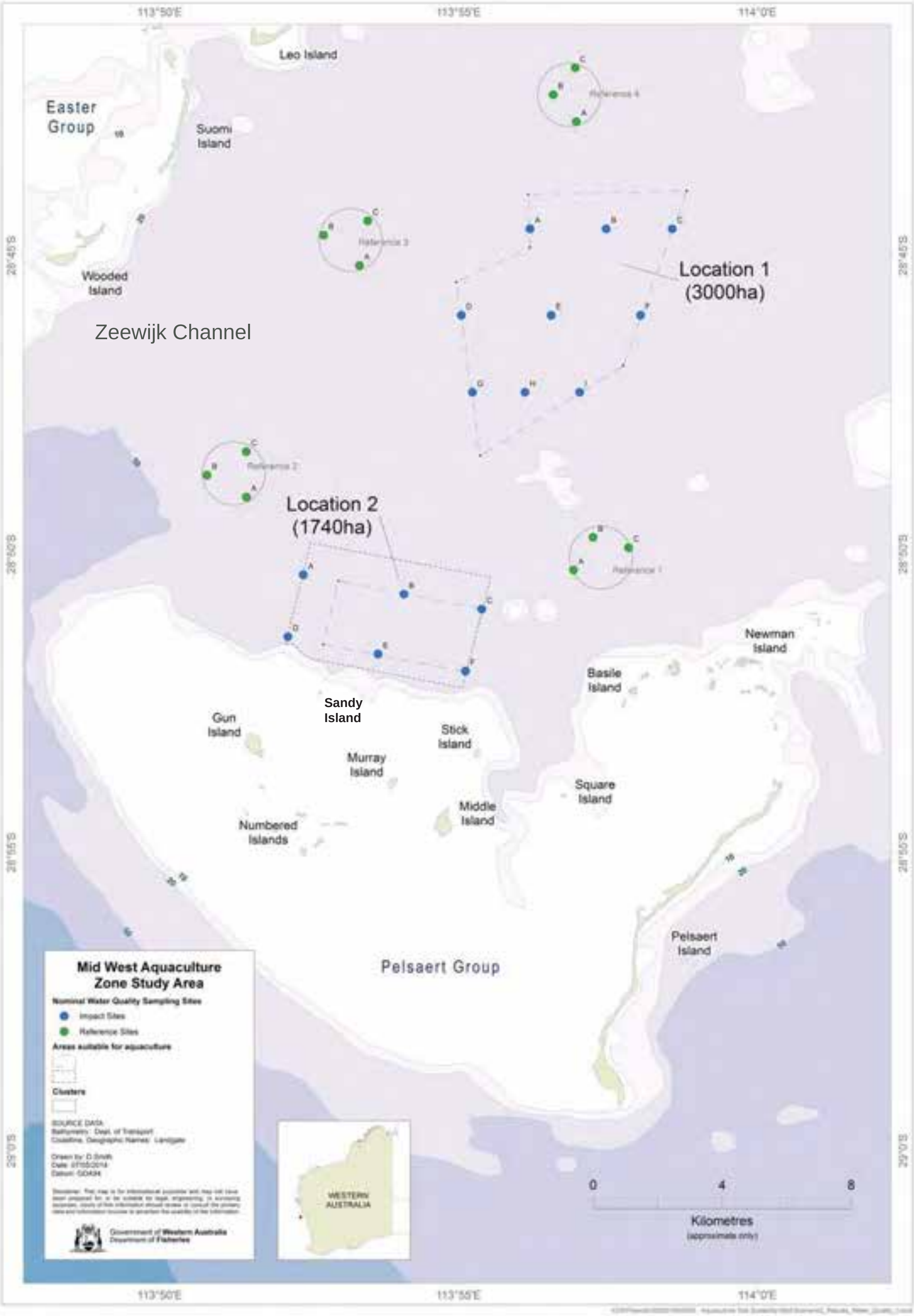


Figure 3 Baseline water quality sampling sites

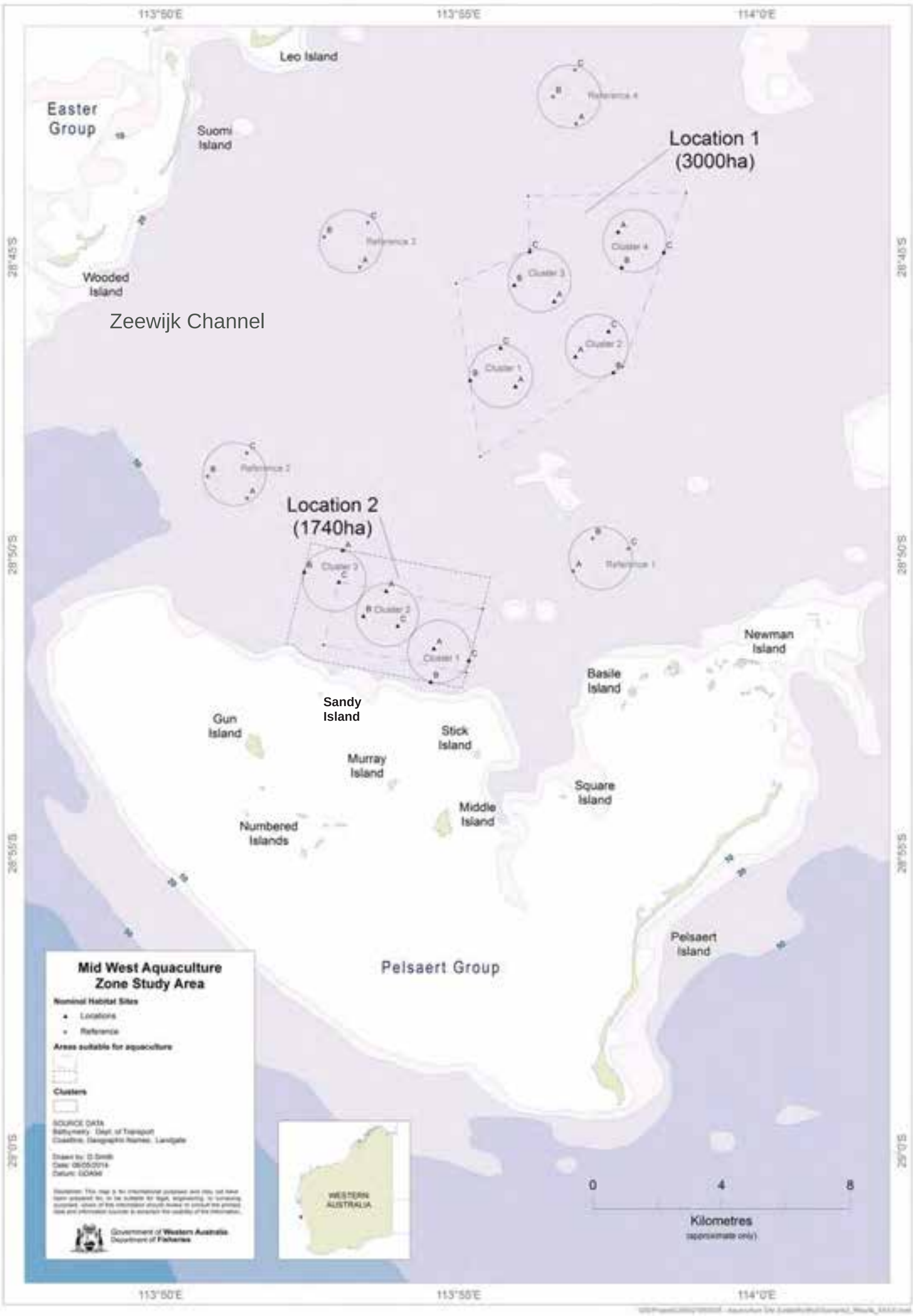


Figure 4 Baseline sediment quality sites

The sampling program will provide insight into the hydrodynamic, water quality and benthic regime in the study area, and will be used to inform the key processes that must be successfully simulated by the modelling framework. The program includes hydrodynamic, water quality, sediment quality and benthic habitat surveying components, which are described in detail below. The frequency of sampling for each component is detailed in Figure 5.

	Autumn				Winter				Spring				Summer			
	May		Jun		Aug		Sep		Nov		Dec		Feb		Mar	
	S	B	S	B	S	B	S	B	S	B	S	B	S	B	S	B
In situ measurements	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
In situ PAR dataloggers		In		Out		In		Out		In		Out		In		Out
Water quality sampling	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Phytoplankton sampling	✓				✓				✓				✓			
Sediment quality sampling						✓								✓		
Single-beam hydroacoustic mapping		✓														
Drop video habitat sampling				✓				✓*				✓*				✓*
Acoustic Doppler Current Profiling		In		Out		In		Out		In		Out		In		Out

Figure 5 MWADZ temporal sampling design. Note S = surface and B = bottom of the water column. Asterix indicates only a sub-sample of the initial drop video sites will be temporally sampled to capture any changes in benthic habitats.

3.1 Hydrodynamic Sampling

Four bottom-mounted Acoustic Doppler Current Profilers (ADCPs) have been deployed in total: one in each of the MWADZ areas (Figure 3) one to the north-east of the study area and one to the south-east (Figure 6). The ADCP located in Location 1, and both the ADCPs located outside of the study area, also collect wave and depth data. Furthermore, a CTD (conductivity, temperature and depth) sensor has been deployed alongside the ADCP north-east of the study area, and both the ADCPs in the study areas are fitted with temperature sensors.

Figure 6 Location of AWAC ADCPs outside of the MWADZ areas

The ADCPs within each MWADZ will be deployed for approximately one month during each season, with the final deployment in approximately March 2015. The first deployment was completed over May and June 2014, although no wave data was collected at this time due to a faulty sensor. The fault was repaired for the subsequent August to September 2015 deployment.

The ADCPs outside of the MWADZs were deployed in July 2014 and will remain *in situ* and log continuously until they are retrieved in approximately March 2015. Each will be serviced in mid-November 2014. It is expected that the long servicing interval for these ADCPs will result in some bio-fouling of the instruments, which will likely affect the conductivity sensor, in particular. The cost constraints of this project preclude more frequent servicing, but the data produced by these instruments will be carefully assessed for any bias that may be introduced over time.

During the deployment and retrieval of the ADCPs, and during maintenance voyages, opportunistic data collection will be conducted which will include conductivity and temperature profiles. *Ad hoc* bathymetry measurements and ADCP transects have also been requested, but collection of these has not been possible to date and it is unlikely they will be on future voyages. In addition to these datasets, some historical data has been made available to the project, including:

- Wave data from the Outer Channel at Geraldton which have been provided by the Mid West Port Authority for a ten year period to 1st May 2014.

- ADCP data collected in October 2002 and September 2003 from a location within the Pelsaert Group just west of MWADZ area 1.
- Wave data from the region have been collected by Mitsubishi Development as part of the Oakajee Port and Rail project and may be provided to this project, although this has yet to be confirmed.
- Tide gauge data from Geraldton port to cover 1st Jan 2014 to present.

3.2 Benthic Sampling

3.2.1 Benthic Habitat Mapping

A benthic habitat mapping exercise will be conducted as part of the sampling program. Surveys will cover the Reference (1-4) and the proposed aquaculture Locations (1&2). Using a Biosonic MX digital single beam echosounder (and associated processing software), surveys of both proposed MWADZ areas will be made. The sounder will be fixed to the operational vessel and linked to a differential Global Positioning System (DGPS). The DGPS system will produce submetre accuracy through corrections via the OmniSTAR correction system.

The hydroacoustic surveys will be conducted along east-west lines through each area, based on the expected prevailing conditions, to try minimising the pitch of the vessel during the May 2014 sampling period. The first phase of soundings will be spaced 1km apart (Figure 7), this is to capture a minimum level of hydroacoustic data for each area accounting for weather redundancies and maximum vessel speed. The total linear distance covered equals 7900 meters for the first phase. The second phases of surveys will infill the 1km spaced survey lines (Figure 7). This will be undertaken if time permits following the first phase of hydroacoustic surveys. This would add an additional linear coverage of 7500 meters.

The Biosonic MX echosounder will capture data on bathymetry (which will need to be corrected for tidal fluctuations using data from the National Tidal Centre to provide lowest astronomical tide (LAT) depths), seafloor hardness and vegetation height (if present). The resulting data will be used to create an ‘unsupervised’ classification of the benthos to broad categories of benthos in the surveyed areas (see MEMS Benthic Mapping SOP).

The unsupervised classification will be used to select ground truthing sites to be verified via drop video in the field during the June 2014 sampling period. The underwater video is a ‘live feed’ system consisting of a progressive scan camera in an underwater housing attached to weighted frame with legs (the weight frame keeps the system directly below the vessel, while the legs provide protection and also a scale reference in the image). The system is connected to the vessel by 10mm rope and a reinforced video umbilical cable. The live feed video, with DGPS overlay, is recorded onto a hard drive recording device or progressive scan HandyCam (see MEMS Benthic Mapping SOP for more details).

The video data will be processed by using the point intercept method to identify the benthic habitats at each sampled site (see MEMS Benthic Mapping SOP for more details). The benthos will be classified into seven broad categories; coral, algae, seagrass, abiotic, filter feeder, other and unknown. Each category also had a number of subcategories;

- Coral - growth form or morphology (i.e. branching, plating, massive etc.)
- Algae – Sargassum sp, Ecklonia sp, other Macroalgae
- Seagrass – Posidonia sp, Amphibiolous sp, Halophila sp or other

- Abiotic – sand, rubble, silt or dead hard coral
- Filter feeder – Sponge, Gorgonian, Other filter feeder
- Other – wrack, rhodoliths
- Unknown – video was not clear enough to analyse.

Percentage cover of each habitat type, latitude, longitude and depth were recorded for each video drop site. This data is then analyses to determine homogenous habitat types to provide the basis for the supervised classification of the habitat (see MEMS Benthic Mapping SOP).

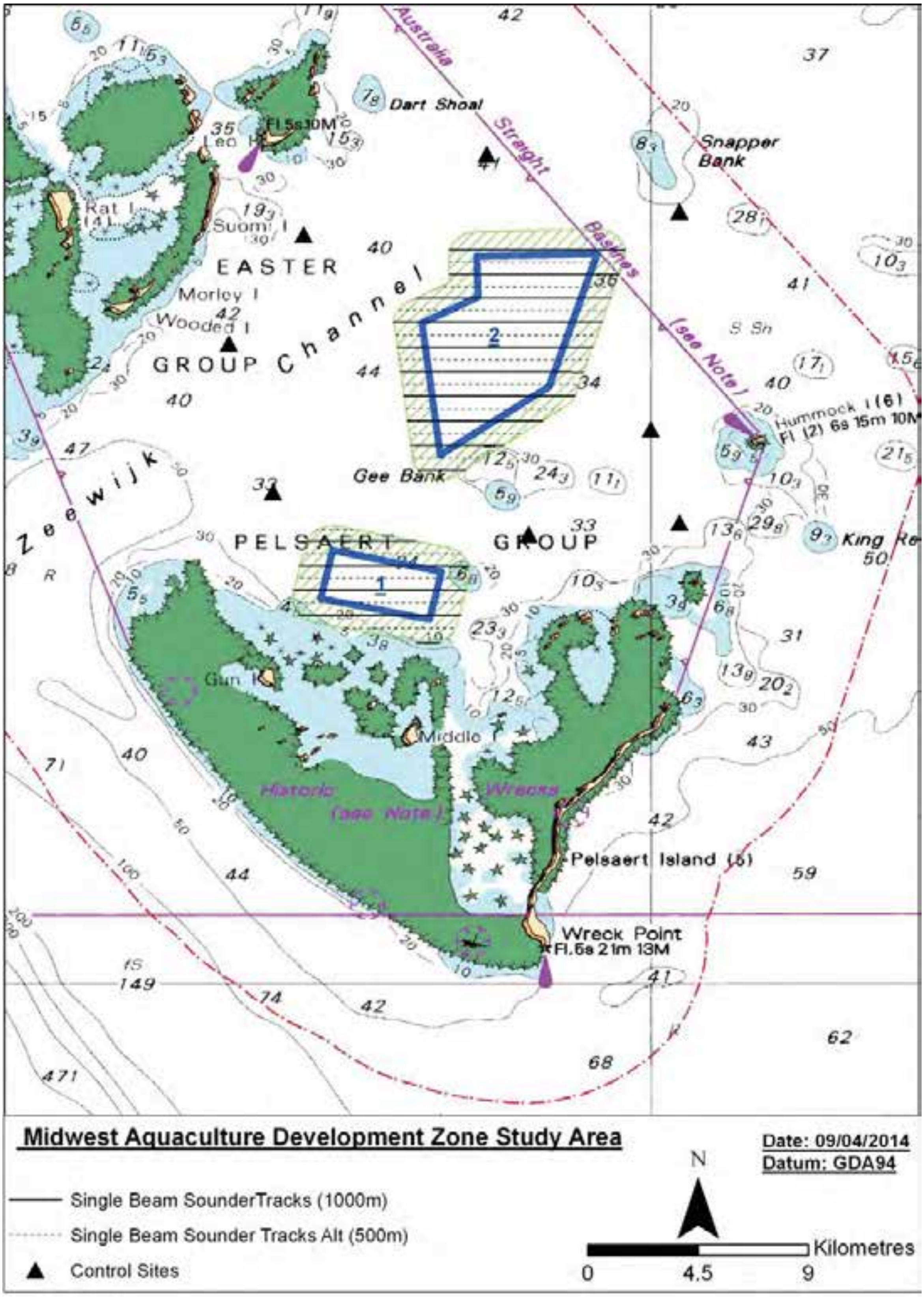


Figure 7 Location of hydroacoustic surveys. Solid lines are the first phase of data collection, and the dashed lines are the second phase. Additional hydroacoustic data will be collected in a 500 m diameter circle around each reference site (indicated by the solid triangles).

3.2.2 Sediment Quality Sampling

Sediment samples will be collected for the determination of:

- Total Phosphorus (TP)
- Total Nitrogen (TN)
- Total Organic Carbon (TOC)
- Trace Metals: Silver (Ag), Arsenic (As), Cadmium (Cd), Cobalt (Co), Chromium (Cr), Copper (Cu), Nickel (Ni), Lead (Pb), Antinomy (Sb), Selenium (Se), Zinc (Zn), and Mercury (Hg)
- Polycyclic Aromatic Hydrocarbons (PAH) (Ultra Trace Level)
- Total Petroleum Hydrocarbons
- pH/ORP
- Particle Size Distribution
- Infauna.

Initially sediment sampling will be attempted using a modified 7kg K-B sediment corer (as per Office of the Environmental Protection Authorities methodologies). If the K-B corer does not capture suitable sediment samples (given the depth of the water column, and potential underlying reef pavement), a Petite Ponar sediment grab will be used. The 33 sites are split into clusters of 3 at 11 locations, comprised of 7 locations within the proposed lease areas and 4 reference locations outside of these zones. A map detailing the sampling layout is included in Figure 4, and Figure 5 details the frequency at which sediment sampling will be conducted. Detailed sampling requirements are outlined in Table 1.

Table 1 Sample requirements for sediment quality analyses during baseline studies of the MWADZ

Parameter	Sample required	Sample container	Preservation technique	Storage conditions	Holding time
TOC, TN, TP	1 x 70 ml	Pre-cleaned polyethylene jar	Refrigeration (freezer for extended storage)	-4°C	14 days
Metals (ICP)	1 x 70 ml	Pre-cleaned polyethylene jar	Refrigeration (freezer for extended storage)	-4°C	30 days
Particle size analysis	Minimum of half a zip-lock bag	Zip-lock bag	Refrigeration (freezer for extended storage)	-4°C	Indefinite
PAHs/TPHs	1 x 250 ml	Pre-cleaned glass jar, with teflon lid	Refrigeration (freezer for extended storage)	-4°C	14 days
Infauna	To be determined	Screw top jar	10% formalin/90% seawater	Cool and in the dark Do not freeze	Indefinite

3.3 Water Quality Sampling

In situ simultaneous measurements of the following water quality parameters will be collected using a Hydrolab Datasonde 5 multiparameter probe:

- Temperature (C)
- pH/ORP (pH units, mV)
- Conductivity/Salinity (mS/cm, ppt)
- Dissolved Oxygen (DO) (mg/L) – measured with Luminescent DO sensor
- Turbidity (NTU)
- Depth
- Photosynthetically Active Radiation (PAR) – measured with dual PAR sensor.

With the exception of PAR, all parameters will be measured in profile, between the surface and bottom of the water column. Data for each parameter will be recorded on field datasheets as outlined in the MEMS Water Quality Sampling Standard Operational Procedure (WQ SOP).

Water samples will be collected for the determination of:

- Ammonium (NH4)
- Nitrate (NO3)
- Nitrite (NO2)
- Orthophosphorus (Ortho-P)
- Chlorophyll-a
- Total Suspend Solids (TSS), including Loss on Ignition
- Total Phosphorus (TP)
- Total Nitrogen (TN)
- Total Organic Carbon (TOC)
- Hydrogen Sulphide (H2S)
- Silica (SiO2)
- Trace Metals (Ag, As, Cd, Co, Cr, Cu, Ni, Pb, Sb, Se, Zn, Hg)
- Polycyclic Aromatic Hydrocarbons (PAH) (Ultra Trace Level)
- Total Petroleum Hydrocarbons.

Water samples will be collected using a 4.2L Van Dorn sampler deployed at a total of 27 sites within the study area. Twelve of the sites are split into clusters of 3 at 4 reference locations, while the remaining 15 sites are split between Location 1 (9 sites) and Location 2 (6 sites). A map detailing the sampling layout is included in Figure 3. Samples will be taken at two time points within each season (Figure 5), and will be collected from both the surface (0-1m) and bottom (approx. 1m from seafloor) of the water column (see MEMS WQ SOP). Each sampling effort will take approximately 1.5 to 2 days in total.

Additionally, samples will be collected for the determination of the Phytoplankton community within the two proposed MWADZ areas. Discrete samples will be taken at three depths within the water column (surface, mid and bottom). Each sample will then be preserved as detailed in Table 2, to await transportation to SydneyWater with its associated CC form for identification of the phytoplankton community to the lowest recognizable taxonomic unit and enumeration of abundance of the phytoplankton community.

Incident irradiance at the sea surface will be measured using a JFE Advantech ALW-CMP PAR logger installed in an open (no shading) area on Rat Island at the DoF research station for a period of 12 months. Data collected by the terrestrial light logger on Rat Island will be multiplied by 0.96 to estimate the intensity just below the water surface. Two identical PAR loggers will be deployed ~1 m from the bottom, within each MWDAZ development area when the ADCPs are deployed. The PAR loggers will be fixed to the deployment frame of the ADCP's, and left in situ for 1 month in each season (Figure 5).

Table 2 Sample requirements for water quality analyses during baseline studies of the MWADZ

TSS	Sample volume	1L
	Sample bottle	Polyethylene bottle
	Preservation technique	Using a pre-weighed GFC filter paper, filter the 1L sample using a Nalgene Vacuum Filter Flask. Rinse filter with at least 250mL of deionized water after filtering sample.
	Maximum sample holding time and storage conditions	1 month, frozen sample
	Reporting limit	1 mg/L
Hydrogen Sulphide (H_2S)	Sample volume	125mL
	Sample bottle	Polyethylene bottle
	Preservation technique	Completely fill sample bottle to exclude air. Preserve with Zinc acetate.
	Maximum sample holding time and storage conditions	1 week, chilled sample
	Reporting limit	1 mg/L
Dissolved Organic Carbon (DOC) **Total Organic Carbon (TOC)**	Sample volume	125mL
	Sample bottle	Polyethylene bottle
	Preservation technique	Fill sample bottle ¾ full.
	Maximum sample holding time and storage conditions	1 month, frozen sample
	Reporting limit	1 mg/L
Ammonia (NH_4) **Nitrate (NO_3)** **Nitrite (NO_2)**	Sample volume	125mL
	Sample bottle	Polyethylene bottle
	Preservation technique	Filter sample through 0.45µm filter. Fill sample bottle ¾ full.

	Maximum sample holding time and storage conditions	1 month, frozen sample
	Reporting limit	0.01 mg/L (NH_4, NO_3), 0.02 mg/L (NO_2)
Total Nitrogen (TN) **Total Phosphorus (TP)**	Sample volume	125mL
	Sample bottle	Polyethylene bottle
	Preservation technique	Fill sample bottle ¾ full.
	Maximum sample holding time and storage conditions	1 month, frozen sample
	Reporting limit	0.005 mg/L (TP), 0.01 mg/L (TN)
Chlorophyll-a	Sample volume	1L
	Sample bottle	Polyethylene bottle
	Preservation technique	Using a pre-weighed GFC filter paper, filter the 1L sample using a Nalgene Vacuum Filter Flask.
	Maximum sample holding time and storage conditions	1 month, frozen sample
	Reporting limit	0.001 mg/L
Trace Metals (Ag, As, Cd, Co, Cr, Cu, Ni, Pb, Sb, Se, Zn, Hg)	Sample volume	250mL (250mL for Hg)
	Sample bottle	Acid washed Polyethylene bottle Hg – Glass jar with Teflon lid
	Preservation technique	Filter sample through 0.45µm filter. Fill sample bottle ¾ full.
	Maximum sample holding time and storage conditions	1 month, chilled sample 6 months, frozen sample
	Reporting limit	0.001 (Ag, As, Cd, Co, Cu, Pb, Se, Sb); 0.005 (Cr); 0.01 (Ni, Zn); and 0.0001 (Hg) mg/L
Polycyclic Aromatic Hydrocarbons (PAH) (Ultra Trace)	Sample volume	1L
	Sample bottle	Polyethylene bottle
	Preservation technique	None
	Maximum sample holding time and storage conditions	14 days, chill sample and keep in dark
	Reporting limit	0.001 µg/L
Total Petroleum Hydrocarbons	Sample volume	1L
	Sample bottle	Polyethylene bottle
	Preservation technique	None
	Maximum sample holding time and storage conditions	14 days, chill sample and keep in dark
	Reporting limit	0.001 µg/L
Phytoplankton Community	Sample volume	250mL

Composition	Sample bottle	Polyethylene bottle
	Preservation technique	Add Lugols solution to final concentration of 1% (2.5mL of Logols stock solution)
	Maximum sample holding time and storage conditions	1 month, chilled sample and kept in dark

4 Modelling Methodology

4.1 Overview

The proposed modelling framework is comprised of three primary components: hydrodynamics, sediments and water quality. Each component will be dynamically linked to ensure a consistent and flexible approach. The broad methodology is as follows:

(1) Develop and calibrate a hydrodynamic model of the region, with mesh resolution focussed on the proposed lease areas.

(2) Using the hydrodynamic model, a wave model and a suitable sediment transport model, simulate the transport of particles arising from aquaculture activities (e.g. food pellets, faecal pellets) to produce a map of deposition rates within the region.

