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Modelling of oceanographic variables for the development of additional finfish aquaculture in Spencer Gulf

Mark J. Doubell, Charles E. James and John F. Middleton

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EXECUTIVE SUMMARY

This report uses oceanographic models to provide estimates of the variability of physical, chemical and biological oceanographic variables in Spencer Gulf relevant to the sustainable development of Yellowtail Kingfish (YTK) aquaculture proposed for the Wallaroo and Boston Bay aquaculture zones. Model output of these parameters was requested by Clean Seas Tuna Ltd. (CS) to assist in the identification of sites and production strategies defined by a change in the maximum on site biomass from 20 to 28.75 t/ha of YTK. Using a validated coupled hydrodynamic-wave-biogeochemical model, information on changes in the spatial and temporal distribution of temperature, currents, circulation, waves, nutrients and phytoplankton are presented at the scale of the Gulf, regions and lease sites. The modelling approach allows for a holistic understanding of the interaction of ocean ecosystem dynamics with proposed aquaculture developments. In particular, modelling scenario studies integrate the effects of realistic hydrodynamics on the assimilative capacity of the pelagic ecosystem. Model output is used to compare and understand the potential cumulative effect of dissolved inorganic nitrogen inputs (i.e. ammonium) from existing and proposed YTK leases, as well as other major sources, on water quality in Spencer Gulf.

For the Boston Bay region seasonal changes in temperature of up to 9 ^{o}C were modelled across the year. Temperature differences of up to 1.5 ^{o}C occurred between the three proposed sites during the warmer months. These variances are driven by local circulation features and include differences in flushing and connectivity with offshore waters. In particular, the sheltered location of Site 2, inshore of Boston Island, was characterised by relatively weak currents with mean and maximum speeds of approximately 0.02 and 0.10 m/s and low wave activity with mean and maximum significant wave heights less than 0.32 and 1.16 m, respectively. Nutrient concentrations under the proposed feeding strategies were predicted to be increased by up to a factor of 10 during peak feeding periods. However, phytoplankton biomass levels largely remained within the levels of intra-annual variability simulated under the control study which is assumed to be representative of the status quo.

For the Wallaroo region, changes in temperatures of up to 12 ^{o}C were modelled across the year. Temperature differences of less than 1.0 ^{o}C were predicted between the three proposed sites. The region experiences strong currents dominated by the tides with mean and maximum current speeds across the sites ranging between approximately 0.20-0.25 and 0.60-0.70 m/s, respectively. Proposed sites experience increased wave activity relative to sites located in

Boston Bay. Mean and maximum significant wave heights were approximately 0.80 and 2.4 m, respectively. Nutrient emissions at proposed lease sites were found to be strongly modulated by the tides and showed high variability over the tidal cycle, with peak concentrations in nutrients and phytoplankton occurring during high and ‘dodge’ neap tides. In comparison with the control study, hourly averaged nutrient and chlorophyll concentrations during the summertime peak feeding period were increased by factors of approximately 10 and 2, respectively. Tidal mixing acted to periodically lower concentrations of ammonium and chlorophyll to levels consistent with the control study. All modelled ammonium levels remained below the recommended ANZECC/ARCMANZ (2000) guideline levels for marine waters.

By simulating the major physical and biological factors controlling water quality, this modelling study provides an estimate of the concentration of nutrients and water quality associated with multiple nutrient sources including the introduction of proposed YTK aquaculture. Notwithstanding the demonstrated validation of the nutrient and phytoplankton components of the biogeochemical model (Doubell et al. 2013) our understanding of Spencer Gulf’s ecological and biogeochemical processes is limited. Important ecosystem components (e.g. macroalgae, sea grasses) and other factors such as nutrient co-limitation (van Ruth and Doubell 2013) which are not included in the model may also moderate, or be affected by, anthropogenic nutrient emissions.

The results for each of the biogeochemical model scenario studies have been included in an update of the CarCap software for use by PIRSA Fisheries and Aquaculture in assessing the location and production strategies of the proposed finfish aquaculture sites. The CarCap software allows managers to assess the transport pathways and concentrations of nutrients and phytoplankton across a range of spatial and temporal scales and to relate these concentrations, through estimates of flushing times (Middleton et al. 2013, Middleton and Doubell 2014), to feed levels relative to published (ANZECC/ARCMANZ 2000) or user-defined water quality guidelines. An understanding of the appropriate water quality triggers/guidelines relative to ecosystem health and function in Spencer Gulf has yet to be determined.