(3) Develop and calibrate a sediment diagenesis model, to simulate the biogeochemical fate of organic matter (e.g. food and faecal matter) once it is deposited on the seabed.

(4) Based on the sediment deposition maps produced in (2) above, simulate a range of deposition scenarios using the standalone sediment diagenesis model developed in (3). Timescales of sediment recovery based on deposition rates would then be calculated to satisfy regulatory requirements.

(5) Develop and calibrate a water quality model of the region, linked with the sediment diagenesis model, to quantify the feedback of sediment processes to water column biogeochemistry.

(6) Run the dynamically linked hydrodynamic, water quality and sediment diagenesis model under a range of scenarios. The exact suite of scenarios to be run is yet to be decided.

Details of each of the proposed modelling components are included below.

4.2 Hydrodynamic Modelling

We propose to use our in-house-developed hydrodynamic modelling engine TUFLOW FV (http://www.tuflow.com/Tuflow%20FV.aspx). TUFLOW FV is a powerful hydrodynamic model engine that solves the Non-Linear Shallow Water Equations (NLSWE) on a 'flexible' (unstructured) mesh comprising triangular and quadrilateral cells. The mesh is not limited to square or rectangular grid arrangements, a feature which we believe will be critical to the successful execution of this study. This unstructured mesh approach has significant benefits when applied to study areas involving complex bathymetric features, flow paths, and hydrodynamic processes, and varying areas of interest, such as this study. A preliminary mesh for the hydrodynamic model has been included in Figure 8 below. The finite volume (as opposed to finite difference (fixed grid) and finite element) numerical scheme is also capable of simulating the advection and dispersion of multiple scalar constituents within the model domain. TUFLOW FV is configured to solve the NLSWE in 2D (vertically averaged) and 3D with the ability to employ both first-order and second-order numerical solution schemes. The model can be run in both 2D vertically-averaged mode and fully 3D by specifying a vertical layer structure. Importantly, the TUFLOW FV engine leverages the parallel processing capabilities of modern computer workstations, using the OpenMP implementation of shared memory parallelism, such that computation capability can be used to its maximum potential.

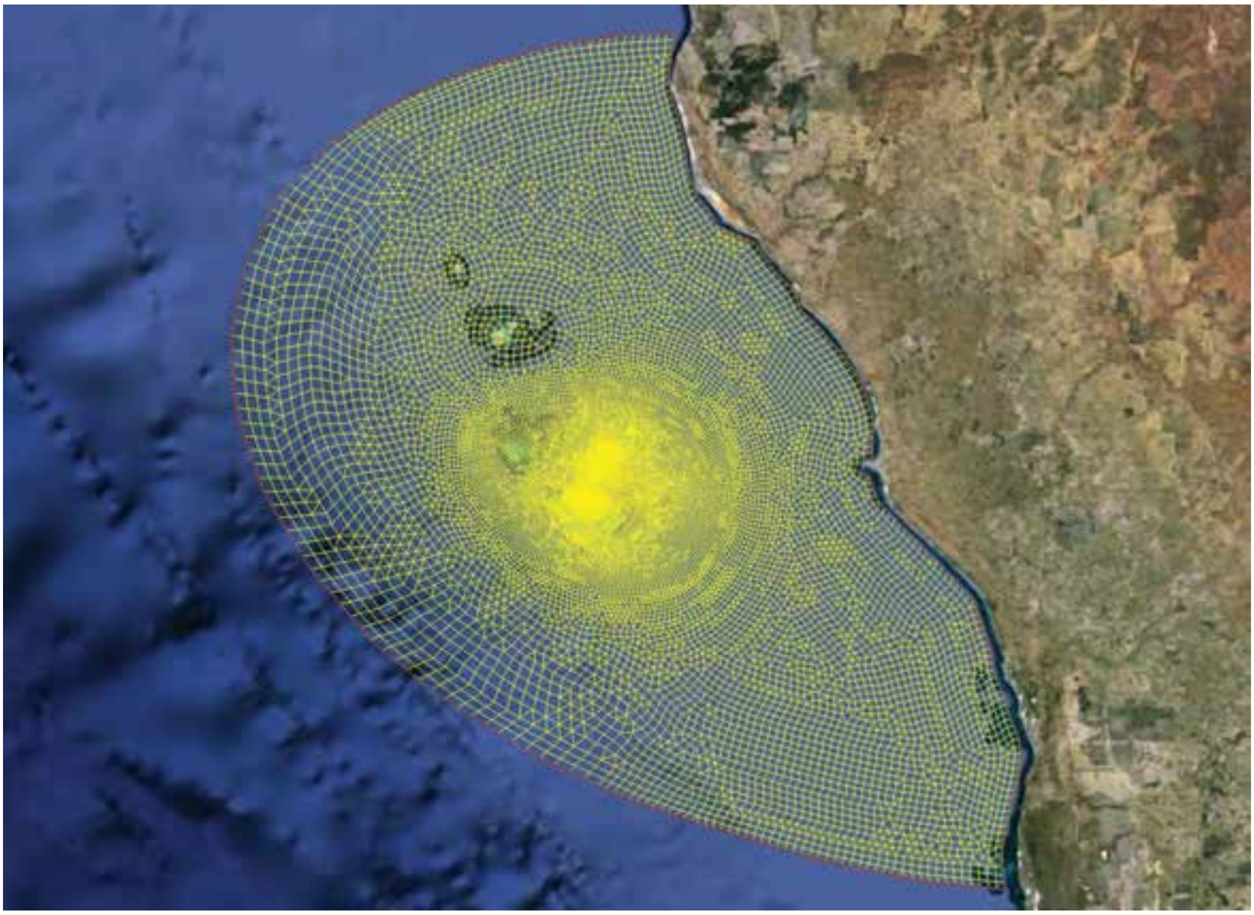


Figure 8 Preliminary TUFLOW FV hydrodynamic model mesh

When run in 3D mode (as will be the case for the Abrolhos Islands study), TUFLOW FV has the ability to simulate temperature, salinity and density stratification in order to fully resolve baroclinic (density) driven processes. Intimately linked with this ability is TUFLOW FV's capability to accept and respond to spatially variable high temporal resolution atmospheric forcing data from global circulation models (including air temperature, relative humidity, long- and short-wave radiation and wind speed and direction) to fully simulate atmospheric heat-exchange processes as required. To do this, a number of forcing datasets are required by TUFLOW FV as initial and boundary conditions, and a bathymetry dataset is required to inform model geometry. The datasets we propose to use are as follows:

- For bathymetry, a digital elevation model will be developed using a variety of sources including the 250m Geosciences Australia bathymetry dataset for regional bathymetry and a dataset of the Abrolhos Islands themselves provided by the Western Australian Department of Transport. Measurements taken by ships of opportunity, including those deploying and retrieving equipment as part of this study, will also be used.
- Tidal boundary conditions will be provided by the TPXO71 global tide model (https://www.esr.org/polar_tide_models/Model_TPXO71.html).
- Regional currents (e.g. Leeuwin Current), residual water levels, temperature and salinity boundary conditions will be provide by the global climate model HYCOM (https://hycom.org/). HYCOM is a data-assimilation model which we have used in several coastal studies of this type.

- Meteorological data will be provided by NCEP (National Centers for Environmental Protection) meteorological models; specifically the NCEP Reanalysis II model and the NCEP Climate Forecast System Reanalysis (CFSR) model. Both are global data-assimilation models which provide the full suite of meteorological data required by TUFLOW FV, namely: air temperature, rainfall, relative humidity, downward short-wave and long-wave radiation, windspeed and wind direction.
- To resolve potential wave-driven currents plus wave-induced drift and to capture suspension/deposition dynamics driven by waves, a wave field will be applied to TUFLOW FV using the model SWAN. SWAN is a third-generation wave model, developed at Delft University of Technology, which computes random, short-crested wind-generated waves in coastal regions and inland waters. In addition to wind data provided by the meteorological datasets above, SWAN also requires swell to be provided on the boundaries. This will be sourced from WAVEWATCH III, which is a global wave prediction model developed by the National Oceanic and Atmospheric Administration (NOAA).

It is possible that some datasets may not be available for the timeframe required. For example, the NOAA and NCEP datasets can have a lag time of several months. If this is the case, then appropriate alternatives will be sourced (e.g. ECMWF [European Centre for Medium-range Weather Forecasting] products) or, failing this, a climatology will be produced based on previous years' data.

Specification of the oceanic boundary, in particular, is expected to be a critical component of a skilful hydrodynamic model of the study area. As noted above, BMT WBM proposes to specify temperature, salinity and regional currents using the HYCOM model, and water-levels using a mix of TOPEX (for tidal dynamics) and HYCOM (for the non-tidal components). These hydrodynamic boundaries will be specified using an active Flather condition (as derived from Flather *et al.,* 1976) which relaxes the barotropic (depth-averaged) component to ensure that the model remains internally consistent.

The horizontal spatial resolution of the unstructured TUFLOW FV model mesh will range from approximately 3.5 km at the offshore boundary down to approximately 200m within the area of interest. Vertical resolution will comprise of approximately 37 fixed-level z layers and 2 surface, variable-level sigma layers, for a total of up to 39 vertical levels with resolution increasing near the surface to approximately 1m. This model resolution will allow the model to capture all important hydrodynamic processes within the area of interest, while still remaining computationally efficient. It is noted that sediment deposition and water quality impacts arising from the aquaculture cages will need to be resolved to smaller spatial scales than 200m. Aquaculture cages will be approximately 38m in diameter and so sediment deposition in particular will need to resolve scales of approximately 5-10m. This will be achieved through Lagrangian particle tracking which is effectively grid-less and will allow for the creation of deposition maps to the required resolution (see Section 4.3 for details). The water quality model is not run in a Lagrangian framework, so to investigate the feedback of biogeochemical fluxes from the sediment into the water column BMT WBM propose to use the 200 m hydrodynamic model for water quality calibration purposes and switch to a higher-resolution model (approximately 50m) for running scenarios with the aquaculture cages in place. If the computational cost is not excessive, the higher-resolution model may also incorporate increased vertical resolution near the sea-bed to more accurately capture the impact of benthic processes on the overlying water column. Full details of the water quality model are included in Section 4.4.

4.3 Sediment Modelling

It is expected that aquaculture activities will result in the deposition of particulate organic matter on the seabed, particularly in the form of faecal pellets and food wastage. To track the transport and deposition/resuspension of these organic particles, particle tracking algorithms will be added to the TUFLOW FV software. The particle tracking capability will simulate a range of particle sizes and material types, and will incorporate processes such as the break-down of organic particles as they pass through the water column. It will also be based on the Lagrangian framework so that the results are not confined to the spatial grid within the hydrodynamic model. In this manner, the fine-grained spatial resolution required by the sediment model can be achieved. Stochastic behaviour and resuspension will also be applied, using the techniques described in Cromey *et al*. 2002, to provide a range of results for a given hydrodynamic and particle-generation scenario. Once completed, the particle tracking results will be used to draw up a series of maps of various deposition scenarios, which in turn will be used as inputs to the sediment diagenesis model. Parameters for relevant processes (e.g. the physical properties of particles) will be sourced from the scientific literature.

The sediment diagenesis model code was developed at UWA by A/Prof Hipsey's research group, which is an extended version of the widely used original version created by Boudreau (1996). The UWA version extends the original version by including improvements for organic matter dynamics (e.g. dissolved organic matter fractions – of interest to the current study), metals and geochemical conditions. It has been validated within Cockburn Sound (Read 2008) and within the Swan Estuary (Paraska et al. 2011, Norlem et al. 2013).

The model simulates different components of organic matter and how they breakdown under varying concentrations of oxidants and other species. Reactions include the hydrolysis of the complex (e.g. high molecular weight) OM pools (POMV R, POMR, DOMR, POML) and transformation of Low Molecular Weight (LMW) dissolved OM by oxidants (O2, MnO2, Fe (III) and SO42- – the so-called 'terminal metabolism'), and the release of resulting nutrients (NO3−, NH4+, PO43-) and reduced by-products (Mn2+, Fe2+, N2, H2S, CH4) and CO2. Oxidants, nutrients, metals and by-products are all capable of interacting, for example through complexation or re-oxidation of reduced species. The model predicts the long-term burial of carbon and other particulates through loss terms, and the benthic flux of all dissolved constituents.

Initial conditions of the sediment diagenesis model will be derived from samples taken as part of habitat mapping exercises and literature values, as appropriate. Boundary conditions will be derived from literature values and the deposition rates determined by the hydrodynamic/sediment transport model.

Our approach will be to calibrate the standalone sediment diagenesis model to the samples taken as part of the benthic habitat mapping exercise, and thereby develop a 'baseline' model.

Once calibrated, the sediment diagenesis model would then be run in standalone mode under a suite of deposition rates as determined by the hydrodynamic/sediment transport model described above. Running the sediment diagenesis model in this way is much less computationally expensive than dynamically linking it to the full hydrodynamic/sediment transport model, so it allows for a full spectrum of deposition scenarios to be examined, and for run periods to extend to 10-15 years and longer if required. By taking this approach, both the impact period (when aquaculture activities are taking place) and the recovery period following cessation of activities (a parameter used to determine the level of impact) can be simulated for multiple years.

Results from the standalone model will then be used to map zones of impact, which will then be applied to the full hydrodynamic/water quality model (described below) to analyse potential impacts of aquaculture activities on both benthic habitats and the overlying water column. The sediment diagenesis model will also be dynamically linked with the hydrodynamic/water quality model at this point to ensure an ongoing interaction between chemical processes in the sediment and in the overlying water column. However, computational constraints will mean only one instance of the sediment diagenesis model will be included per mapped zone, rather than one per model grid cell. Combining the models in this manner will allow for a dynamically-calculated benthic flux to be applied to the full hydrodynamic/water quality model, while maintaining computational efficiency and the ability to run multi-year simulations.

4.4 Water Quality Modelling

We will use the Aquatic Ecodynamics (AED) model library, linked with TUFLOW FV, to simulate nutrient, sediment and algal dynamics within the water column (http://aed.see.uwa.edu.au/research/models/GLM/). AED was also developed at UWA by the research group led by A/Prof. Matt Hipsey and has been linked with TUFLOW FV and used to simulate water quality and plankton dynamics in a number of projects to date. It can simulate a number of biogeochemical pathways relevant to water quality, as illustrated by the schematic presented in Figure 9.

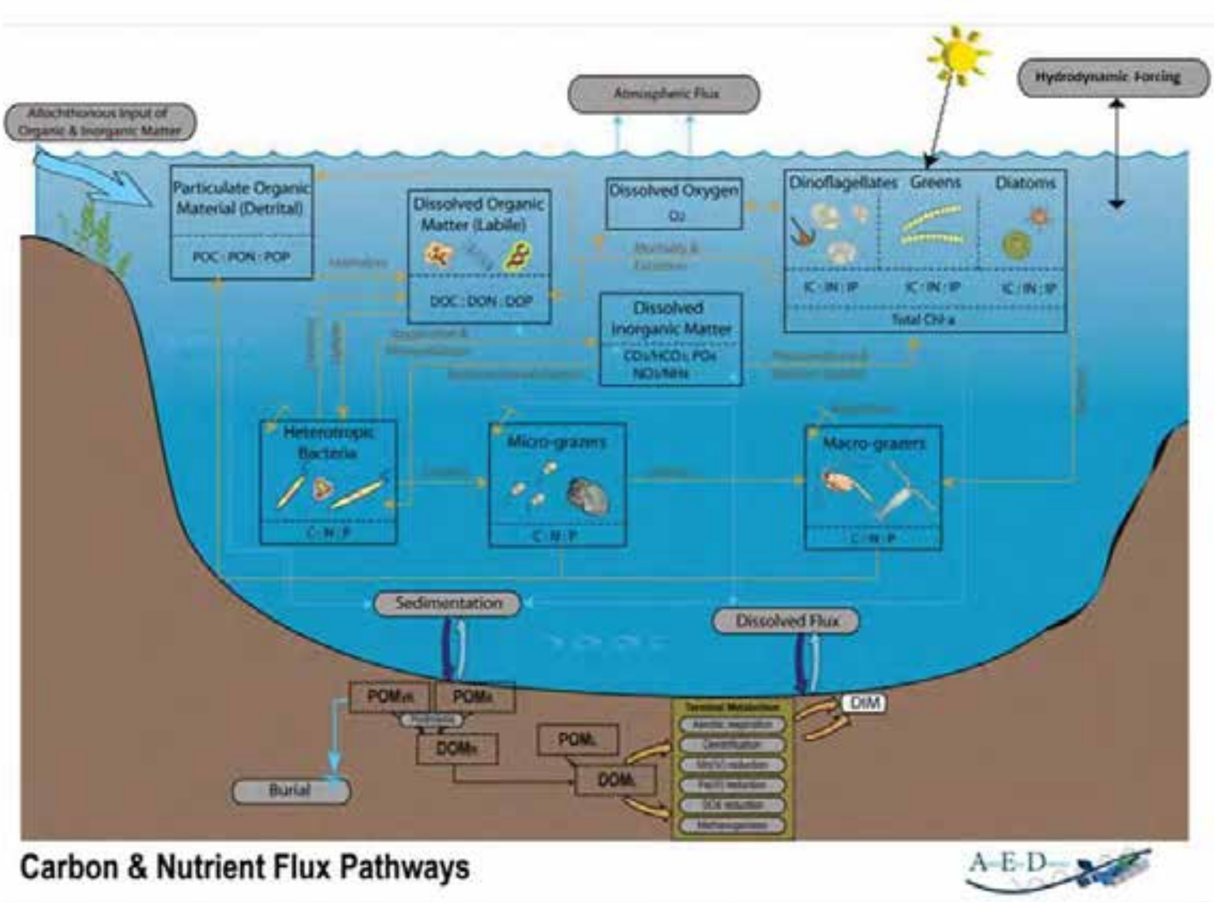


Figure 9 Carbon and nutrient processes simulated in AED

Boundary and initial conditions are required for each of the variables simulated by AED. These will be derived from a combination of:

- Water quality samples conducted as part of this study.
- The CSIRO Atlas of Regional Seas (CARS) climatology (http://www.marine.csiro.au/~dunn/cars2009/).
- Literature values, as appropriate.

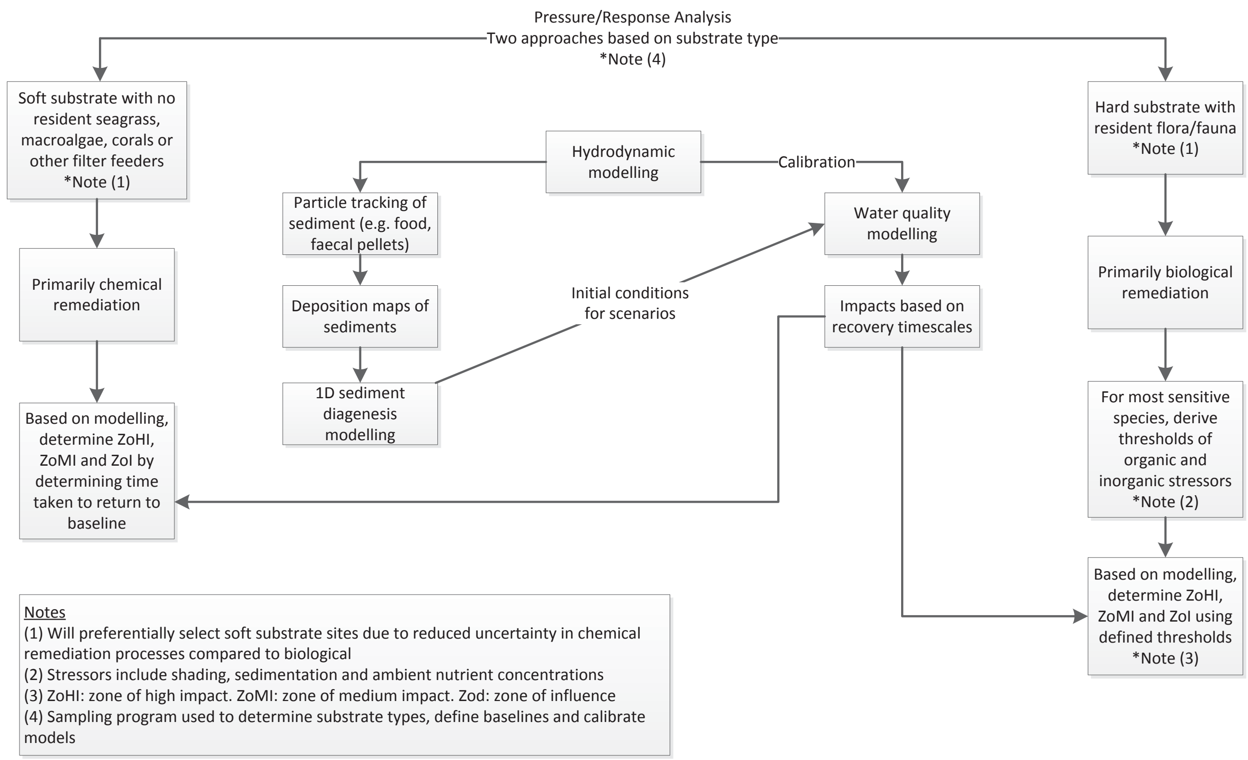
Similarly to the sediment diagenesis model, our approach will be to parameterise the water quality model using the samples taken as part of the monitoring program described above, and thereby develop a 'baseline' model. For the parameterisation exercise, the water quality model will be linked to the hydrodynamic model with 200 m spatial resolution in the vicinity of the lease areas. This will be sufficient resolution for the purposes of creating a baseline model, and it will greatly improve model runtimes and the efficiency of the calibration process. For the scenario runs, however, resolution will be increased to 50 m to capture the aquaculture-related flux of nutrients and dissolved organic matter from the benthos into the water column that will be predicted using the sediment diagenesis model described above.

Once parameterised, a suite of metrics comparing model results to water quality samples will be used to verify that the model has skill in simulating water quality dynamics. As part of this verification process, a relationship between TSS and turbidity will be derived from the sample data so that model TSS concentrations can be compared to the turbidity profiles taken during the monitoring program.

Following the verification process, the full hydrodynamic/water quality model will be run to examine the recovery period following cessation of aquaculture activities under a variety of scenarios (yet to be decided). It is expected that each scenario run will incorporate an initial period of one year where aquaculture activities are ongoing, followed by up to five years following cessation. The benthic initial conditions applied to each scenario will be derived from the standalone sediment diagenesis model described in Section 4.3, and may incorporate periods much longer than one year. By linking the standalone sediment diagenesis model and full hydrodynamic/water quality model in this way, scenario simulations can be made of multiple years of impact, followed by multiple years of recovery, which would otherwise not be possible due to the computational overhead of the full hydrodynamic/water quality model.

5 Summary

The following is a summary of the proposed overall monitoring and modelling strategy, including how model link together and deliver a series of results regarding benthic impacts to DoF (specifically ZoHI, ZoMI & ZoI) in terms of recovery timescales following removal of stressors. The schematic presents this visually, and this is supported by subsequent dot point commentary.



- The habitat remediation processes based to a large extent of the type of substrate in place:
  - Soft substrate with no benthic flora/fauna requires primarily chemical remediation processes
  - Hard substrate with corals/macroalgae/seagrass requires primarily biological remediation processes.
- Two approaches based on type of substrate:
  - Soft substrate: recovery timescales based on direct modelling of chemical processes and return to baseline conditions
  - Hard substrate: determine stressor thresholds of most sensitive species with desktop analysis then use modelling of stressor processes to determine zones of impact.
- Sampling program designed to determine baseline conditions including substrate type, sediment composition, hydrodynamic regime, etc. Also designed to provide calibration and validation data to the hydrodynamic, sediment diagenesis and water quality models.
- Hydrodynamic model developed to provide background conditions to analysis and to determine fate of organic particles (e.g. faeces, food pellets) through Lagrangian particle tracking.
- Particle deposition maps derived from hydrodynamic modelling to be used as sedimentation inputs to 1D sediment diagenesis model, and to inform sedimentation stressors for sensitive organisms as part of pressure-response analysis.
- 1D sediment diagenesis model developed and results used to define zones of impact for benthic chemistry, and to inform possible benthic stressor thresholds for sensitive organisms (biological remediation processes).

- Water quality model developed using above benthic modelling as a boundary condition and results used to define zones of impact for water-column chemistry, and to inform possible pelagic stressor thresholds for sensitive organisms (biological remediation processes).

6 References

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EPA (2011) Environmental Assessment Guideline for Marine Dredging Proposals. Environmental Protection Authority, Report No EAG 7, Perth, Western Australia, December 2009.

Flather RA. 1976. A tidal model of the northwest European continental shelf. Mem. Soc. R. Sci. Liege 10(6): 141–164.

Appendix B Additional Calibration Plots

B.1 Water levels

This section contains additional plots comparing simulated water-levels against observations. The time-series presented in Section 4.1.1 above are decomposed into calendar months and included in Section B.1.1 below, while results of the sensitivity testing of tidal boundary conditions are presented in Section B.1.2.

B.1.1 Monthly plots of long term deployments

The following plots present the same data as Figure 4-2 and Figure 4-3 but decomposed into calendar months for clarity. Statistics presented in each figure refer only to the time-series plotted and not to the entire time-series of each deployment.

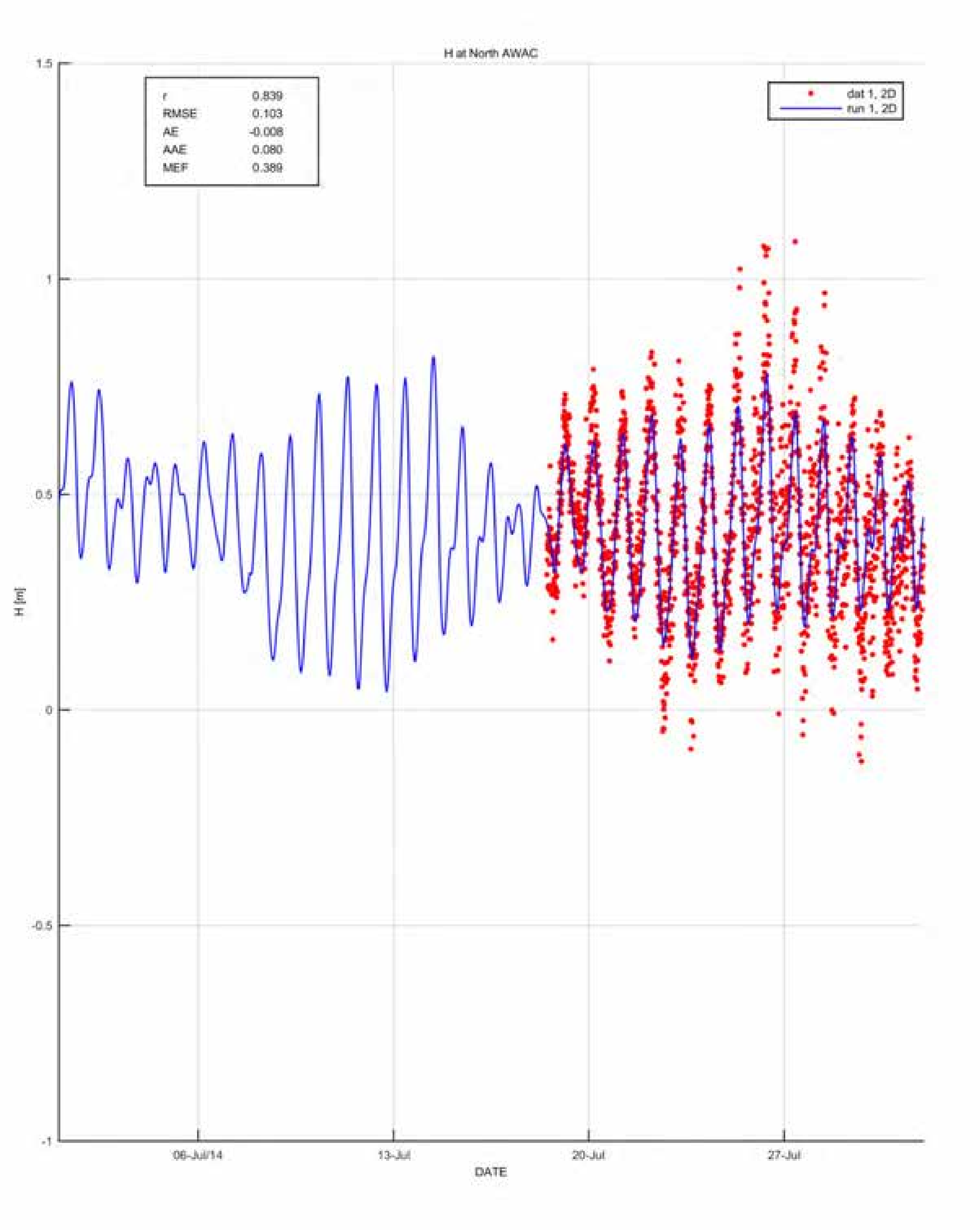

Figure B-1 Water levels at northern regional site – July 2014

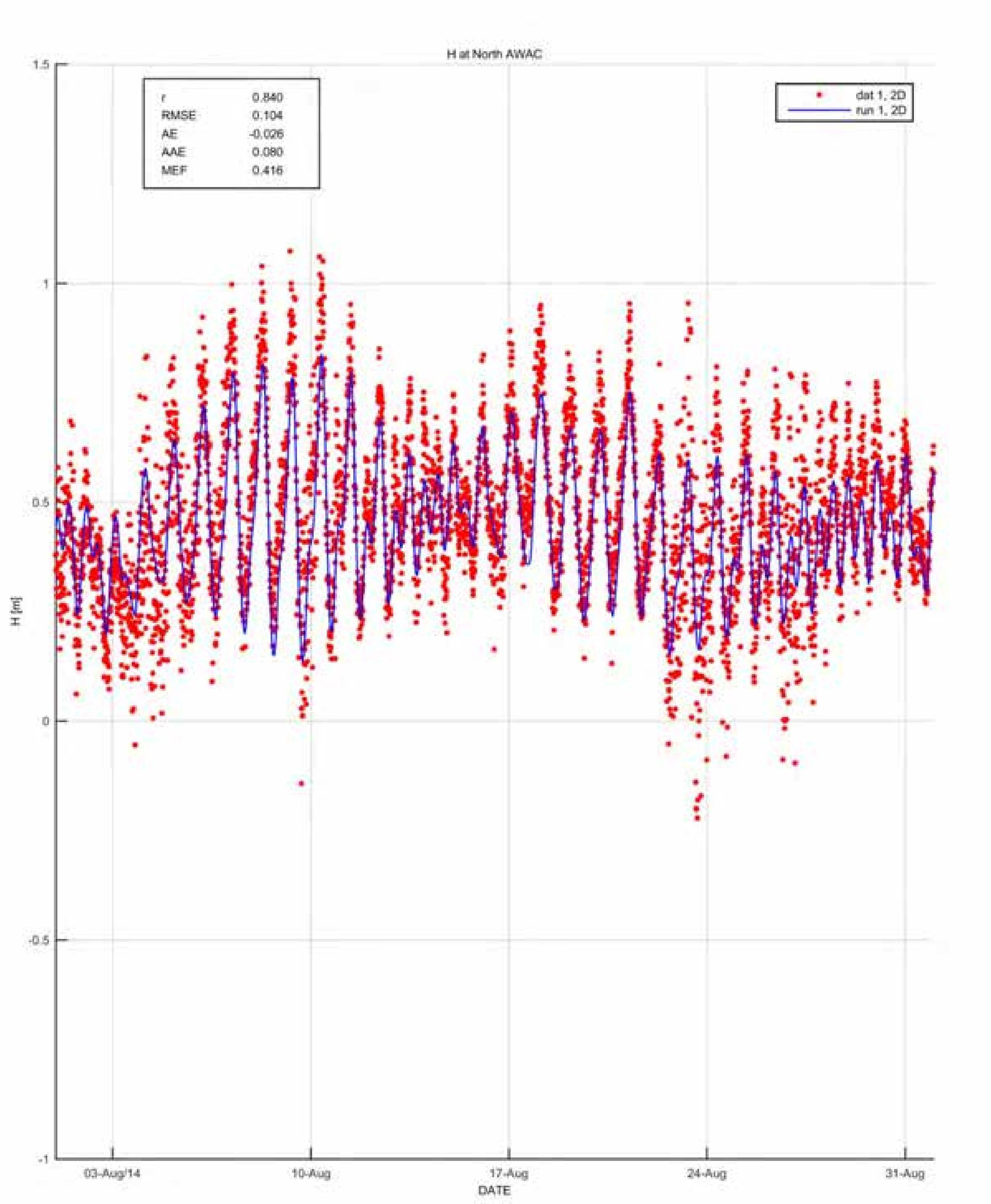

Figure B-2 Water levels at northern regional site – August 2014

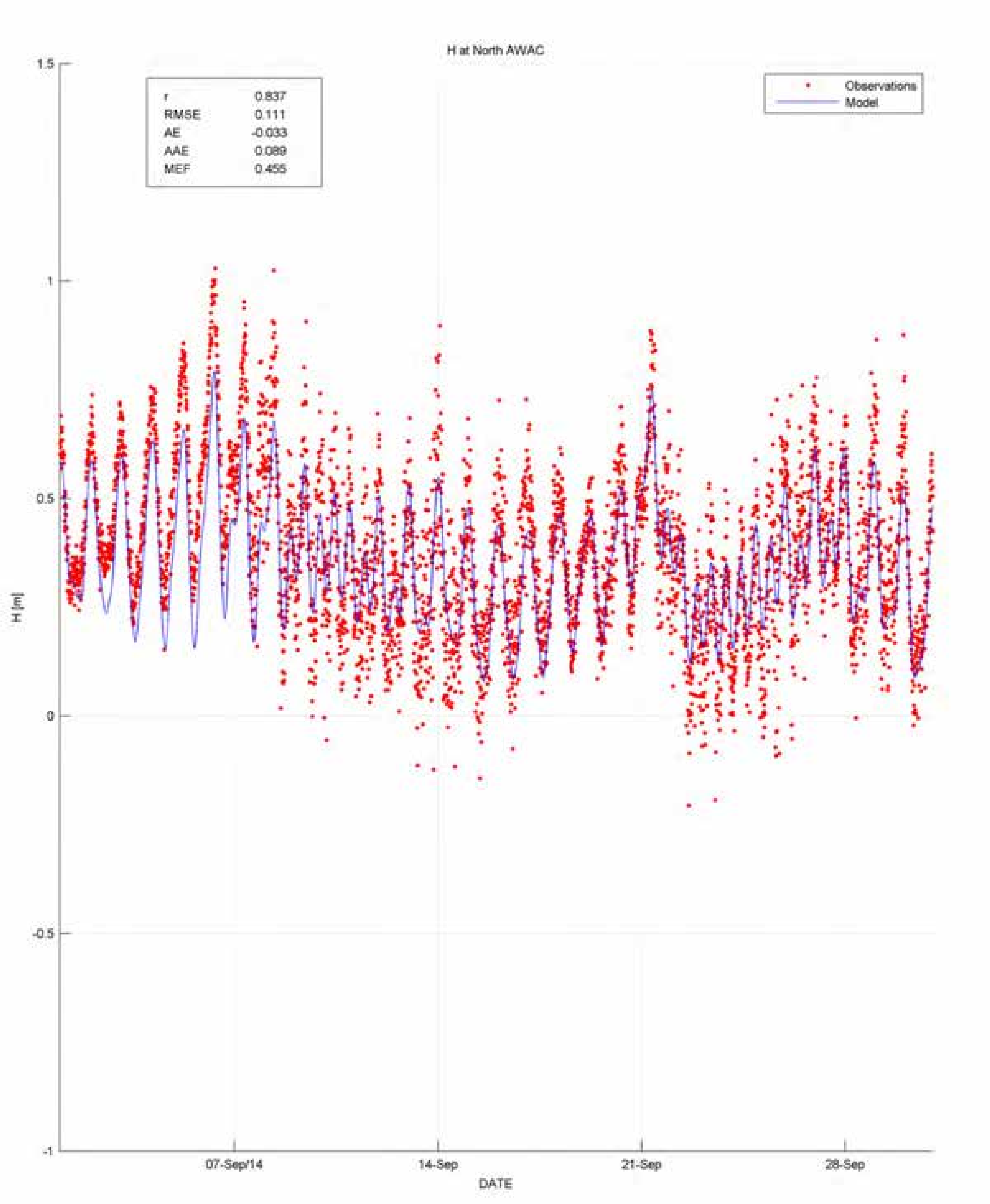

Figure B-3 Water levels at northern regional site – September 2014

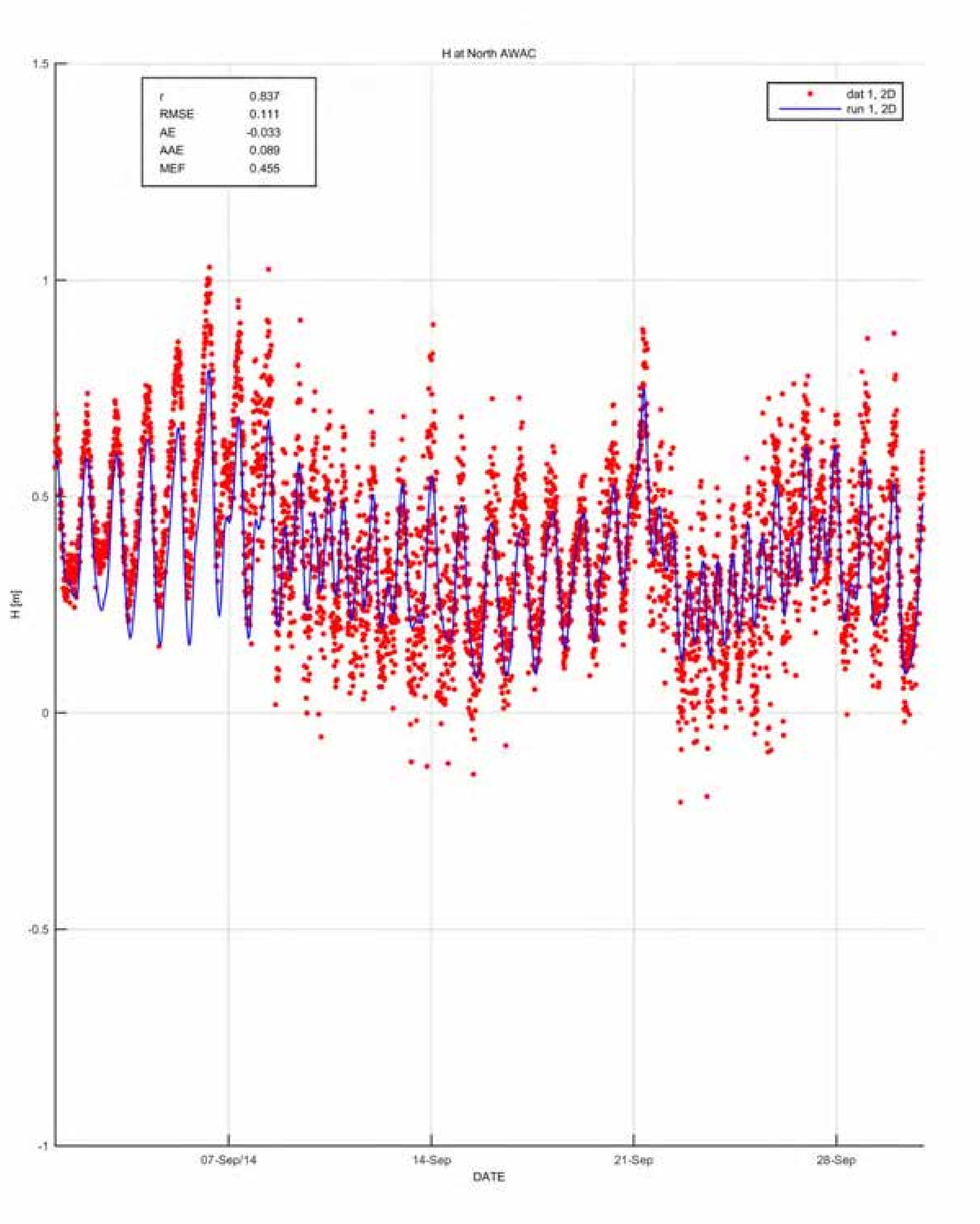

Figure B-4 Water levels at northern regional site – October 2014

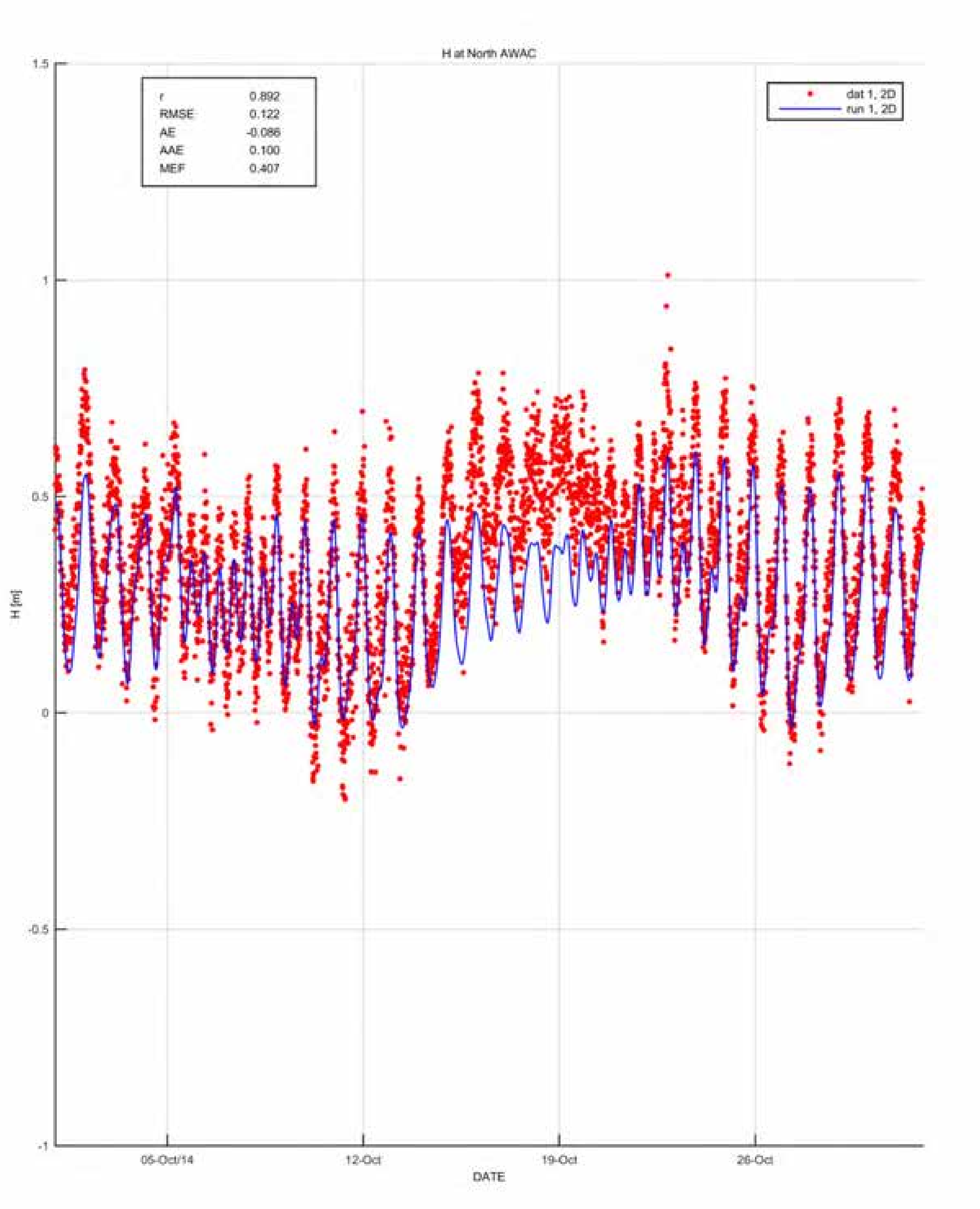

Figure B-5 Water levels at northern regional site – November 2014

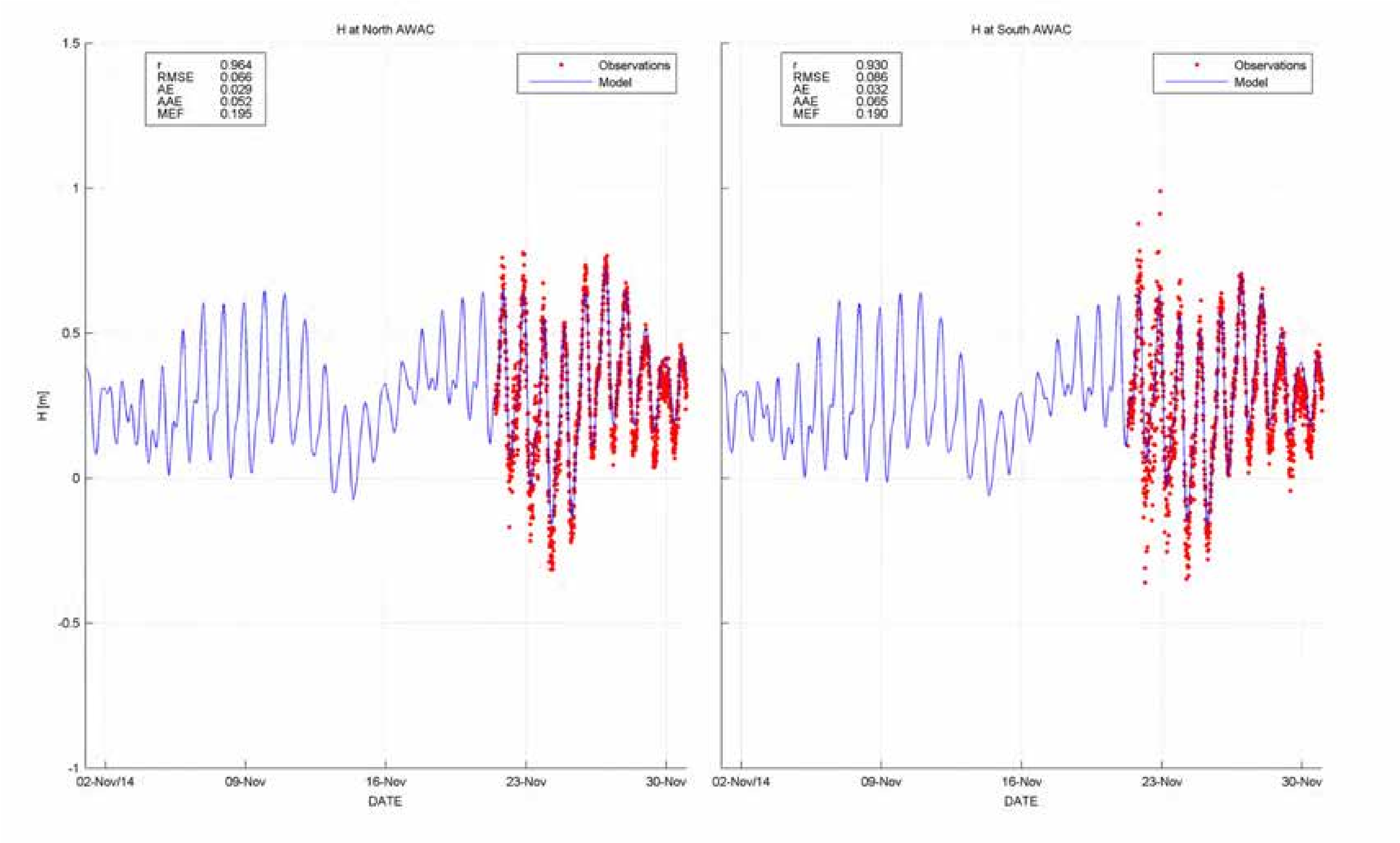

Figure B-6 **Water levels at regional sites – November 2014 (second deployment)**