1. INTRODUCTION

1.1. Background

The sustainable development of supplementary-fed, sea-cage based, finfish aquaculture in Spencer Gulf requires information on the interaction of aquaculture activities with the marine environment. Natural environmental variability is of direct relevance to finfish aquaculture and strongly influences aquaculture productivity (e.g. temperature effects on fish growth rates) and the capacity of marine ecosystems to assimilate additional nutrient inputs arising from such anthropogenic sources as those emitted from supplementary fed finfish aquaculture (Olsen and Olsen 2008).

Clean Seas Tuna Limited (hereafter CS) seeks to expand its production of Yellowtail Kingfish (YTK). Specifically, CS wants to increase YTK aquaculture biomass in Boston Bay from 20 t/ha to 28.75 t/ha. Additionally, the Wallaroo aquaculture zone is being investigated for its potential for YTK aquaculture. Of particular concern is the potential cumulative impact of nutrient emissions arising from finfish aquaculture, and other sources, on coastal water quality and the ecosystem. Modelling work in Boston Bay has indicated reduced flushing relative to other regions of the Gulf (Middleton et al. 2013, 2014) which may influence the assimilative capacity of the ecosystem and hence limit the nutrient load sourced from supplementary feed. In contrast, the Wallaroo aquaculture zone is characterised by elevated flushing due to strong currents and increased wave activity. These characteristics suggest the Wallaroo region may have an increased capacity to absorb the impact of nutrient inputs from aquaculture. However, the area within and surrounding the zone supports significant seagrass meadows (*Posidonia* and *Halophila* species) which are potentially sensitive to nutrient inputs (Burkholder 2007).

Coastal systems receive nutrient inputs from a range of natural and anthropogenic sources. Typically, nitrogen is considered the key nutrient which limits plant growth in many temperate coastal marine systems (Nixon 1995, Howarth and Marino 2006) including Spencer Gulf (van Ruth and Doubell 2013). However, when the cumulative nutrient load exceeds the assimilative capacity of ecosystems the effects of eutrophication may lead to environmental degradation. Approximately 80% of the nitrogen supplied as a part of supplementary fed finfish aquaculture is released as dissolved inorganic nutrients (mainly ammonium; NH_4). The remaining fraction released as particulate and dissolved organic nutrients (Fernandes et al. 2007, Fernandes and Tanner 2008). The majority of the nutrient load from finfish aquaculture is released into the water column in the dissolved form. Dissolved nutrients are then typically transported and diluted by currents and mixing processes. Consequently, the effects of dissolved nutrients on marine ecosystems typically occur away from the source. Marine ecosystems absorb the impact of nutrient inputs through two main mechanisms; (i) dilution driven by hydrodynamics (Middleton and Doubell 2014) and (ii) the assimilation and cycling of nutrients through the pelagic food web (Olsen and Olsen 2007, Doubell et al. 2013). Oceanographic models, therefore, provide a useful tool to estimate the cumulative effects of multiple nutrient sources on water quality across a range of spatial and temporal scales.

The South Australian Research and Development Institute (SARDI) has developed and validated a suite of oceanographic models for Spencer Gulf including hydrodynamic, wave and biogeochemical models (Middleton et al. 2013). All models provide simplified representations of complex systems and are bounded by assumptions and limitations. For example, phosphorus has been shown to potentially limit phytoplankton growth at times in Spencer Gulf (van Ruth et al. 2013). The dynamics and effects of nitrogen-phosphorus co-limitation are not well understood and not represented by the current biogeochemical model. Despite the limitations of the current model, validation against *in situ* datasets (Doubell et al. 2013) has shown the coupled modelling system is capable of accurately reproducing the general distribution of currents, waves and hydrographic properties (e.g. temperature). For nutrients and phytoplankton, hourly averaged model predictions of dissolved inorganic nitrogen and chlorophyll concentrations were found to be predictable to within a factor of 2.