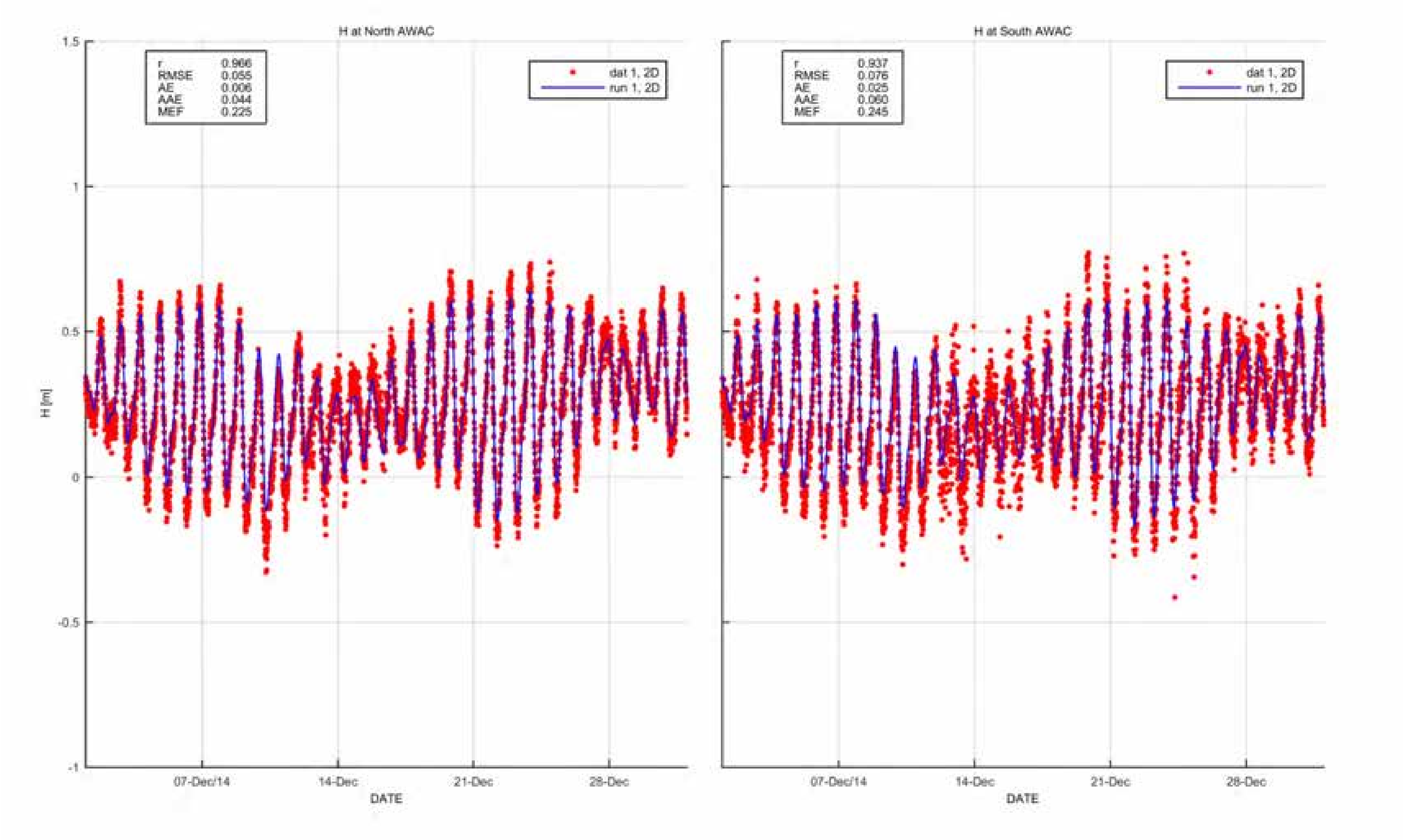

Figure B-7 Water levels at regional sites – December 2014

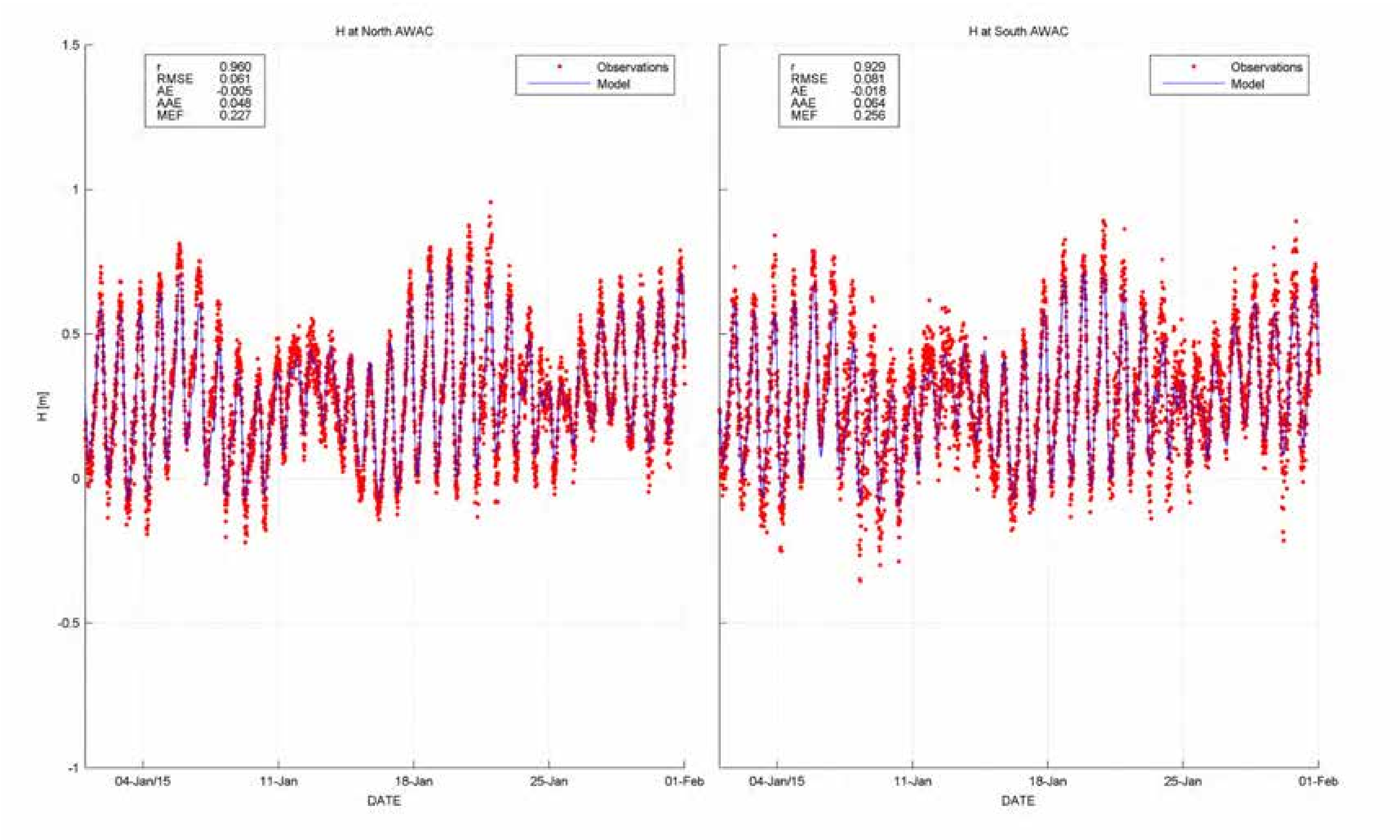

Figure B-8 Water levels at regional sites – January 2015

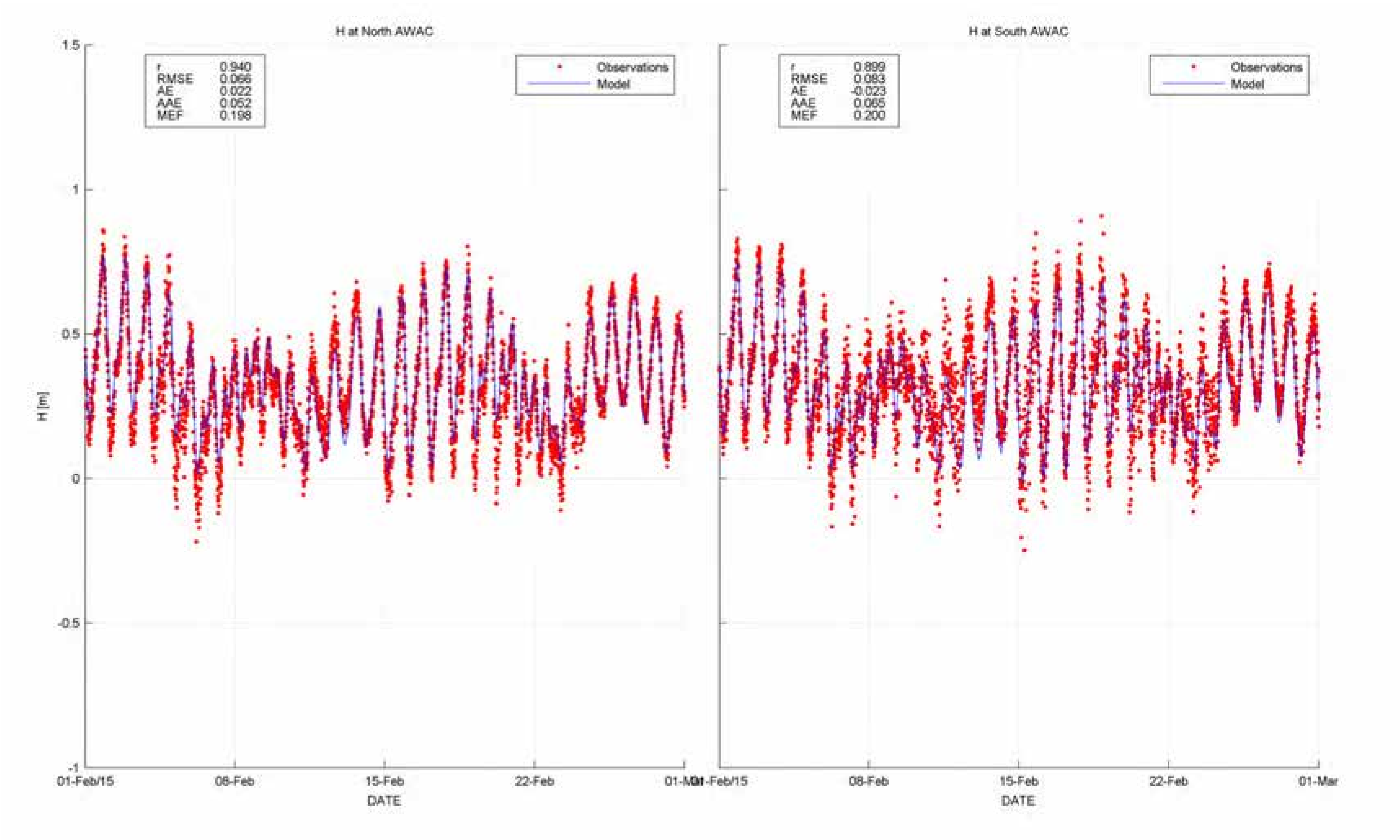

Figure B-9 Water levels at regional sites – February 2015

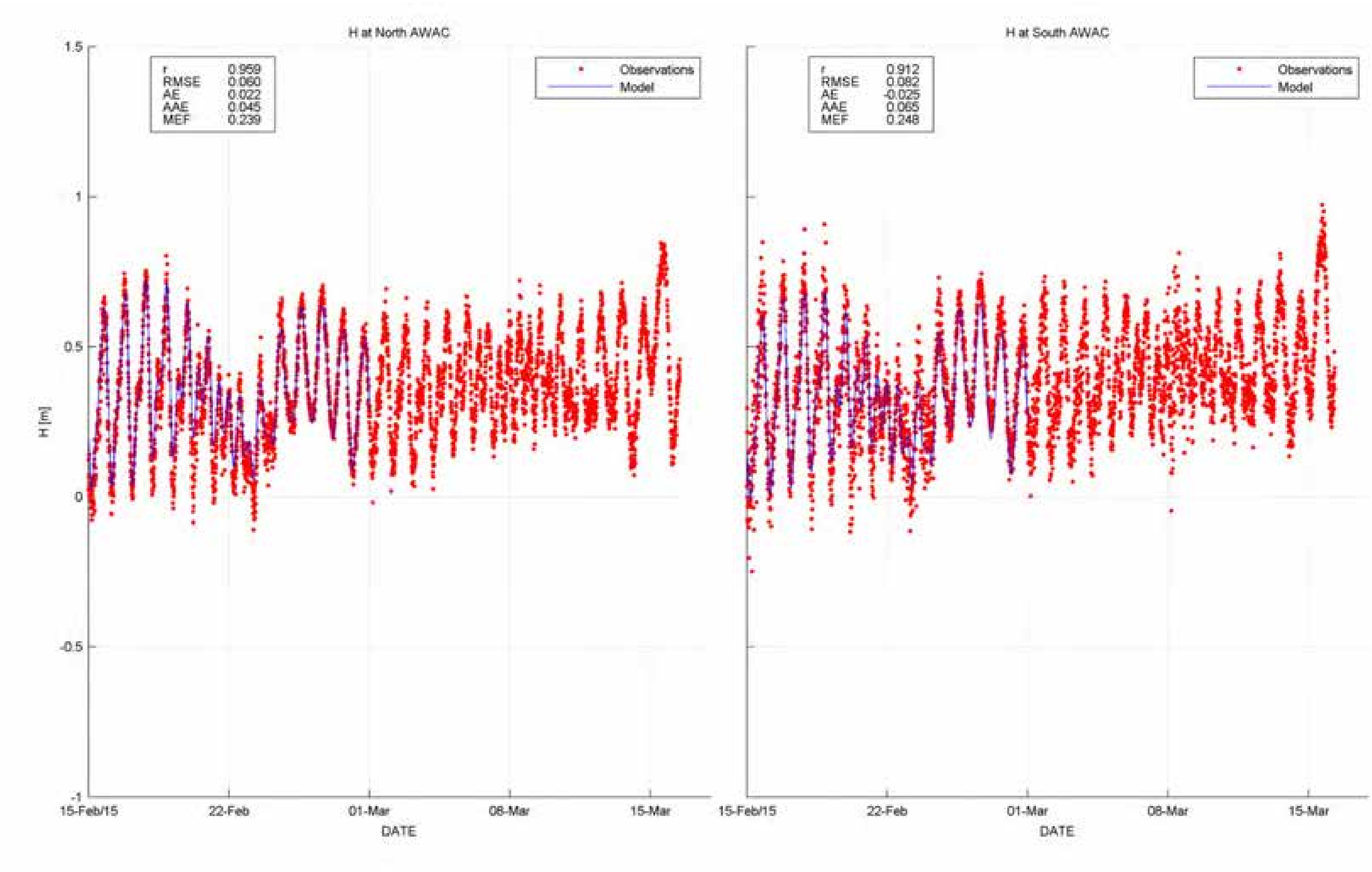

Figure B-10 Water levels at regional sites – March 2015

B.1.2 Tide forcing sensitivity testing

To attempt to overcome the under-prediction of water levels by the model, as illustrated in Figure 4-2, the tidal range at the model boundary was increased by 30%. As noted in section 4.1.1., this improved the water-level calibration at regional sites, but was detrimental to the water-level calibration at lease-area sites. Additionally, the velocity calibration at the lease-area sites was worse when the increased tidal range was applied. The figures below present model results from both the final calibration run and the sensitivity test with increased tidal range.

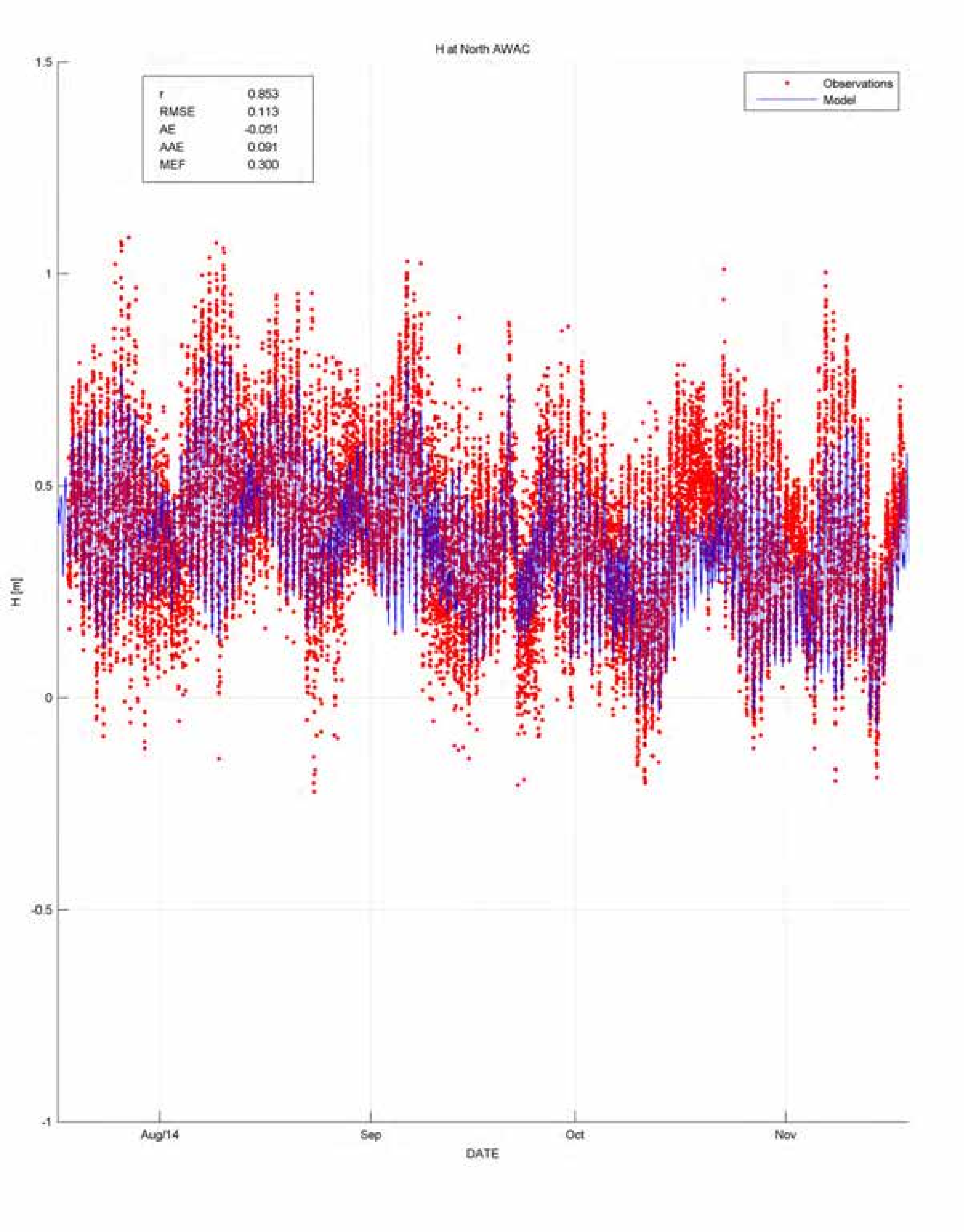

Figure B-11 Water-level comparisons at northern regional site – original tidal forcing

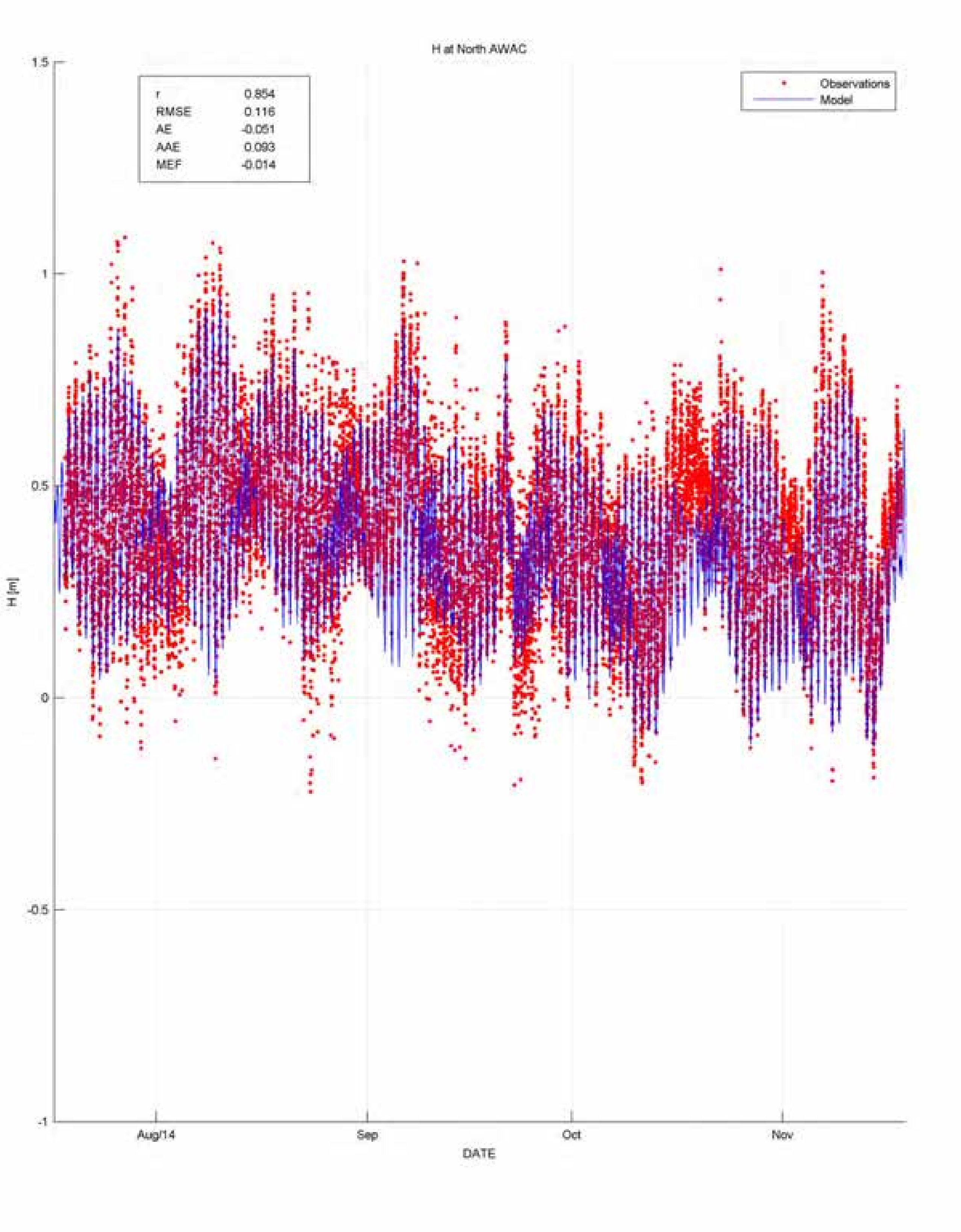

Figure B-12 Water-level comparisons at northern regional site – increased tidal range