The oceanographic modelling suite has been applied successfully to understand water quality issues and the overall carrying capacity of the Spencer Gulf marine system (Middleton et al. 2013). Importantly, the predictive capabilities of the coupled model are comparable with similar models used nationally and internationally for understanding nutrient cycling (Fennel et al. 2006) and assessing the expansion of supplementary fed aquaculture in coastal ecosystems (Wild-Allen et al. 2009). Key findings of modelling studies in Spencer Gulf (Doubell et al. 2013) were the importance of both physical and biological processes for the sustainable development of finfish aquaculture. Hydrodynamic modelling demonstrated the spatial variability and importance of tidal currents in Spencer Gulf for flushing and diluting nutrient sources (Middleton and Doubell 2014, Middleton et al. 2014). Biogeochemical modelling indicated the largest source of nutrients into the Gulf was natural exchange processes with adjacent shelf waters (Doubell et al. 2013). An understanding of the annual variability of nutrient supply from the shelf is yet to be determined. Model scenario studies also indicated denitrification may mitigate the effects of up to a 5-fold increase in the annual finfish aquaculture production in Spencer Gulf. For all model scenarios, water quality levels for dissolved inorganic nitrogen were within the ANZECC/ARMCANZ (2000) water quality guideline values.

This report outlines the results of new modelling scenario studies using the validated Spencer Gulf model. The modelling work assumes the same hydrodynamics as the 2010/11 year. The model has been updated to include 2012-13 Southern Bluefin Tuna (SBT) lease locations and associated nutrient inputs which were estimated from monthly feed data provided by PIRSA Fisheries and Aquaculture. Recent (2013/14) monthly feed data for YTK farming located near Boston Bay was provided by CS. A second scenario study is used to examine the potential cumulative effect of nutrient loads related to new feeding schedules proposed for YTK farms in the Wallaroo and Boston Bay aquaculture zones. Predictions of physical, chemical and biological parameters from the model relevant to the proposed aquaculture production are presented across a range of spatial and temporal scales. Finally, model results detailing the spatial and temporal variability in the concentration of key water quality variables have been included into an update of the CarCap software for use by PIRSA Fisheries and Aquaculture to assist in the spatial planning and management of aquaculture in Spencer Gulf.

1.2. Objectives

CS sought advice to assist in determining the suitability of proposed lease sites and associated production strategies, including modelling data to describe:

1. Variation in the physical oceanographic environment (e.g. temperature, waves, currents and flushing).
2. The potential cumulative impact of nutrient emissions arising from supplementary-fed finfish aquaculture and other activities on water quality.

To achieve the above, several scenario studies were undertaken using the validated Spencer Gulf hydrodynamic-biogeochemical model (SGM) of Middleton et al. (2013). Information from the modelling studies is used to provide:

I. Estimates of the spatial distribution of temperature, in the form of time averaged maps of surface water temperature, in the Boston Bay and Wallaroo regions. These are provided as images and as a video animation.

II. Time-series of hourly estimates of temperature, currents (speed and direction) and 3-hourly estimates of waves (height, period, direction, orbital velocities) at proposed lease sites in the Boston Bay and Wallaroo aquaculture zones.

III. Predictions of concentrations of key water quality parameters (i.e. ammonium and chlorophyll) associated with finfish aquaculture and their regional connectivity.

IV. Update of the 'CarCap' software provided to PIRSA to include the above scenario studies. This information will be used by PIRSA to assist in the assessment of aquaculture carrying capacity and optimal feed loads relative to ANZECC, or alternative water quality guideline values.

This report provides a holistic view of the major physical and biogeochemical dynamics of Spencer Gulf most relevant to finfish aquaculture. As requested by CS a summary of the model predictions is presented for variables which have been validated and have shown good predictive ability. To achieve this, temporal variations in the value/concentrations of relevant key variables are reported at the scale of the Gulf, greater regional area surrounding aquaculture zones and the scale of individual lease sites.

2. METHODS

Ocean models have become standard tools for achieving best practice marine resource management (e.g. Wild-Allen 2009). This chapter describes a brief overview of the Spencer Gulf models used in this report. A robust validation of each of the models is presented in Middleton et al. (2013). Importantly, the essential physical processes which ultimately influence circulation, flushing and the distribution of physical (e.g. temperature), chemical (e.g. nutrients) and biological properties (e.g. phytoplankton biomass), and the assimilative capacity of the pelagic ecosystem, have been shown to be accurately simulated for the period from July 1, 2010 to June 30, 2011.