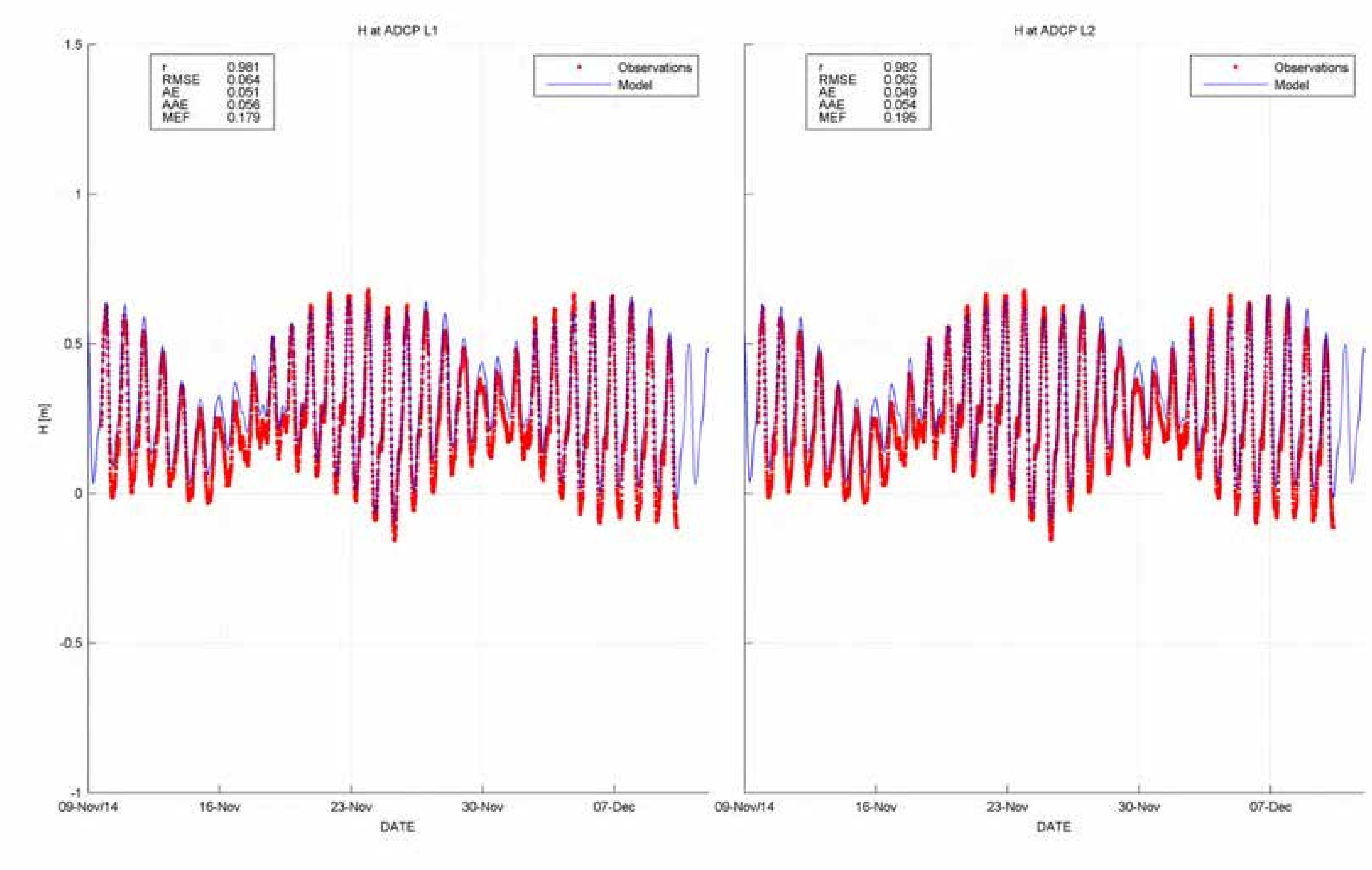

Figure B-13 Water-level comparisons at lease-area sites – original tidal forcing

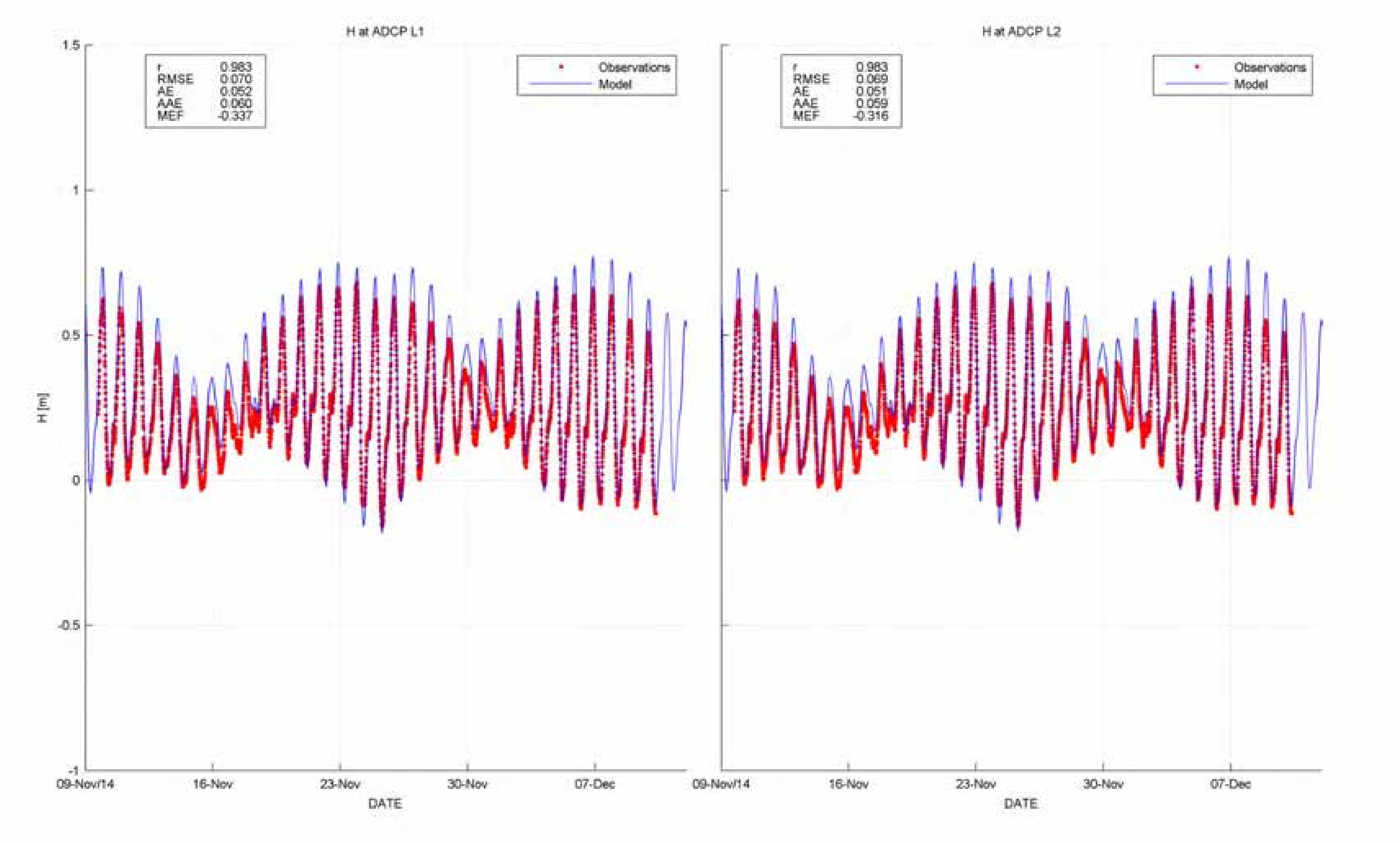

Figure B-14 Water-level comparisons at lease-area sites – increased tidal range

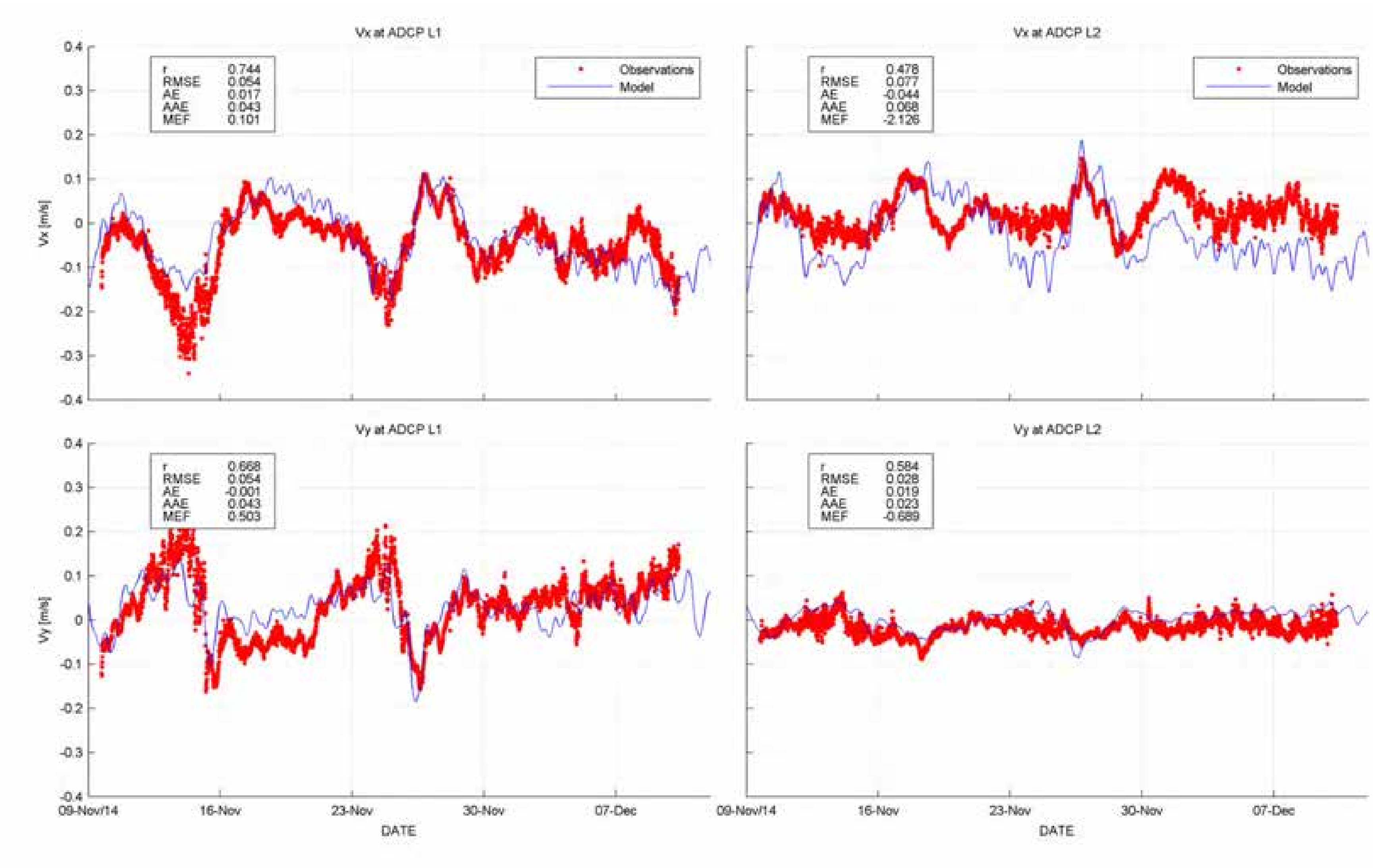

Figure B-15 Velocity comparisons at lease-area sites – original tidal forcing

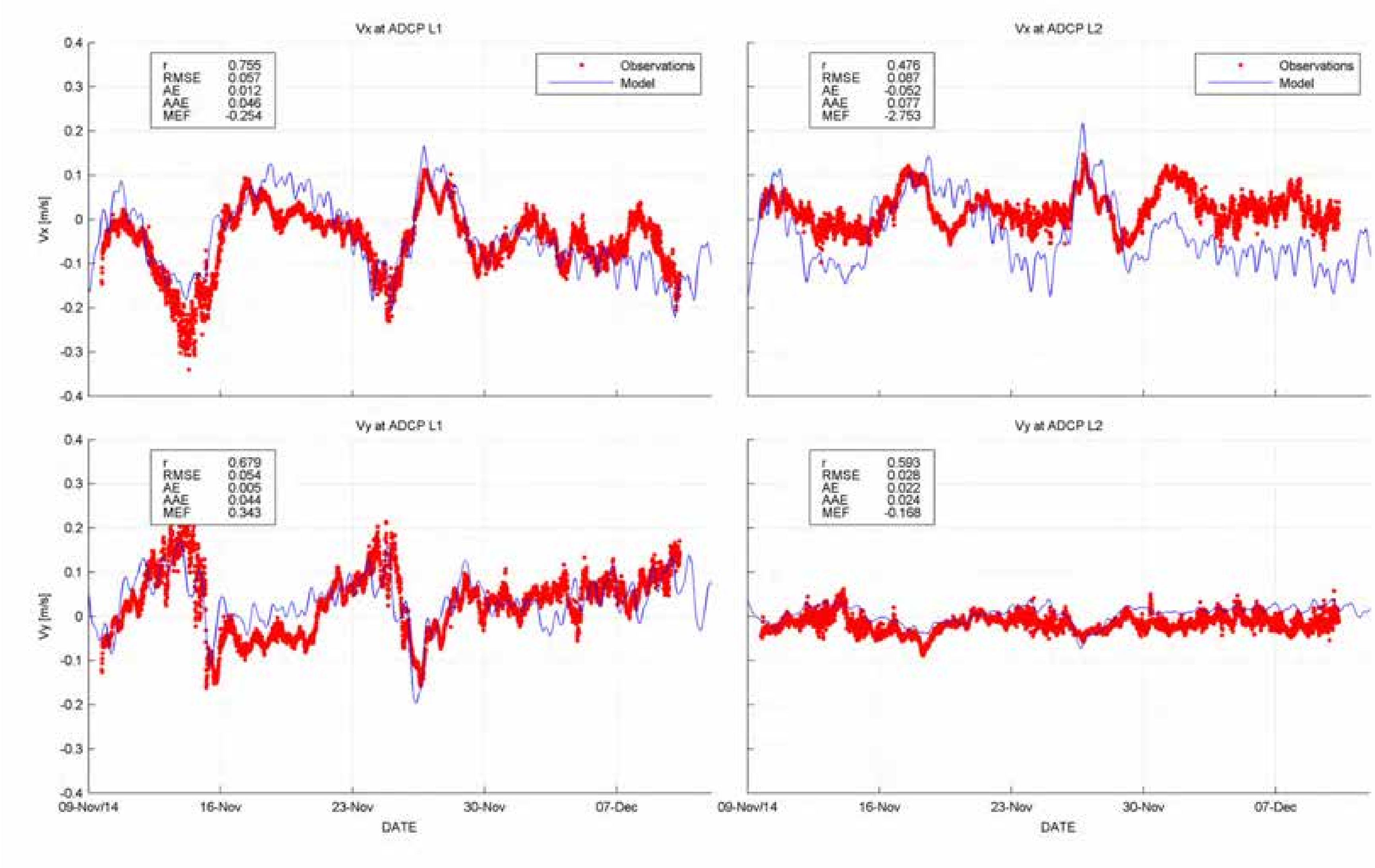

Figure B-16 Velocity comparisons at lease-area sites – increased tidal range

B.2 Velocities

Additional plots, complementing Section 4.1.2, are provided in this section. Section 4.1.2 contains a number of figures comparing simulated, depth-averaged velocities against depth-averaged observations. This section contains comparisons of surface velocities (Figure B-17 to Figure B-22) and bottom velocities (Figure B-23 to Figure B-28) at the same times and locations. The model appears to be similarly skilful for surface, bottom and depth-averaged velocities, although some of the surface variability is not reproduced, resulting in lower r values.

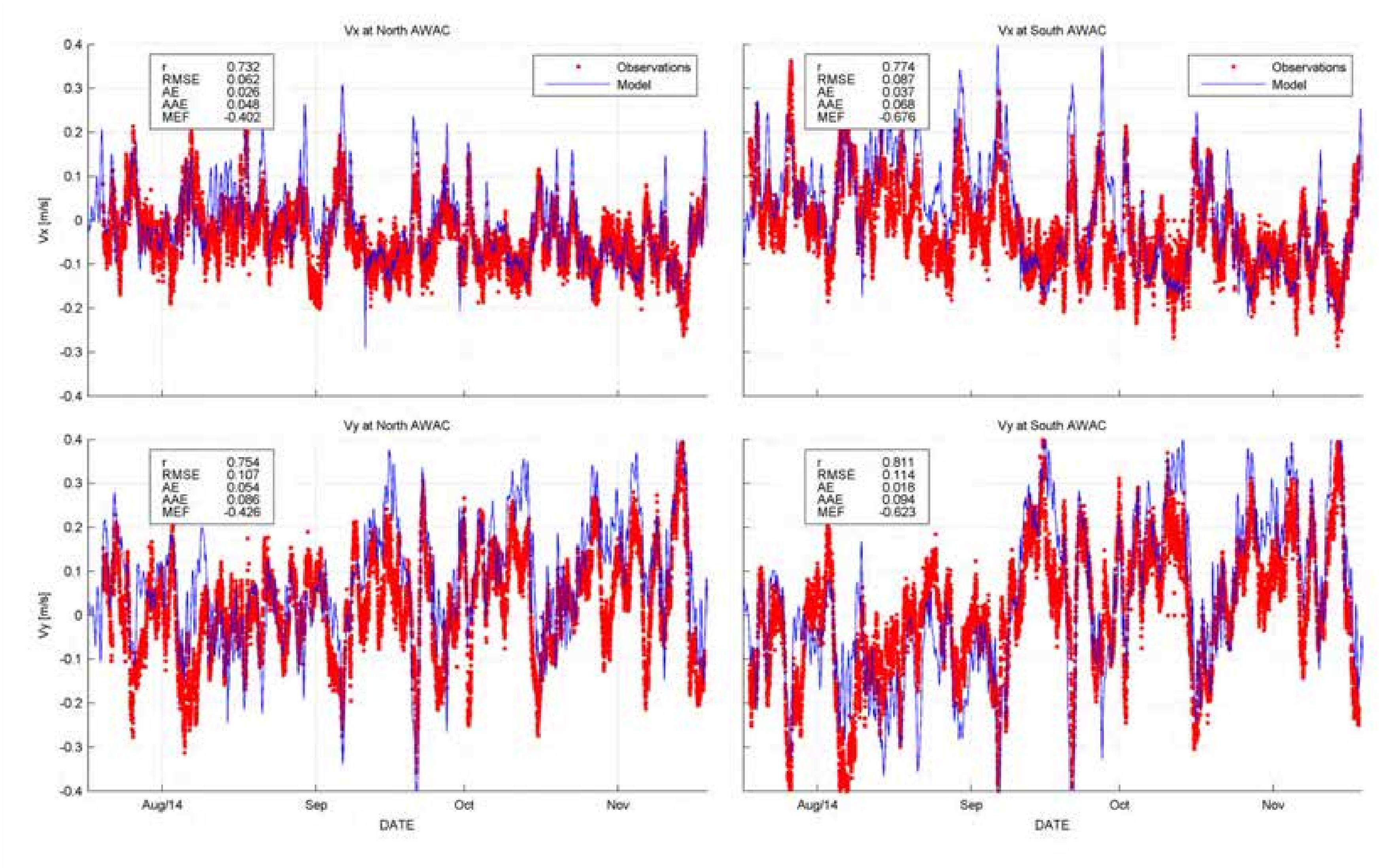

Figure B-17 Time-series of surface velocity (0-5 m depth) at regional sites – Jul 2014 to Nov 2014 deployment

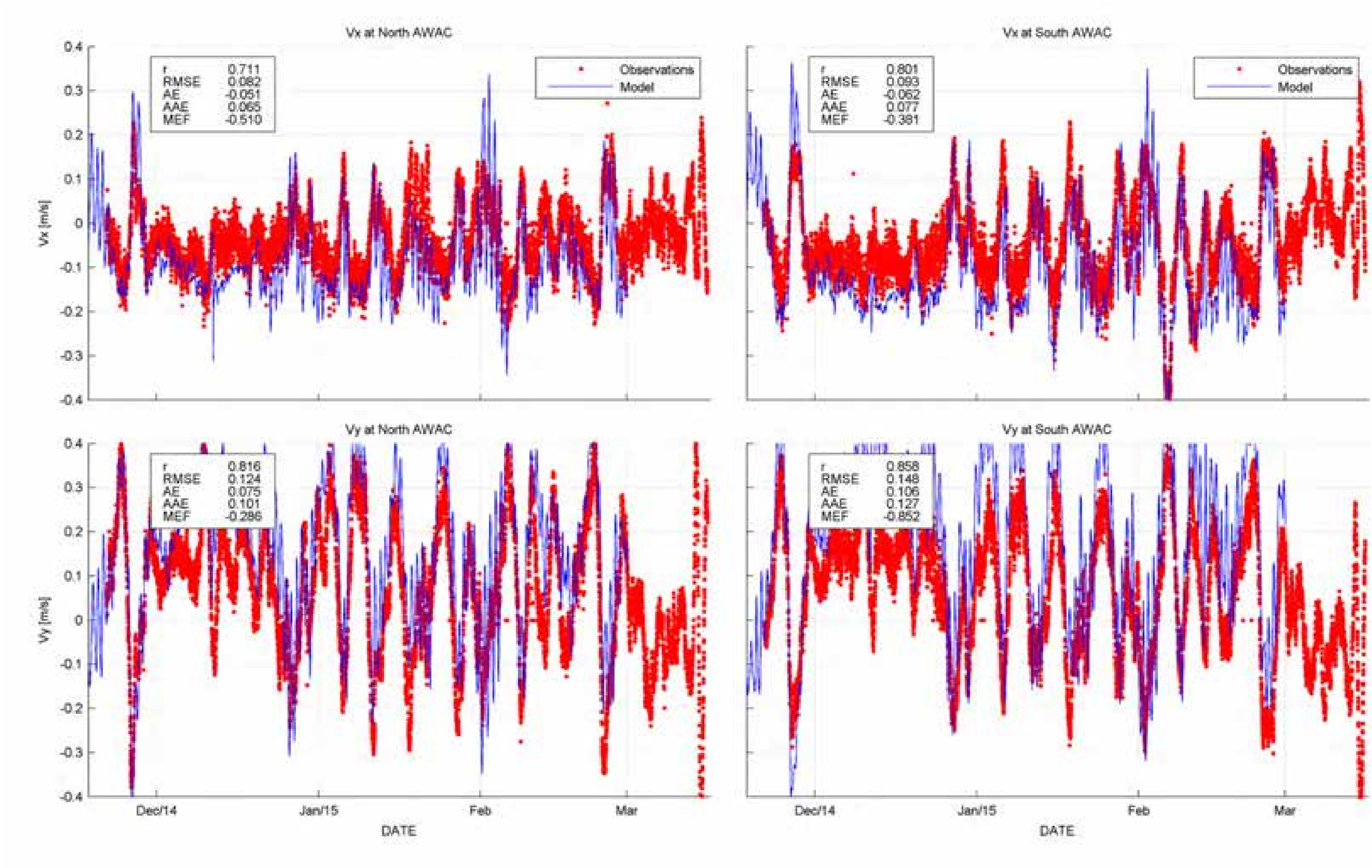

Figure B-18 Time-series of surface velocity (0-5 m depth) at regional sites – Nov 2014 to Mar 2015 deployment

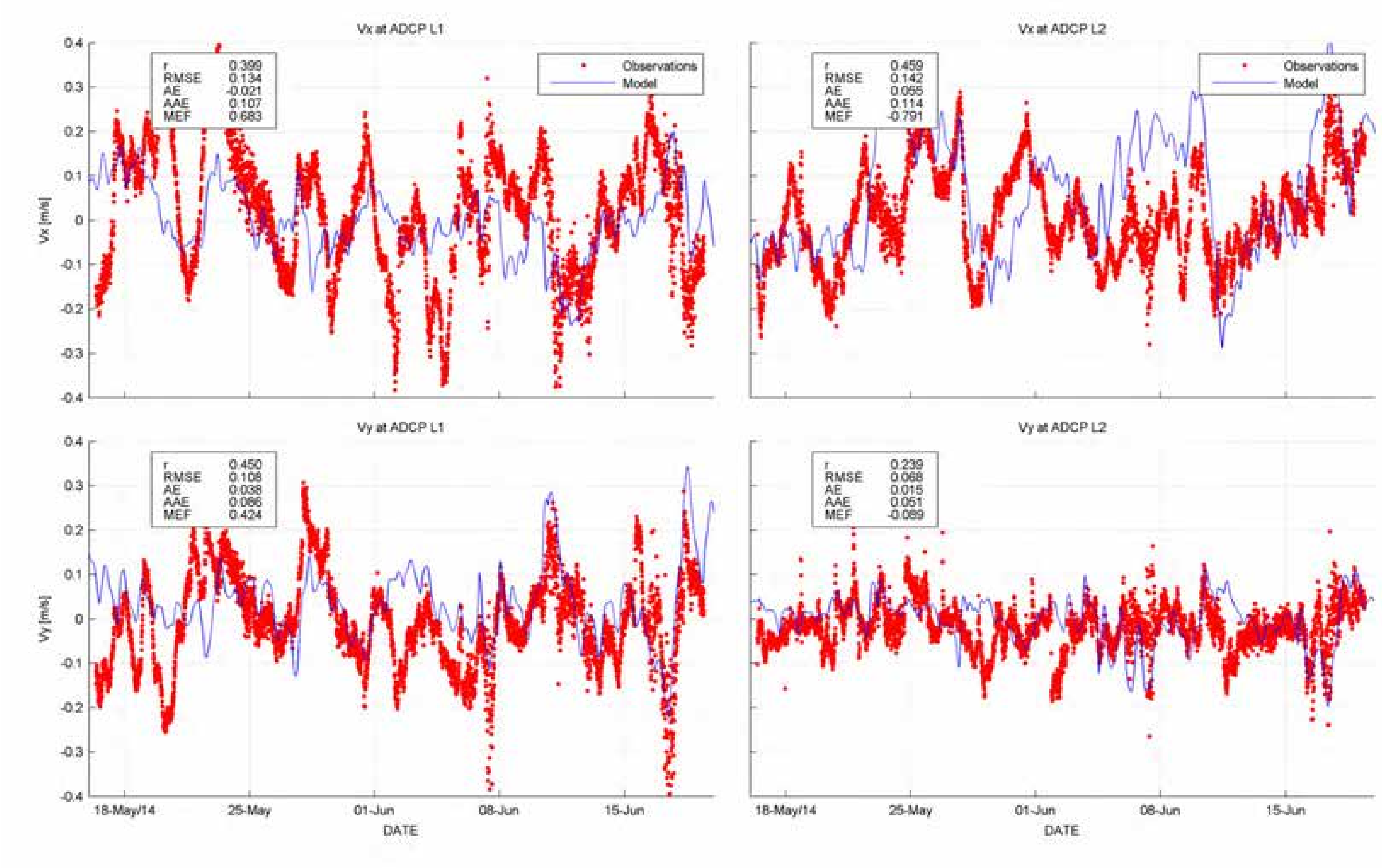

Figure B-19 Time-series of surface velocity (0-5 m depth) at lease-area sites – May 2014 to Jun 2014 deployment

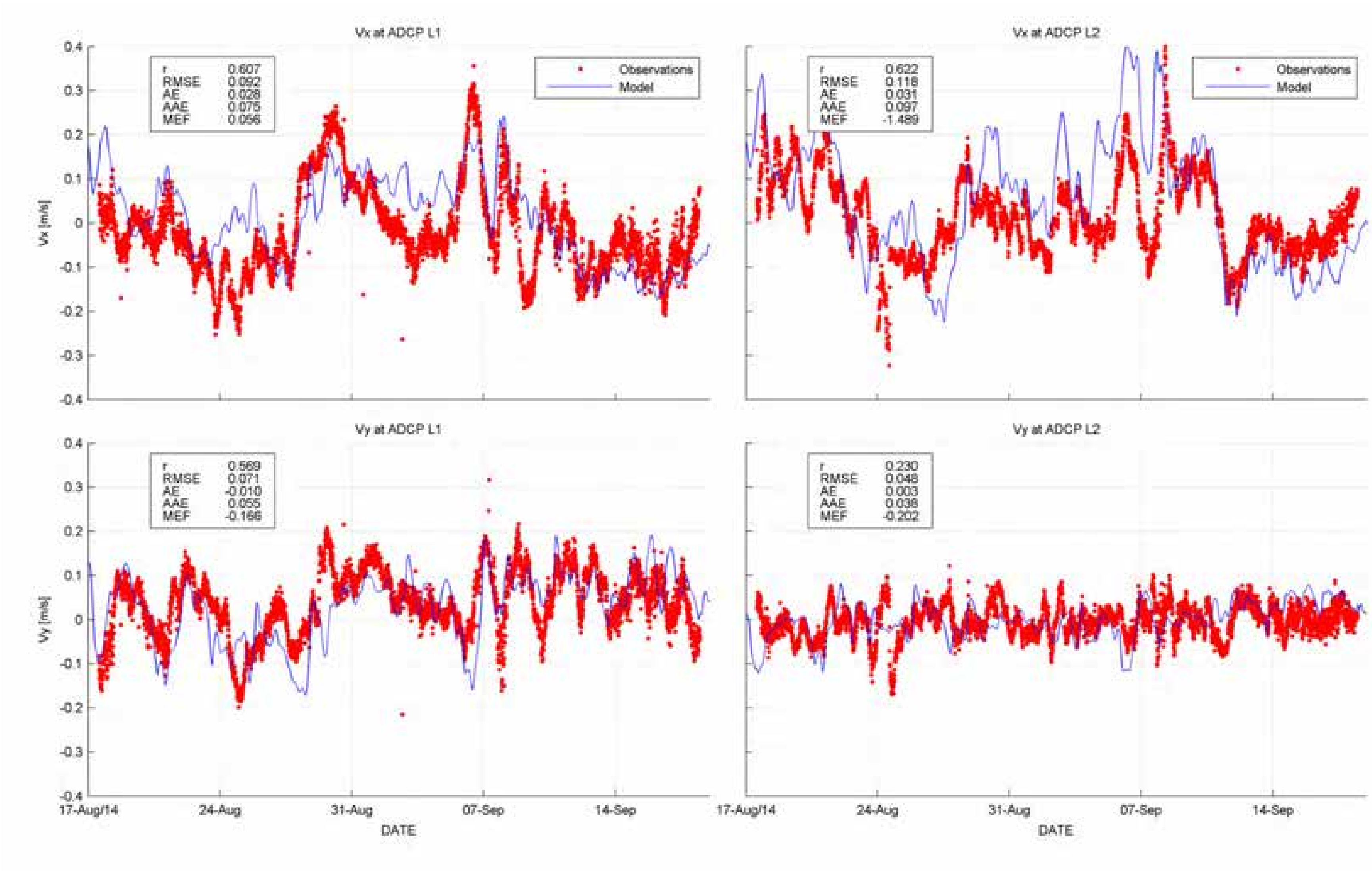

Figure B-20 Time-series of surface velocity (0-5 m depth) at lease-area sites – Aug 2014 to Sep 2014 deployment

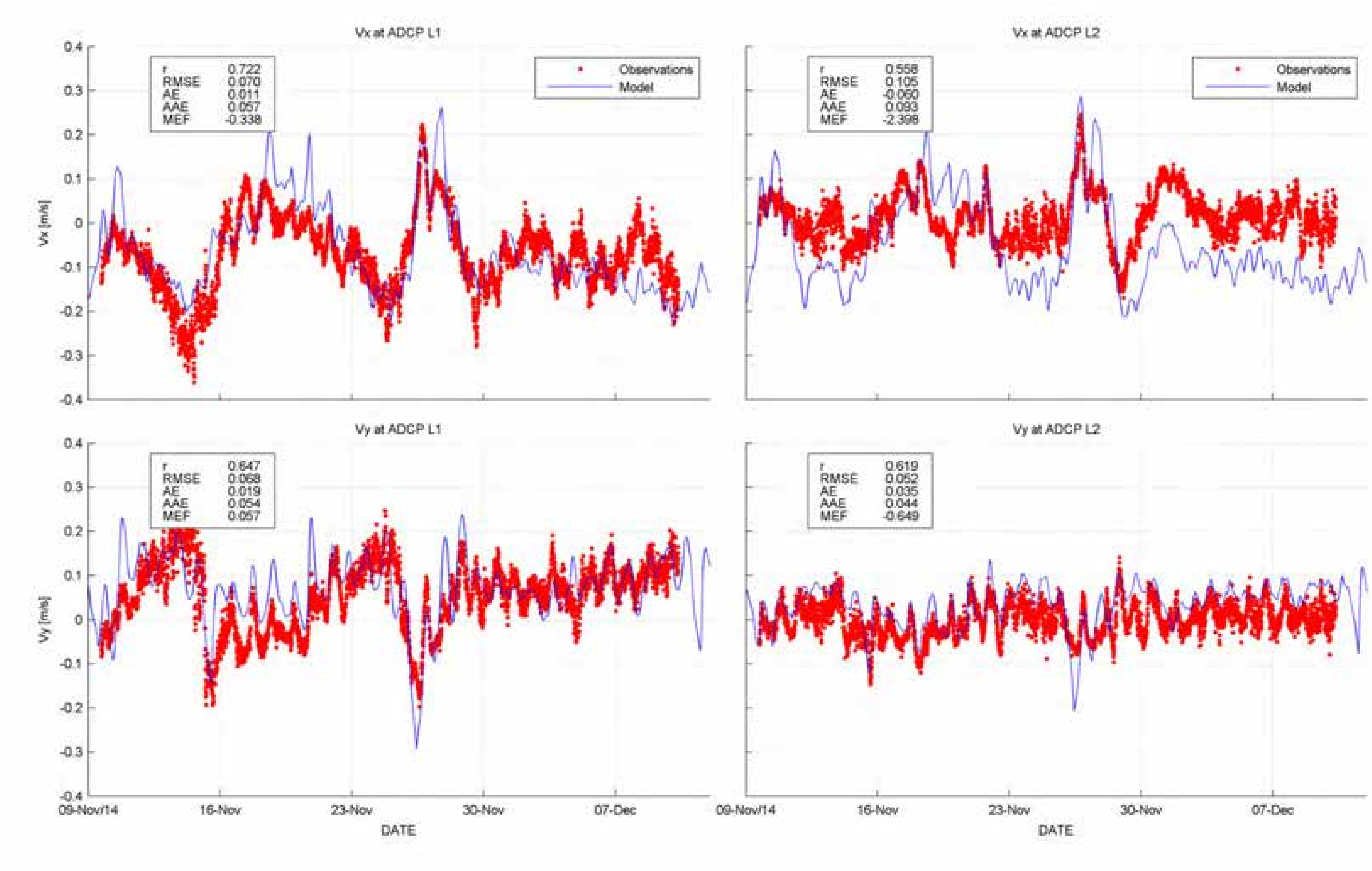

Figure B-21 Time-series of surface velocity (0-5 m depth) at lease-area sites – Nov 2014 to Dec 2014 deployment