To provide an update of the assimilative capacity of marine ecosystems and their holistic influence on water quality levels in the Gulf two new model scenario studies were run. Each scenario study assumed the same hydrodynamics as previously validated for the 2010/11 period. This assumption is not unreasonable because tidal currents vary little on an inter-annual basis and generally dominate horizontal diffusion. Moreover, inter-annual variability in the seasonal circulation and temperature is also expected to be small (Middleton et al. 2013).

The first control scenario study was run to include updated (2012-2013) SBT monthly feed/nutrient data provided by PIRSA Fisheries and Aquaculture. Nutrient inputs from other industry sources (i.e. wastewater treatment plants and the Onesteel steelworks) were assumed to be the same as the 2010/11 period.

A second comparative scenario study was run to assess the potential impact of nutrient emissions arising from new feed schedules proposed for YTK in the Boston Bay and Wallaroo aquaculture zones. For each region, the proposed feeding schedules are based on 3-year production strategies spread across three leases to allow for fallowing. Moreover, the proposed feeding schedules assume the biomass on an individual lease can reach a maximum of 28.75 t/ha, with the total finfish biomass remaining within 1650 t zone limit. This presents a shift in stocking from the existing PIRSA policy which only permits the maximum biomass to reach 20 t/ha (normally 15 t/ha without an exemption) at an individual site.

The hydrodynamics for each successive year of the model run across the 3-year production strategy were assumed to be the same as the 2010/11 year. Hence, changes in the predicted concentration of water quality variables are solely due to biogeochemical processes.

2.1. Hydrodynamic model

Circulation in Spencer Gulf was simulated using the Regional Ocean Modelling System (ROMS; myroms.org). ROMS is the *de facto* standard in coastal modelling and is a full 3-dimensional ocean model (Schepetkin and McWilliams, 2005). The ROMS Spencer Gulf model (SGM) has a horizontal grid spacing of 1200 m and 7 vertical layers. A time step of 150 seconds allowed the model to solve the dominant tidal currents in the Gulf. Conditions for velocity, temperature, and salinity at the open boundaries were obtained from the output of a large-scale regional model, the South Australian Regional Ocean Model (SAROM). All model domains contain Spencer Gulf and the adjoining shelf, from which oceanographic data for validation are obtained (Figure 2.1.1).

Tidal forcing was imposed at the open boundaries of each model and values for the tidal constants were obtained from the latest version of the TPXO tide model (Egbert et al. 1994). Bureau of Meteorology "ACCESS" atmospheric model data are used for forcing the hydrodynamic model. The vertical eddy viscosity and diffusivity were computed using the Mellor-Yamada 2.5 level turbulence closure scheme and the horizontal eddy viscosity and diffusivity were set to 20 $m^2 s^{-1}$ and 1 $m^2 s^{-1}$, respectively.

The SGM open boundary conditions were pushed towards SAROM model values to keep the boundary conditions close to long-term values of the open ocean while allowing the Gulf interior to evolve independently. Boundary 'nudging' coefficients decreased linearly from a 3-day timescale at the boundary to 30 days 5 grid points from the boundary (and were zero beyond that). SGM initial conditions of temperature and salinity were determined from SAROM.