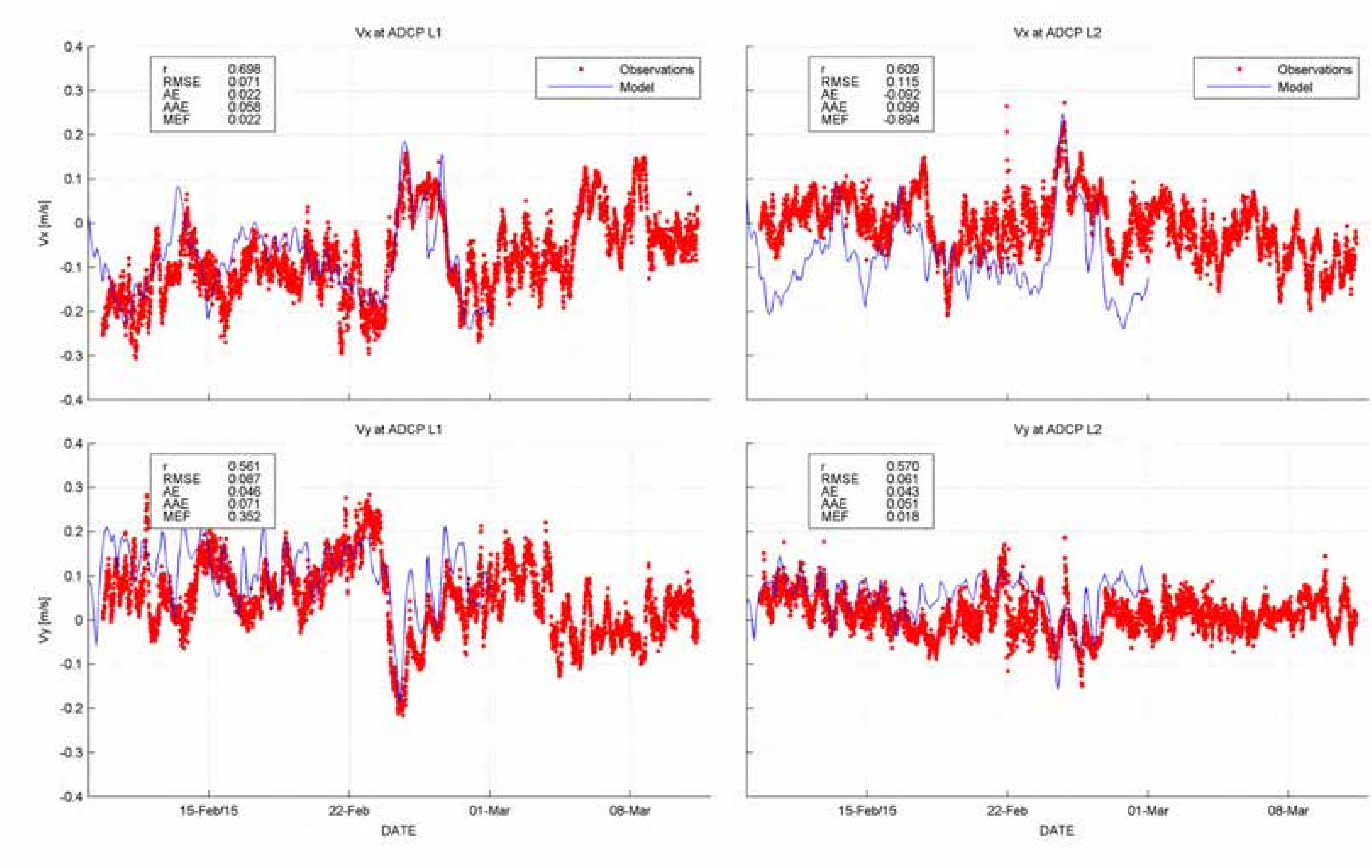

Figure B-22 Time-series of surface velocity (0-5 m depth) at lease-area sites – Feb 2015 to Mar 2014 deployment

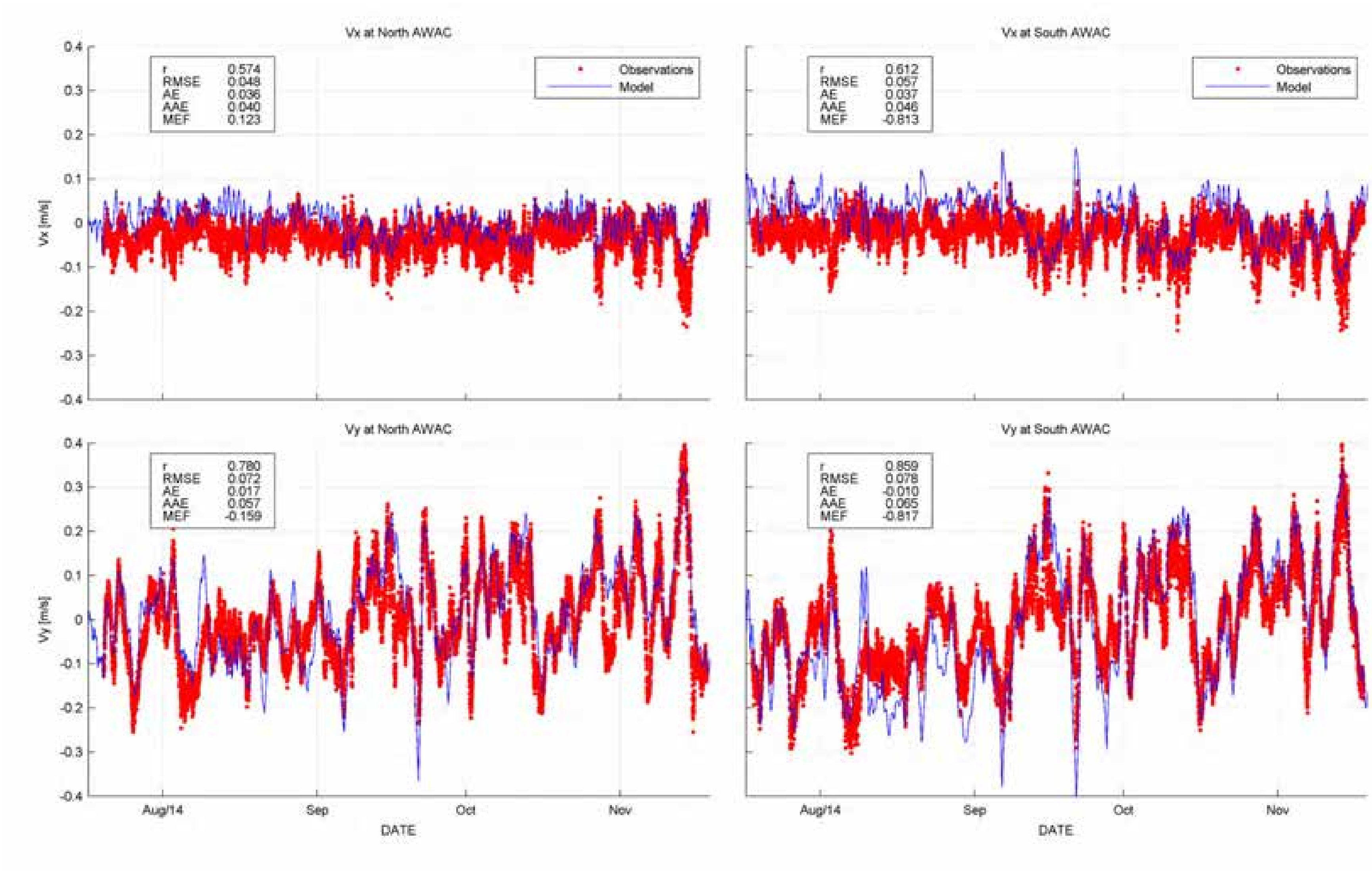

Figure B-23 Time-series of bottom velocity (0-5 m above seabed) at regional sites – Jul 2014 to Nov 2014 deployment

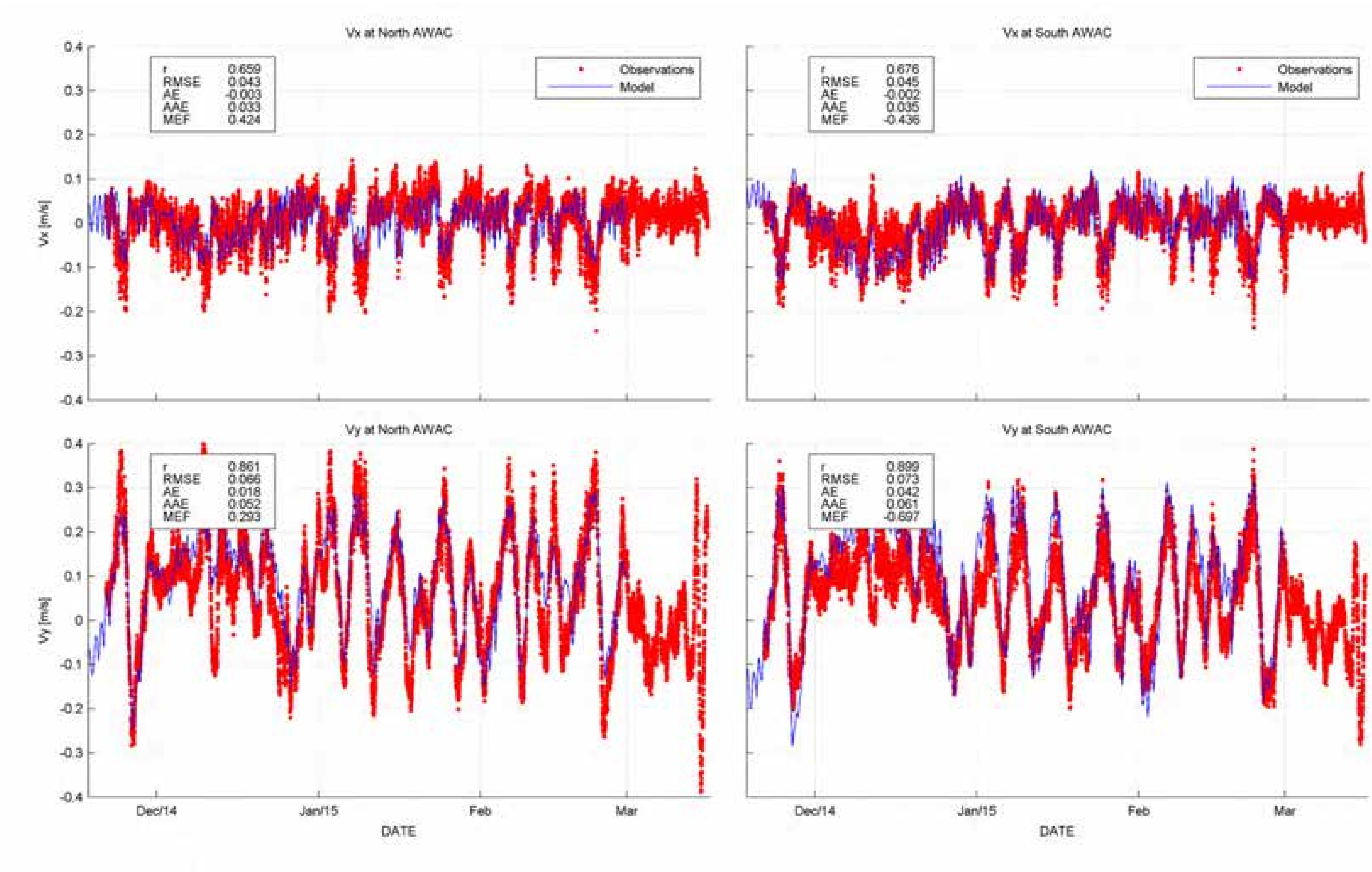

Figure B-24 Time-series of bottom velocity (0-5 m above seabed) at regional sites – Nov 2014 to Mar 2015 deployment

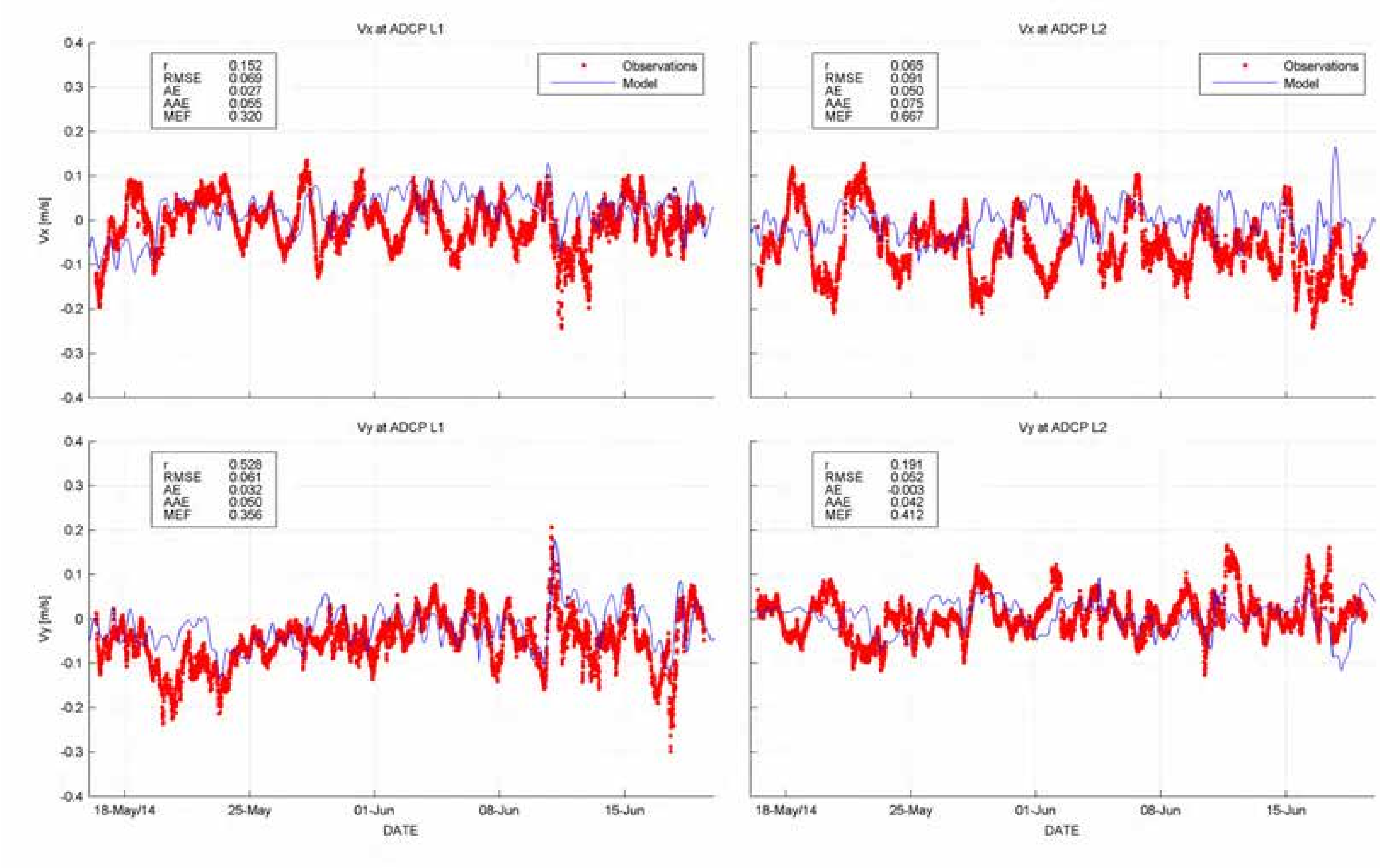

Figure B-25 Time-series of bottom velocity (0-5 m above seabed) at lease-area sites – May 2014 to Jun 2014 deployment

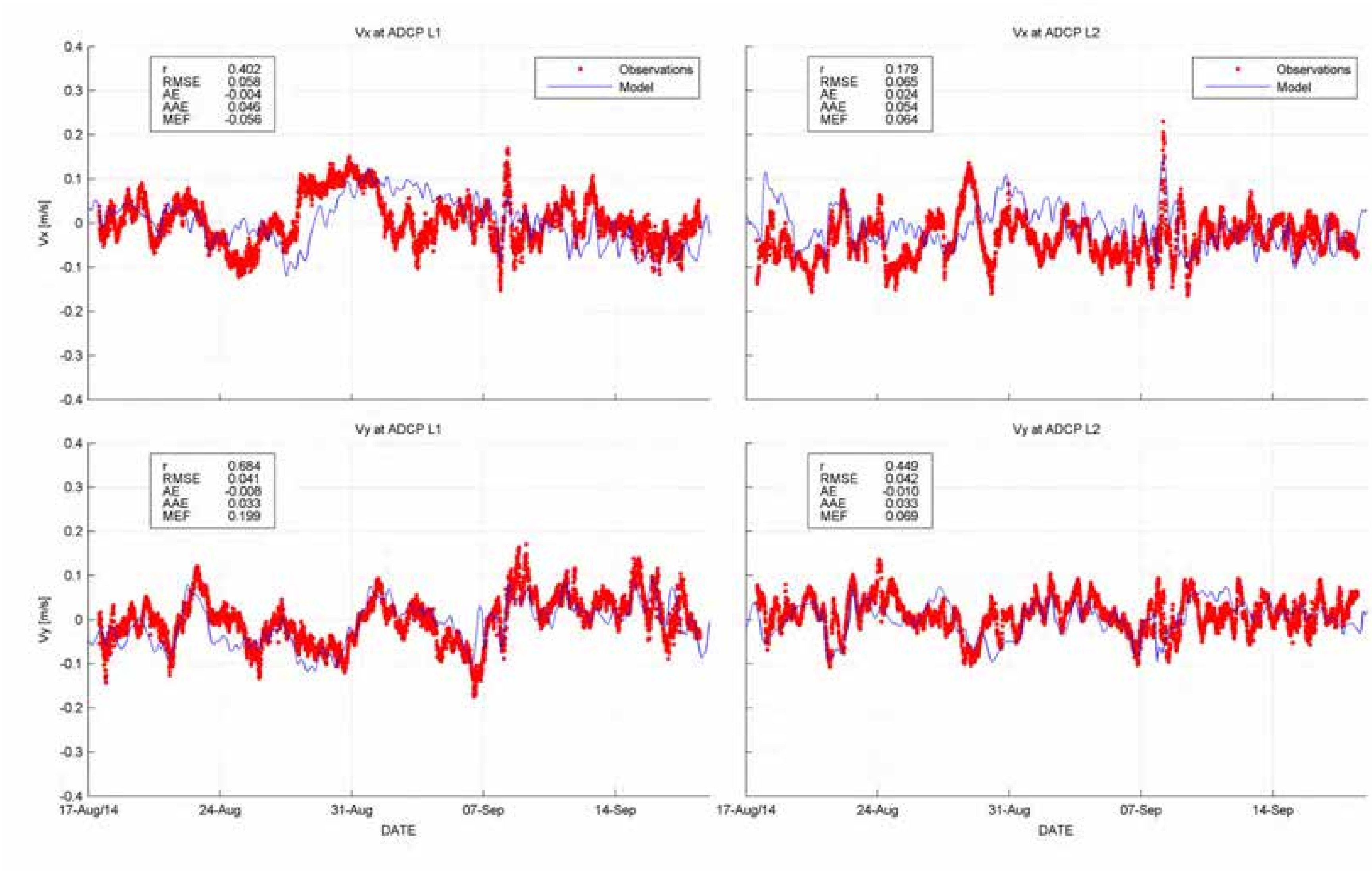

Figure B-26 Time-series of bottom velocity (0-5 m above seabed) at lease-area sites – Aug 2014 to Sep 2014 deployment

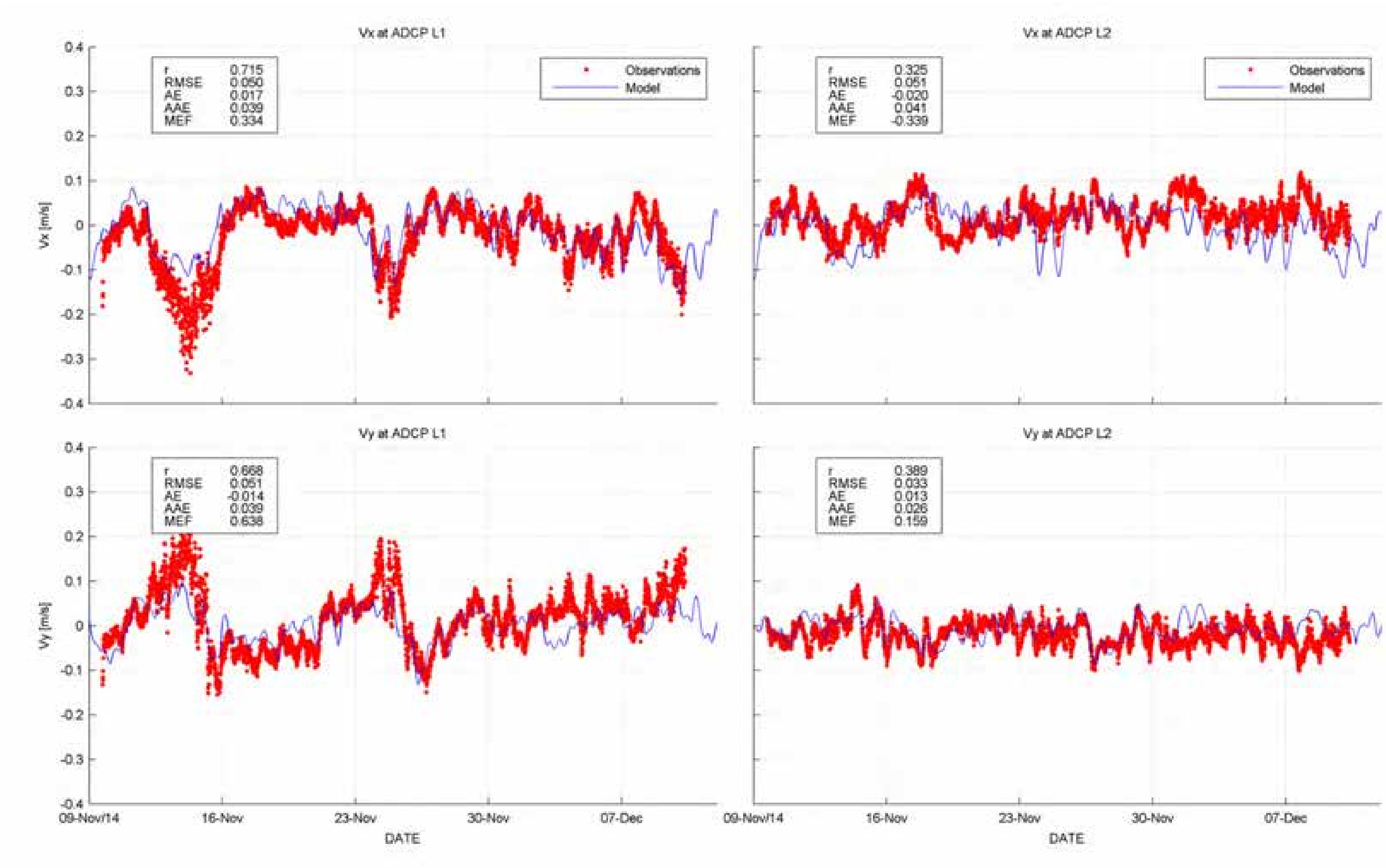

Figure B-27 Time-series of bottom velocity (0-5 m above seabed) at lease-area sites – Nov 2014 to Dec 2014 deployment

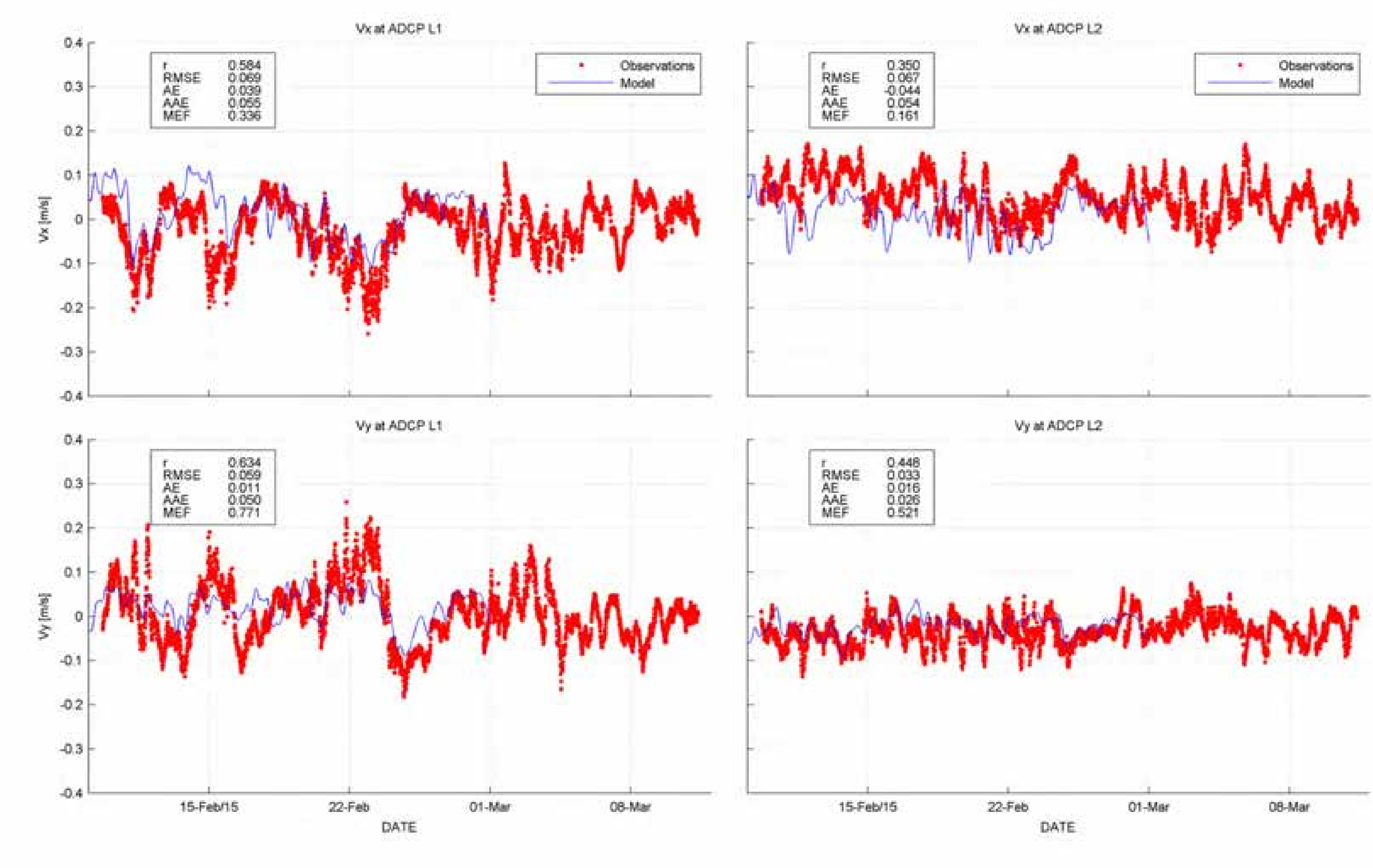

Figure B-28 Time-series of bottom velocity (0-5 m above seabed) at lease-area sites – Feb 2015 to Mar 2014 deployment

B.3 Temperature

This section includes time-series of seabed temperature collected at the regional sites, decomposed into calendar months for clarity. The first deployment is detailed in Figure B-29 to Figure B-33, and the second in Figure B-34 to Figure B-38.

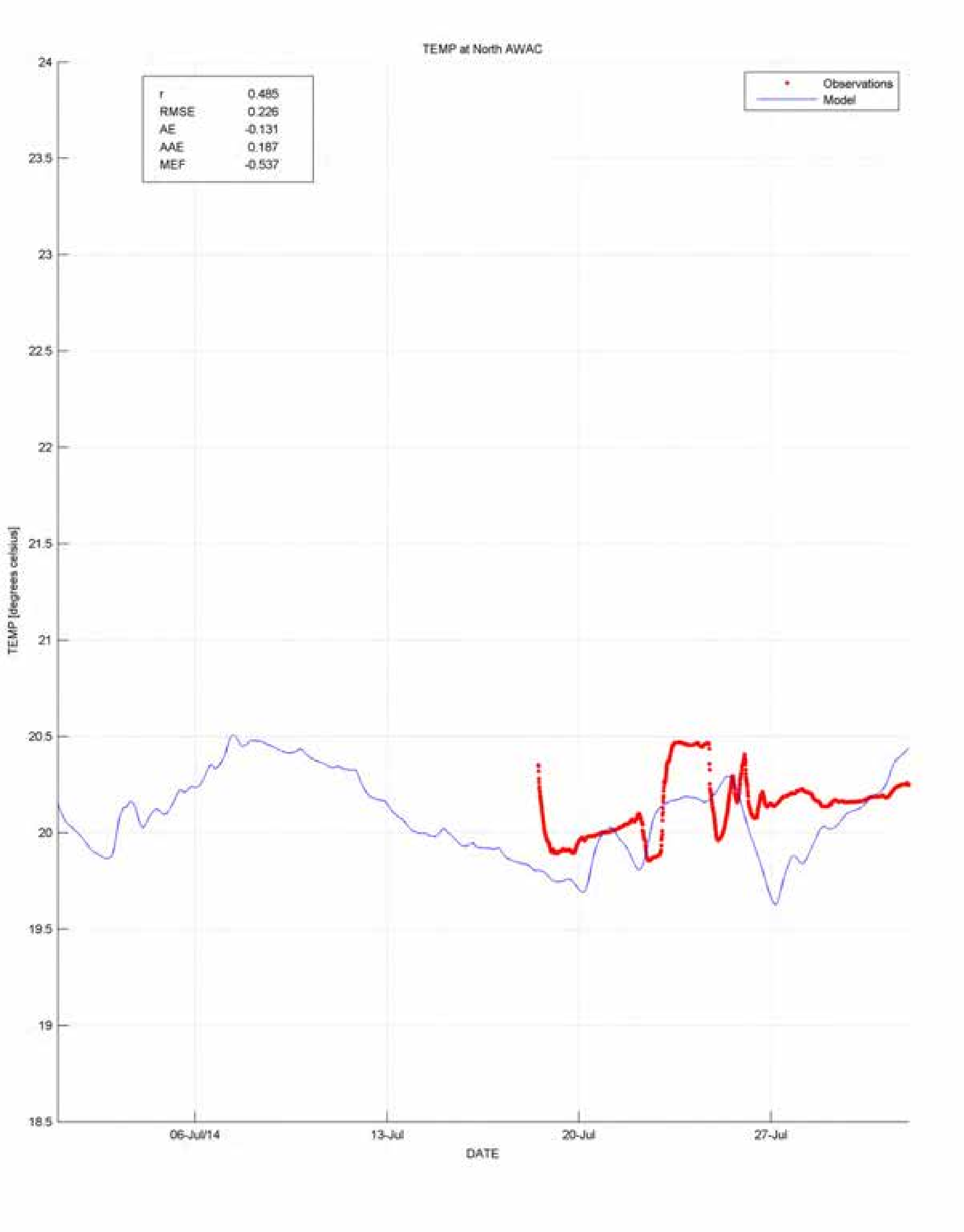

Figure B-29 Time-series of seabed temperature at northern regional site – July 2014

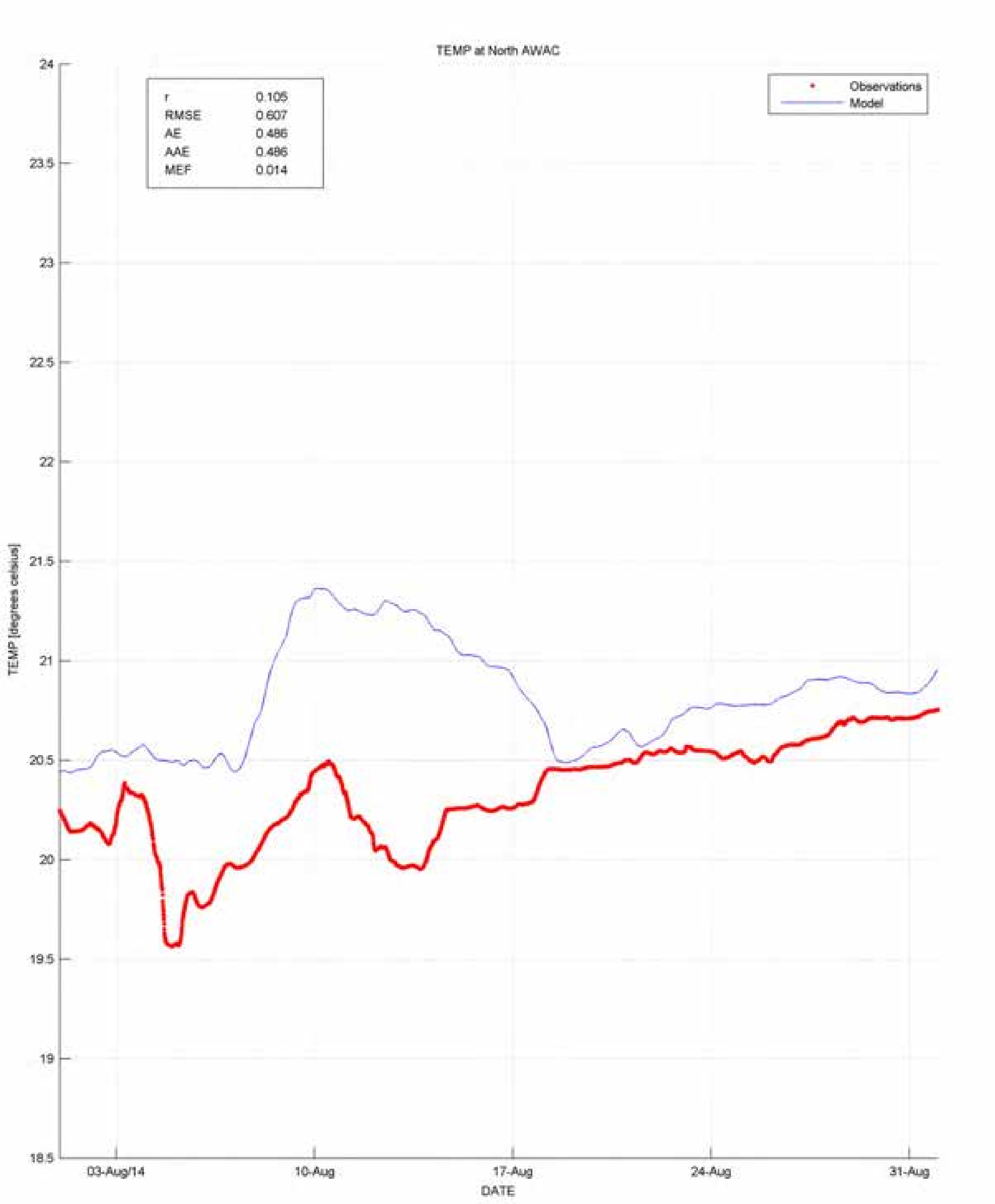

Figure B-30 Time-series of seabed temperature at northern regional site – August 2014

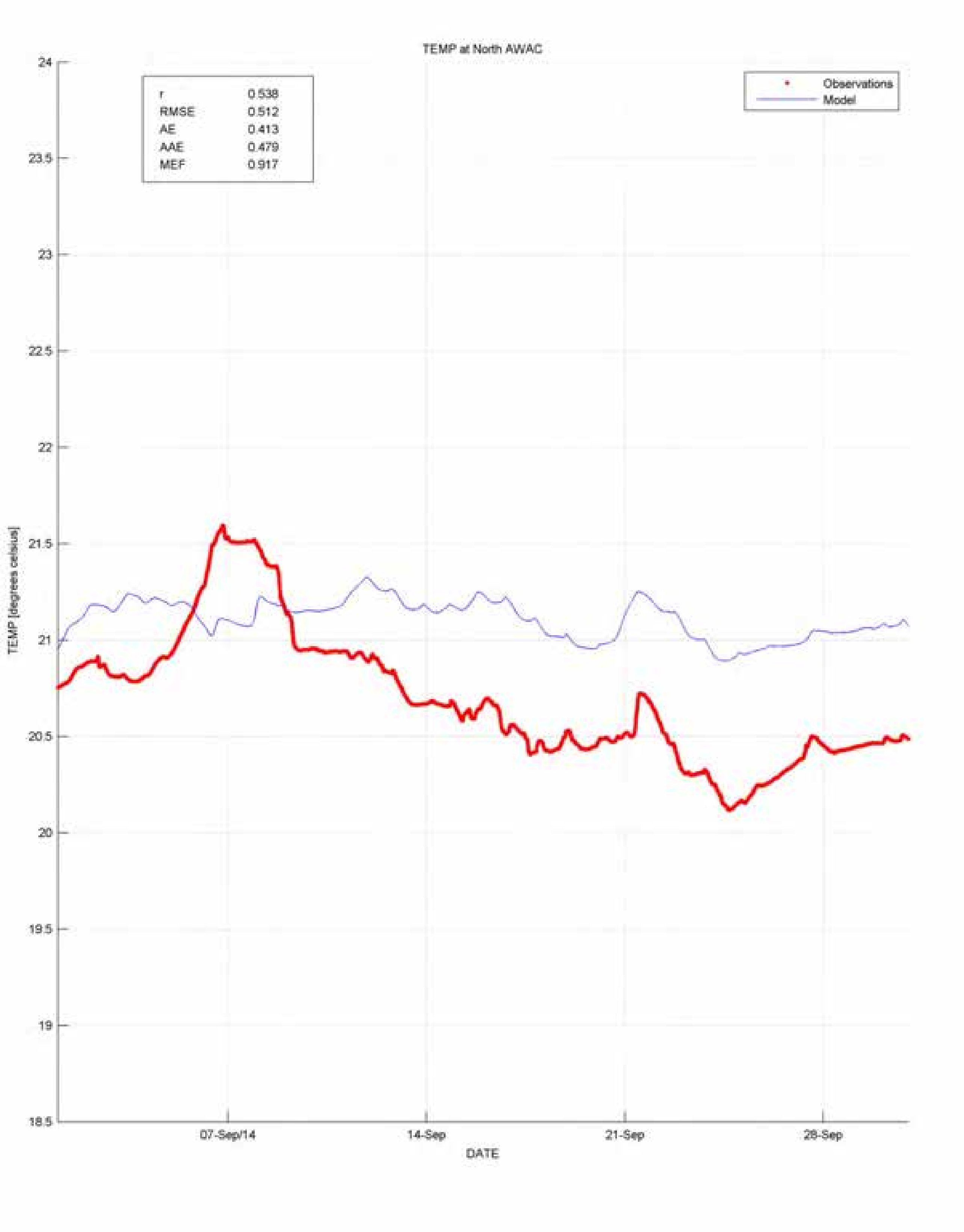

Figure B-31 Time-series of seabed temperature at northern regional site – September 2014

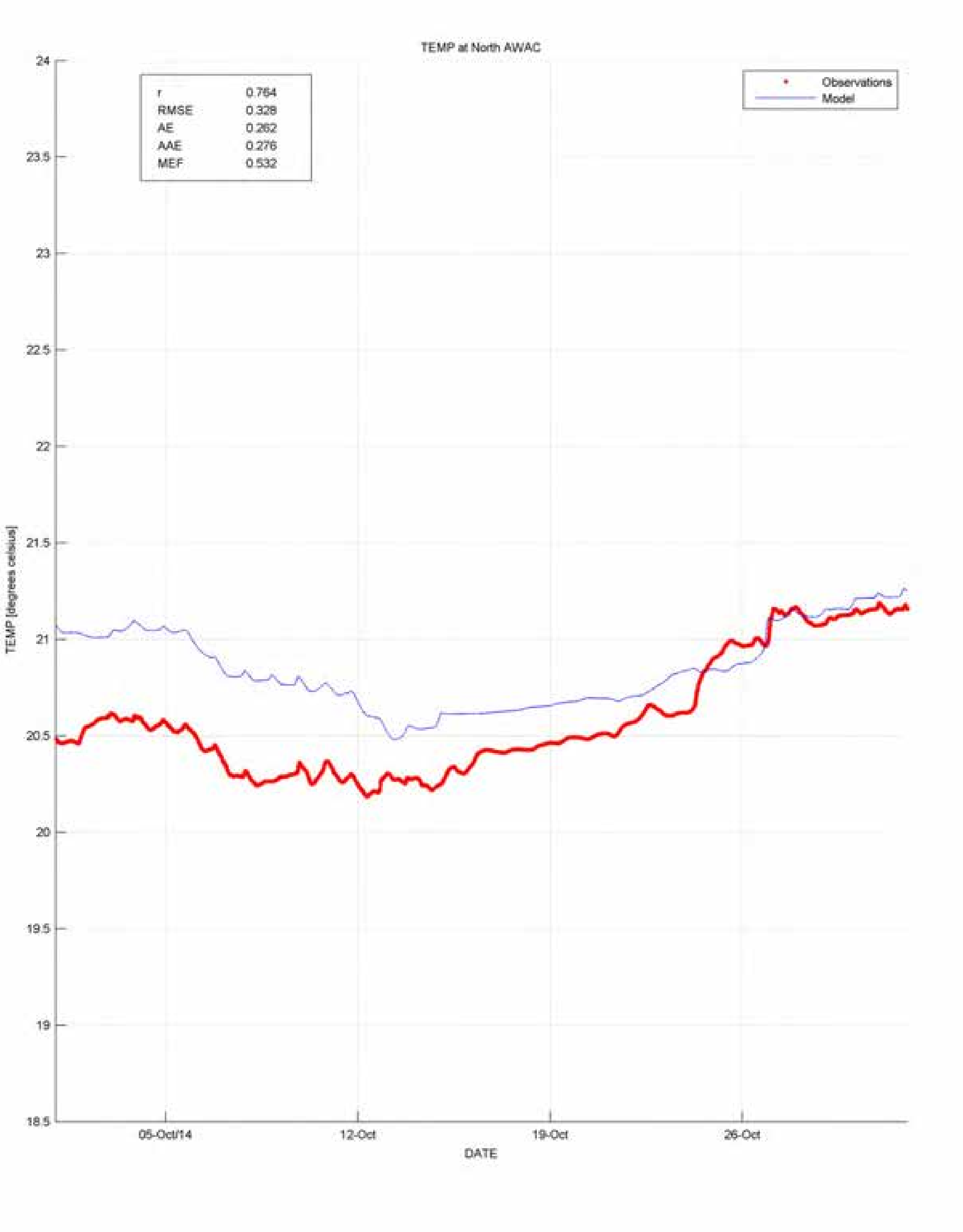

Figure B-32 Time-series of seabed temperature at northern regional site – October 2014

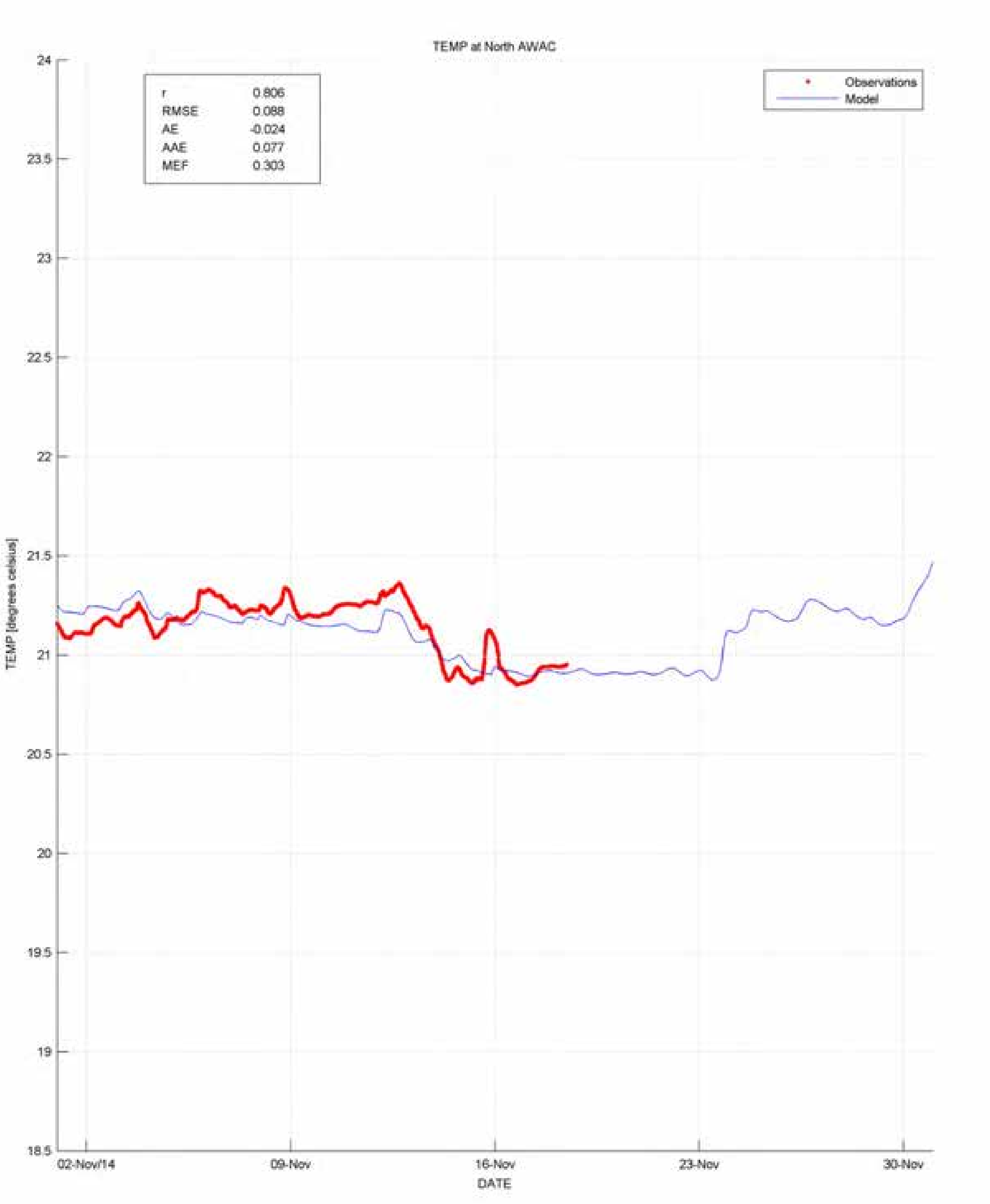

Figure B-33 Time-series of seabed temperature at northern regional site – November 2014

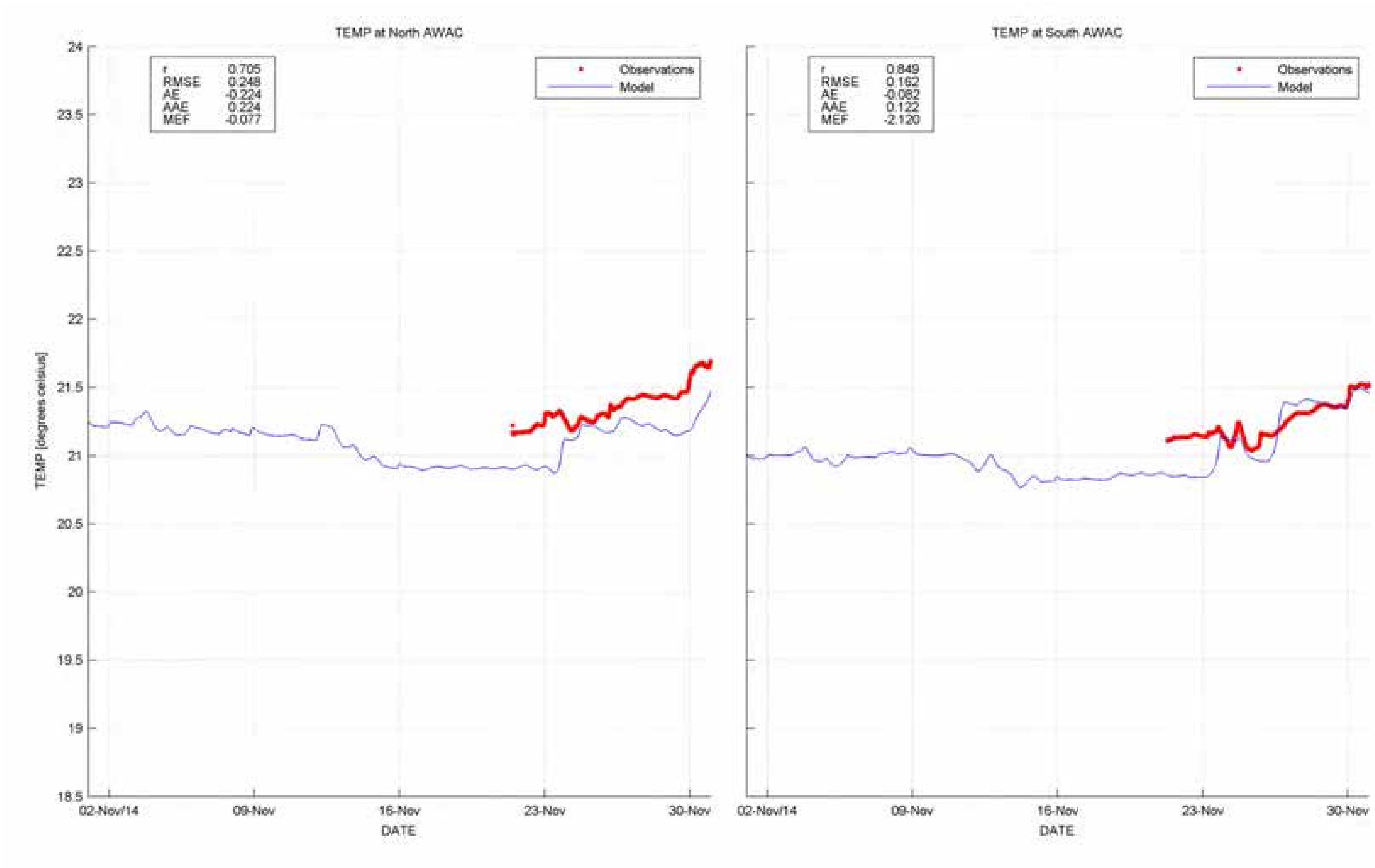

Figure B-34 Time-series of seabed temperature at northern regional site – November 2014 (second deployment)

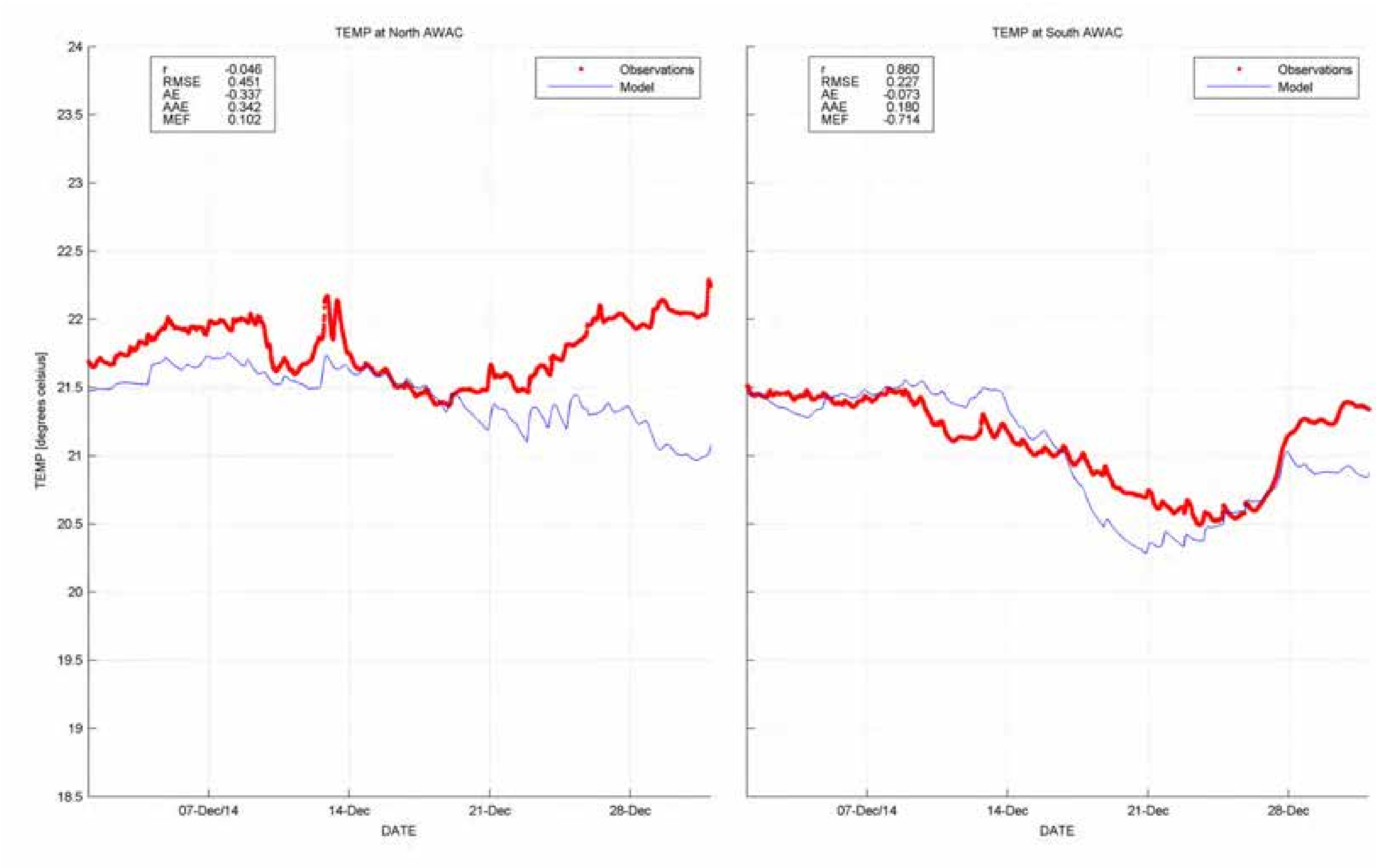

Figure B-35 Time-series of seabed temperature at northern regional site – December 2014