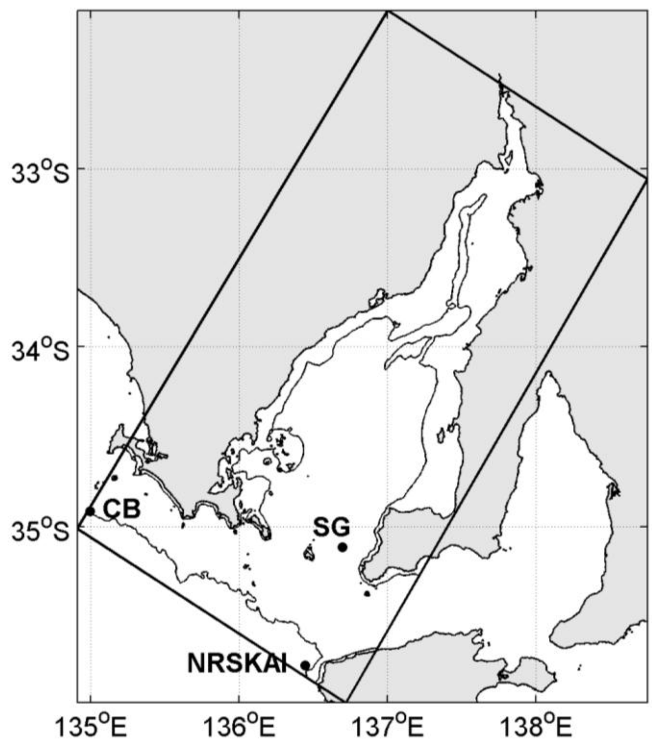

Figure 2.1.1. Aerial extent of Spencer Gulf model domain. The SAIMOS mooring locations used for validation of the hydrodynamic model are indicated for Coffin Bay (CB), Spencer Gulf (SG) and Kangaroo Island (NRSKAI). Nutrient and chlorophyll data from the NRSKAI and CB sites were used to form boundary conditions for the biogeochemical model. The 20 and 100 m depth contours are plotted.

2.2. Waves model

The Simulating Waves Near-shore (SWAN) model (Booij et al. 1999) used in this study was coupled to the hydrodynamic SGM. SWAN computes the significant wave height and peak wave characteristics (direction, period and wavelength), wave dissipation and bottom orbital velocities, which in turn modify the hydrodynamic results. Surface winds from the Bureau of Meteorology (BoM) and time-series of oceanic swell are used to drive the model. The swell data are obtained from the global NOAA/NCEP Wavewatch III model (Alves et al. 2005) and used to force SWAN at the open boundary of the SGM as shown in Figure 2.1.1. Wave model results obtained for July 2010 to June 2011 have shown a strong agreement with *in situ* wave measurements taken in lower and upper Spencer Gulf (James et al. 2013).

2.3. Biogeochemical model

The ROMS open-source biogeochemical model developed by Fennel et al. (2006) was coupled to the hydrodynamic SGM. The model was developed to understand and quantify biogeochemical cycling in coastal systems (e.g. Fennel et al. 2006, Bianucci et al. 2012) and has been tuned and validated for the Spencer Gulf environment following extensive field studies (Doubell et al. 2013, van Ruth and Doubell 2013). The model is a representation of the pelagic nitrogen cycle (Figure 2.3.1) and includes seven state variables; dissolved inorganic nitrogen (DIN), nitrate (NO_3), ammonium (NH_4), phytoplankton (P), zooplankton (Z), small detritus (D_s) and large detritus (D_L). The model also tracks dissolved oxygen (DO) and includes a sediment component which provides a representation of benthic microbial mineralization processes (Nixon and Pilson 1983). Benthic processes act to return a fraction of deposited particulate organic matter (detritus) to either the water column as an influx of ammonium or to the atmosphere through denitrification.

The model was first run for a 'spin up' period of one year commencing on 1 July using the nutrient loads estimated from 2012/13 SBT feed data and 2010/11 waste water treatment plants (WWTP) and Onesteel outputs. Initial values for each state variable were set to the final values (30 June) at the end of the 1 year hydrodynamic model run. Conditions for nutrients and chlorophyll along the southern and western model boundaries were assumed to be the same as the validated 2010/11 model and obtained from observations taken through the Southern Australian Integrated Marine Observing System (Doubell et al. 2013). Daily averaged values for each state variable output at the end of the 'spin up' simulation on 30 June were then used as the initial conditions for the control scenario study and the 1st year of the second scenario study simulation. For the second scenario study, all subsequent years of the model simulation used the final concentrations on 30 June as the initial conditions commencing on 1 July for the following years simulation. The proposed 3-year feed schedule undertaken in the second scenario study encompasses four June-to-July periods of model simulations. We assumed the proposed feeding schedule commenced in October 2012 and finishes in March 2016. SBT nutrient emissions were estimated from feed data provided by PIRSA Fisheries and Aquaculture for the period June 2012 to July 2013 and were repeated for each successive year of the simulations.