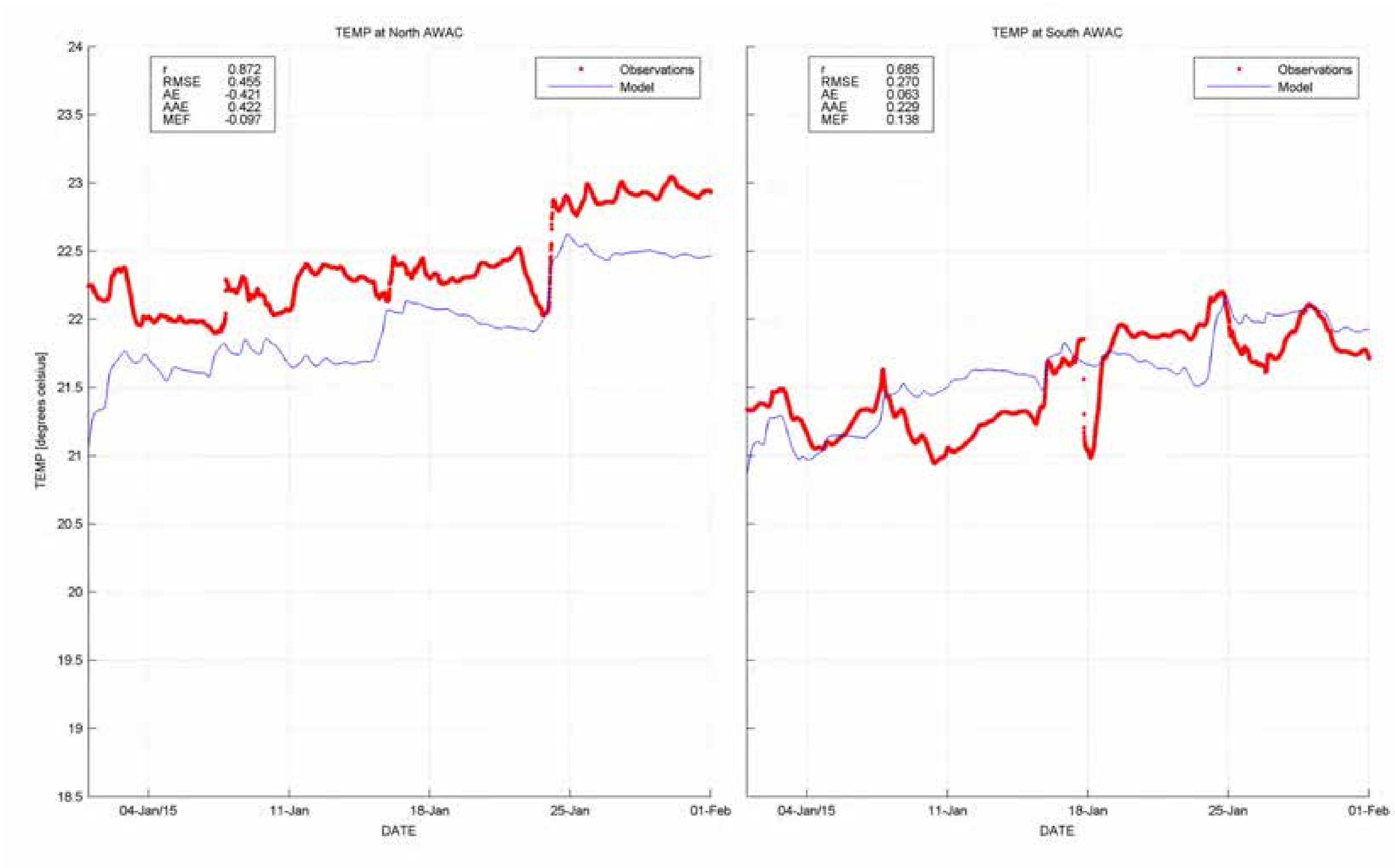

Figure B-36 Time-series of seabed temperature at northern regional site – January 2015

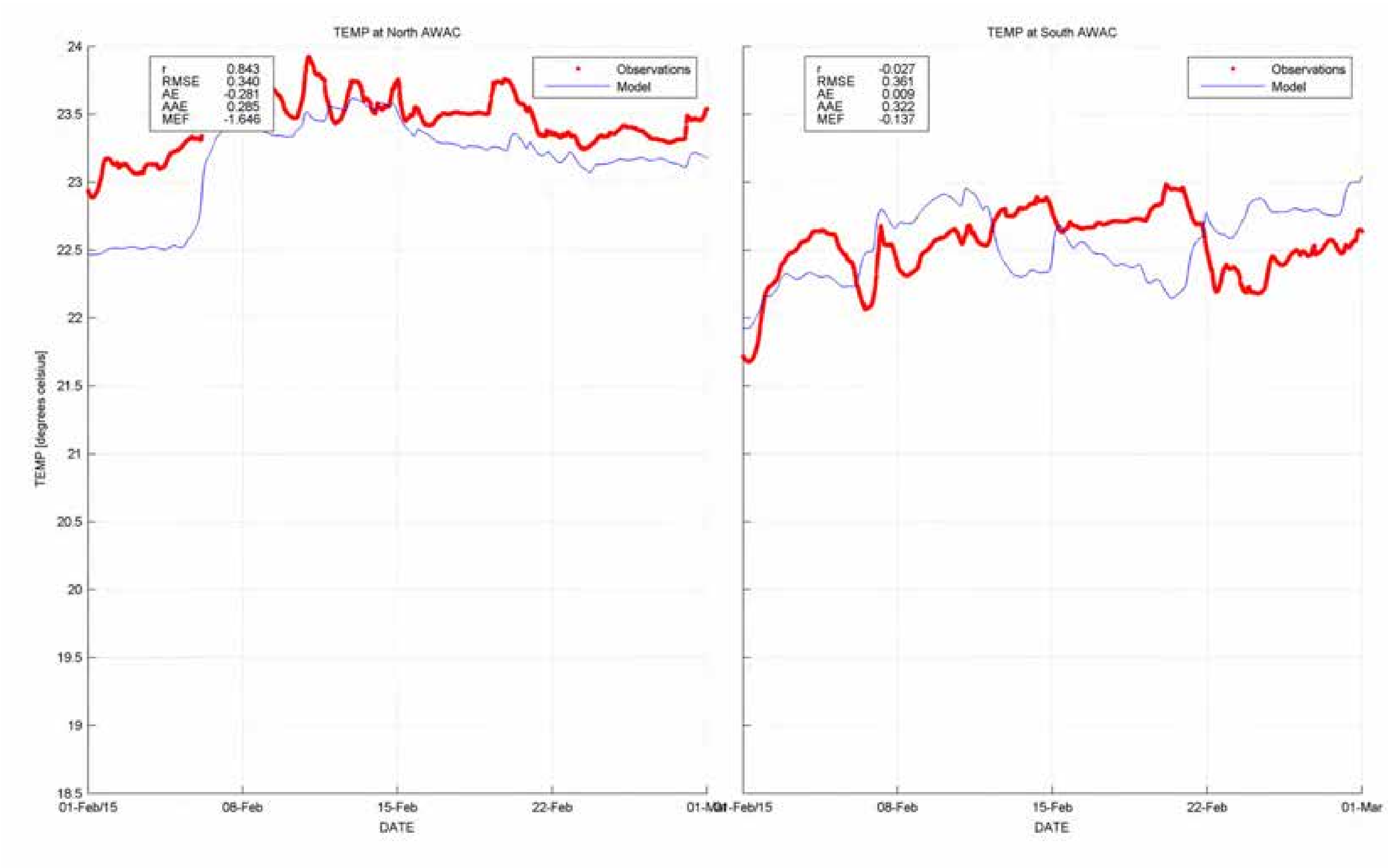

Figure B-37 Time-series of seabed temperature at northern regional site – February 2015

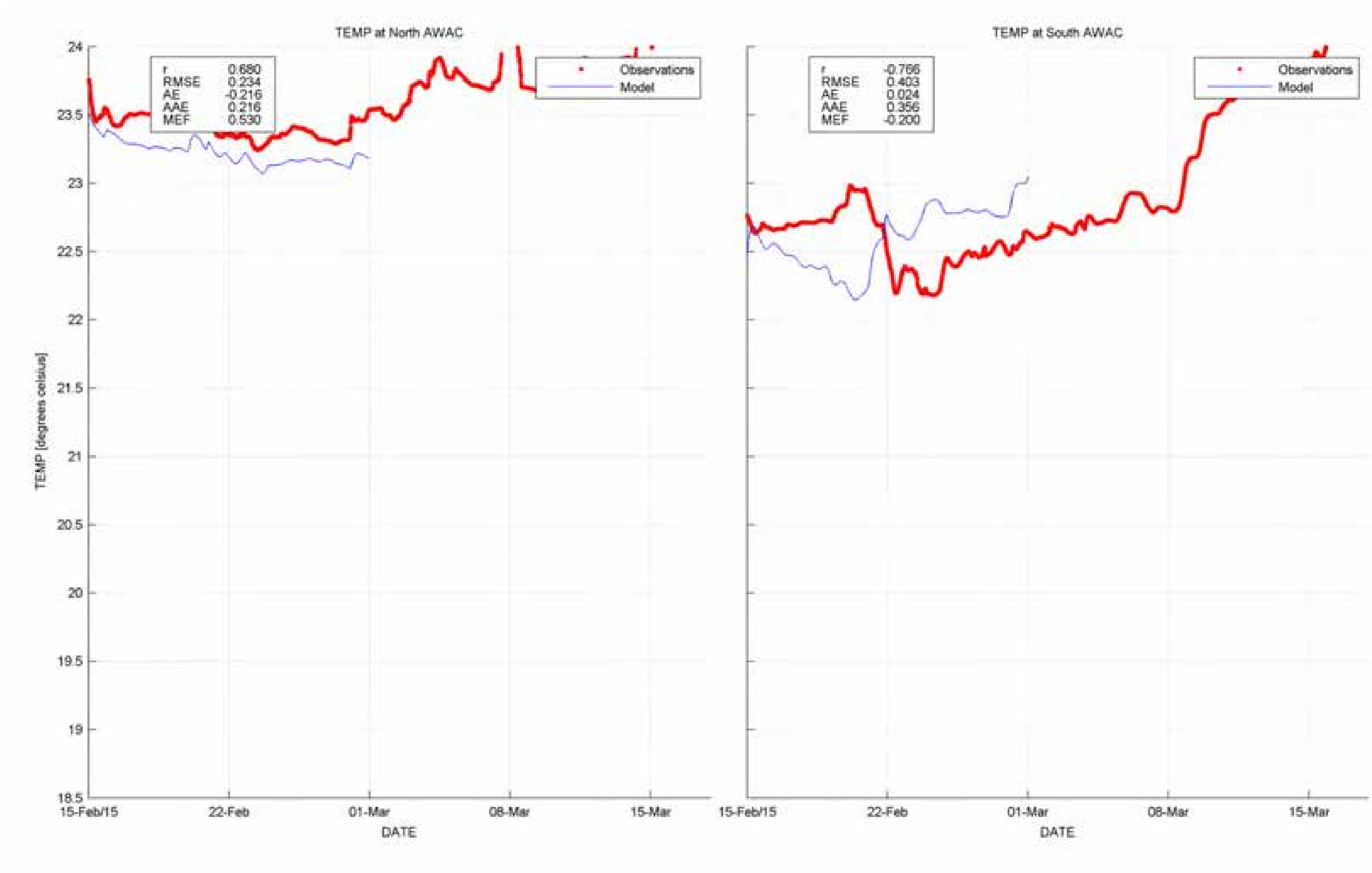

Figure B-38 Time-series of seabed temperature at northern regional site – March 2015

B.4 Waves

Additional calibration plots for the SWAN wave model are included in this section for the period 19th November 2014 to 1st January 2015. Comparisons of significant wave height, peak wave period and wave direction at the regional sites are presented in Figure B-39, Figure B-40 and Figure B-41, respectively.

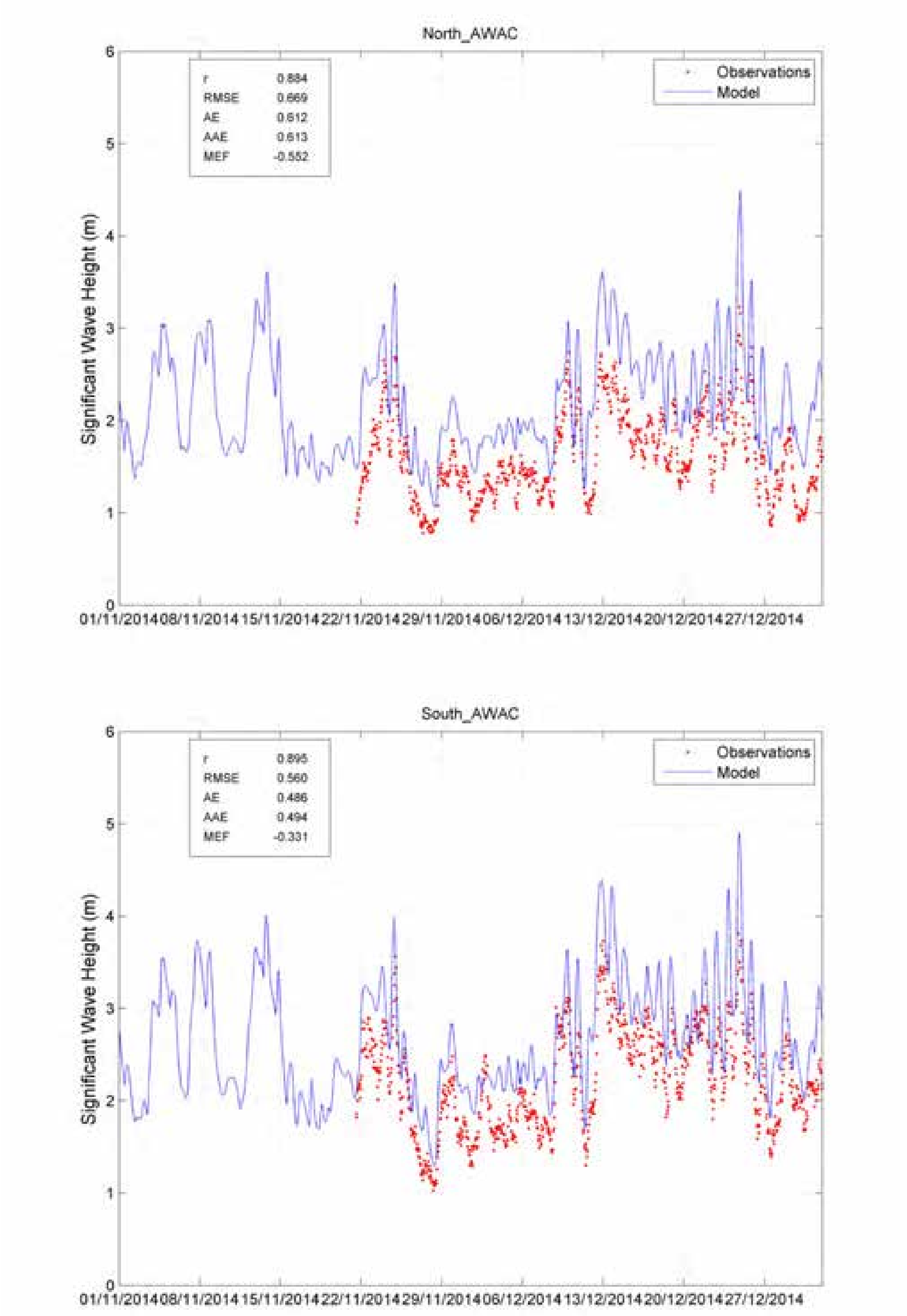

Figure B-39 Significant wave height at regional sites – Nov 2014 to Mar 2015 deployment

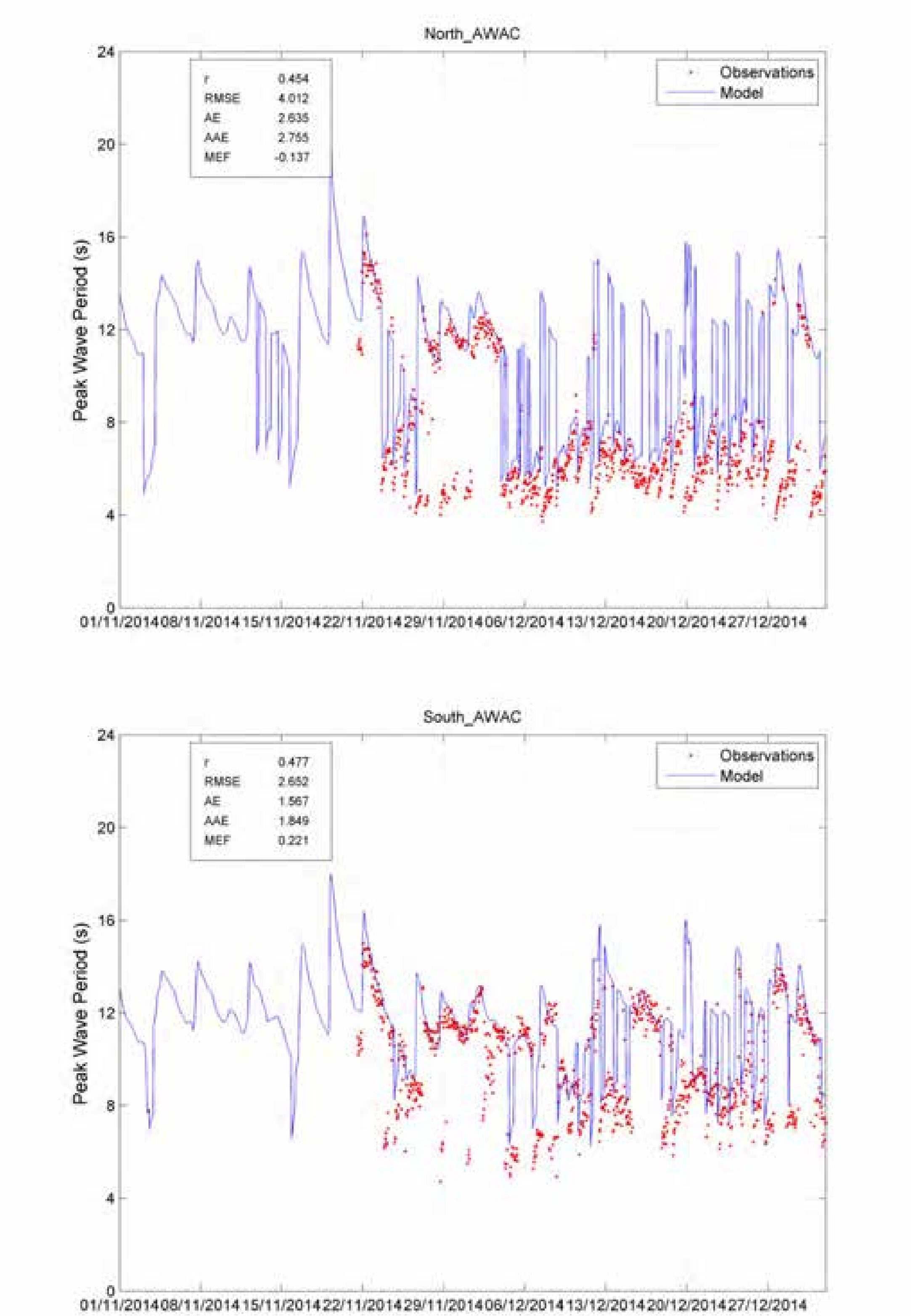

Figure B-40 Peak wave period at regional sites – Nov 2014 to Mar 2015 deployment

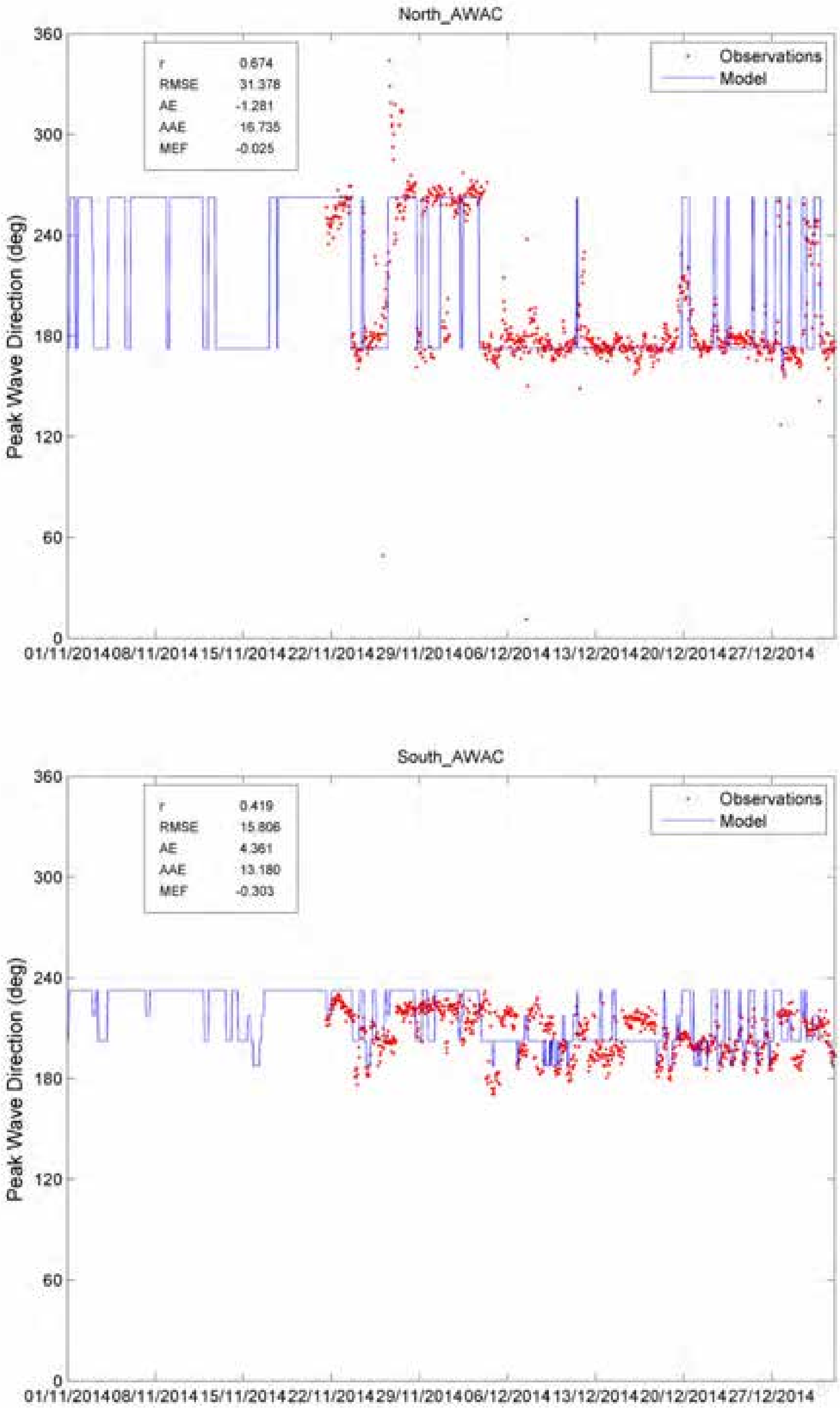

Figure B-41 Wave direction at regional sites – Nov 2014 to Mar 2015 deployment

BMT WBM Bangalow	6/20 Byron Street, Bangalow 2479 Tel +61 2 6687 0466 Fax +61 2 66870422 Email bmtwbm@bmtwbm.com.au Web www.bmtwbm.com.au
BMT WBM Brisbane	Level 8, 200 Creek Street, Brisbane 4000 PO Box 203, Spring Hill QLD 4004 Tel +61 7 3831 6744 Fax +61 7 3832 3627 Email bmtwbm@bmtwbm.com.au Web www.bmtwbm.com.au
BMT WBM Denver	8200 S. Akron Street, #B120 Centennial, Denver Colorado 80112 USA Tel +1 303 792 9814 Fax +1 303 792 9742 Email denver@bmtwbm.com Web www.bmtwbm.com
BMT WBM London	International House, 1st Floor St Katharine's Way, London E1W 1AY Email london@bmtwbm.co.uk Web www.bmtwbm.com
BMT WBM Mackay	PO Box 4447, Mackay QLD 4740 Tel +61 7 4953 5144 Fax +61 7 4953 5132 Email mackay@bmtwbm.com.au Web www.bmtwbm.com.au
BMT WBM Melbourne	Level 5, 99 King Street, Melbourne 3000 PO Box 604, Collins Street West VIC 8007 Tel +61 3 8620 6100 Fax +61 3 8620 6105 Email melbourne@bmtwbm.com.au Web www.bmtwbm.com.au
BMT WBM Newcastle	126 Belford Street, Broadmeadow 2292 PO Box 266, Broadmeadow NSW 2292 Tel +61 2 4940 8882 Fax +61 2 4940 8887 Email newcastle@bmtwbm.com.au Web www.bmtwbm.com.au
BMT WBM Perth	Level 3, 20 Parkland Road, Osborne, WA 6017 PO Box 1027, Innaloo WA 6918 Tel +61 8 9328 2029 Fax +61 8 9486 7588 Email perth@bmtwbm.com.au Web www.bmtwbm.com.au
BMT WBM Sydney	Level 1, 256-258 Norton Street, Leichhardt 2040 PO Box 194, Leichhardt NSW 2040 Tel +61 2 8987 2900 Fax +61 2 8987 2999 Email sydney@bmtwbm.com.au Web www.bmtwbm.com.au
BMT WBM Vancouver	Suite 401, 611 Alexander Street Vancouver British Columbia V6A 1E1 Canada Tel +1 604 683 5777 Fax +1 604 608 3232 Email vancouver@bmtwbm.com Web www.bmtwbm.com