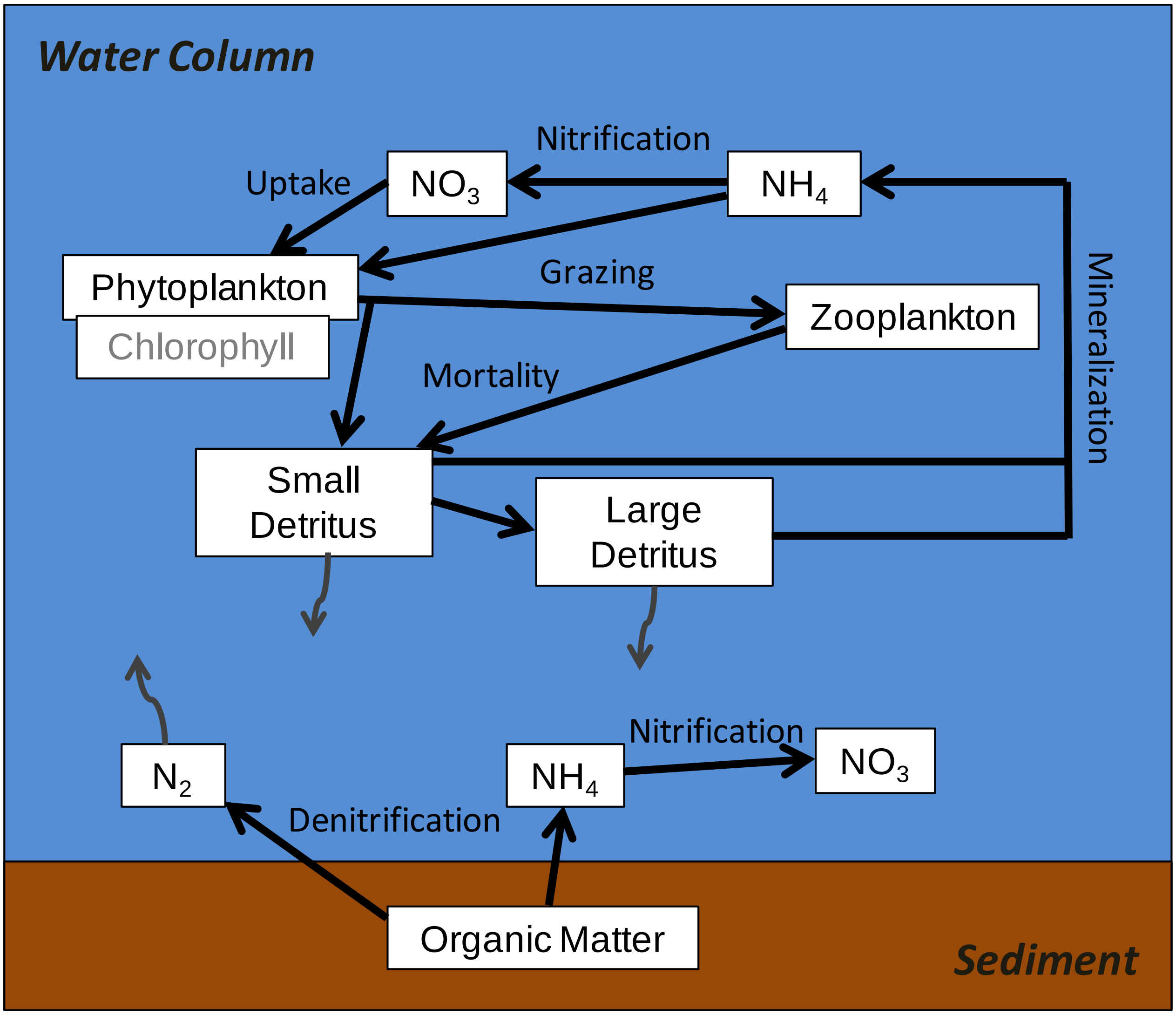

Figure 2.3.1. Schematic representation of the Fennel et al. (2006) biogeochemical model. The model is a representation of the pelagic nitrogen cycle using the state variables; nitrate (NO_3), ammonium (NH_4), phytoplankton (P), zooplankton (Z), small detritus (D_s) and large detritus (D_L). All state variables have common units (mmol N m^{-3}). The model also tracks phytoplankton chlorophyll (CHL) and dissolved oxygen (DO) and includes a sediment component. Microbial mineralization processes in the sediment return a fraction of deposited organic matter to the water column as an influx of ammonium, with the remainder lost (as nitrogen) to the atmosphere through nitrate reduction (denitrification).

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2.4. Anthropogenic nutrient sources

The model contains the major sources of anthropogenic nitrogen in Spencer Gulf (Gaylard 2014) including: nutrients inputs estimated from aquaculture supplementary feeds for baitfish and pellets, three SA Water WWTPs and the Onesteel steelworks (Figure 2.4.1). Aquaculture monthly feed data for individual leases for the 2012-13 periods were provided by PIRSA fisheries and Aquaculture. Feed data were converted into model units using the relationships given by Fernandes et al. (2007) for baitfish fed to Southern Bluefin Tuna (SBT) and Fernandes and Tanner (2008) for pellets fed to Yellowtail Kingfish (YTK). Feed nitrogen contents of 3.25% and 7.20% were used for baitfish and pellets, respectively. The amount of soluble nitrogen released from feeds was assumed to be 86% and 72% for SBT and YTK, respectively. As the soluble nitrogen released during farming is primarily the result of excretion, faecal leaching and sediment remineralization (Fernandes et al. 2007, Tanner et al. 2007) dissolved nitrogen inputs from aquaculture are assumed to be in the form of ammonium (Avnimelech 1999, Schendel et al. 2004, Olsen and Olsen 2008).

During 2012/13, SBT ranching was undertaken only within the Port Lincoln aquaculture zone. The centre point locations of SBT leases included in the modelling scenario studies are shown as blue circles in Figure 2.4.1. For the second scenario study, the locations of proposed lease sites for YTK in the Boston Bay and Wallaroo zones are shown as red circles in Figure 2.4.1. Nutrient emissions from SBT provide the largest source of anthropogenic nutrients emitted into the Gulf. Simulated nutrient loads associated with the 2012/13 SBT aquaculture and newly proposed YTK aquaculture are shown in Figure 2.4.2. Simulated total nutrient emissions from the SBT peak through the months of February to August of each year, while monthly nutrient emissions associated with YTK peaked from October to May each year. Maximum monthly loads from SBT are approximately 3-fold greater than those collectively from YTK. Nutrient loads from WWTPs and Onesteel were significantly smaller compared to those from aquaculture and contributed less than 10% of the annual anthropogenic load.

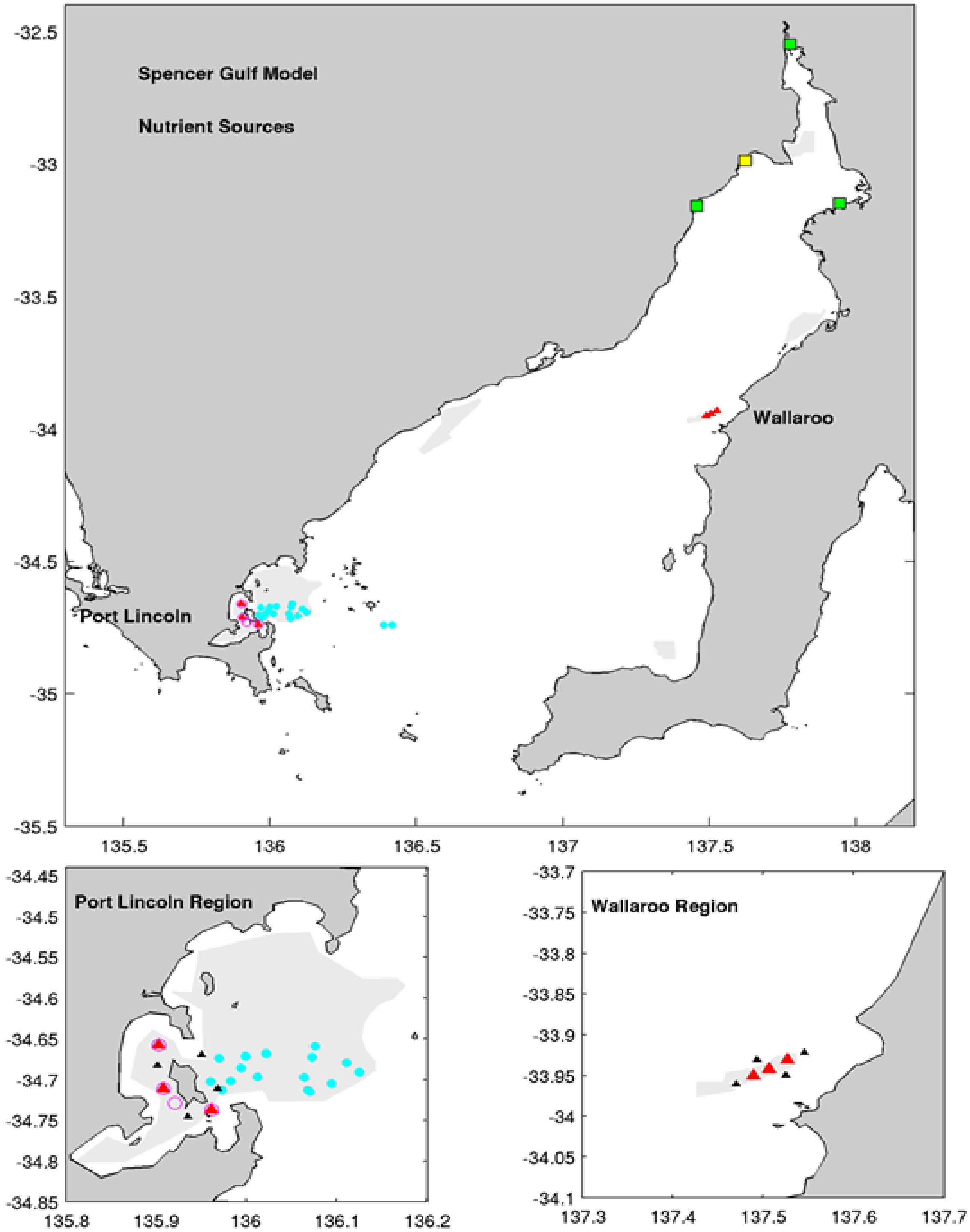
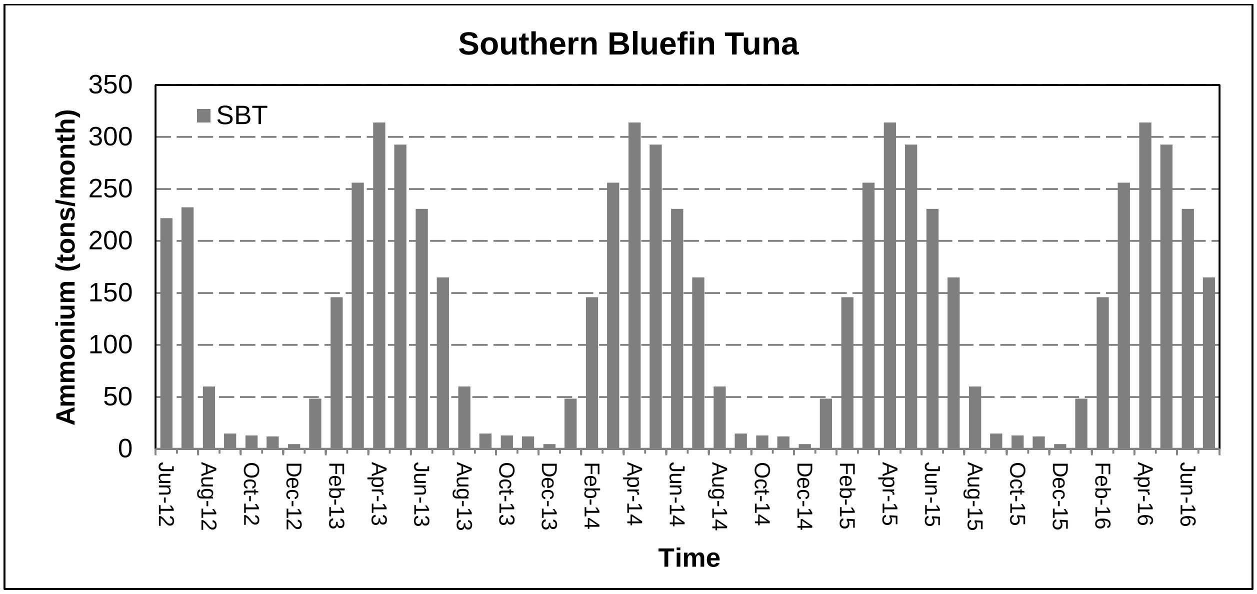


Figure 2.4.1. Map of Spencer Gulf showing the, (top) location of major anthropogenic nutrient sources including SBT lease sites (blue circles), current (magenta circles) and proposed YTK lease sites (red triangles) within aquaculture zones (grey shaded regions), wastewater treatment plants (green squares) and the Onesteel steel works (yellow square). (Bottom panels) Maps of the greater area surrounding the aquaculture zones of (left) Port Lincoln and (right) Wallaroo including the location of current (magenta circles) and proposed (red triangles) YTK lease sites and surrounding virtual monitoring stations (black triangles).



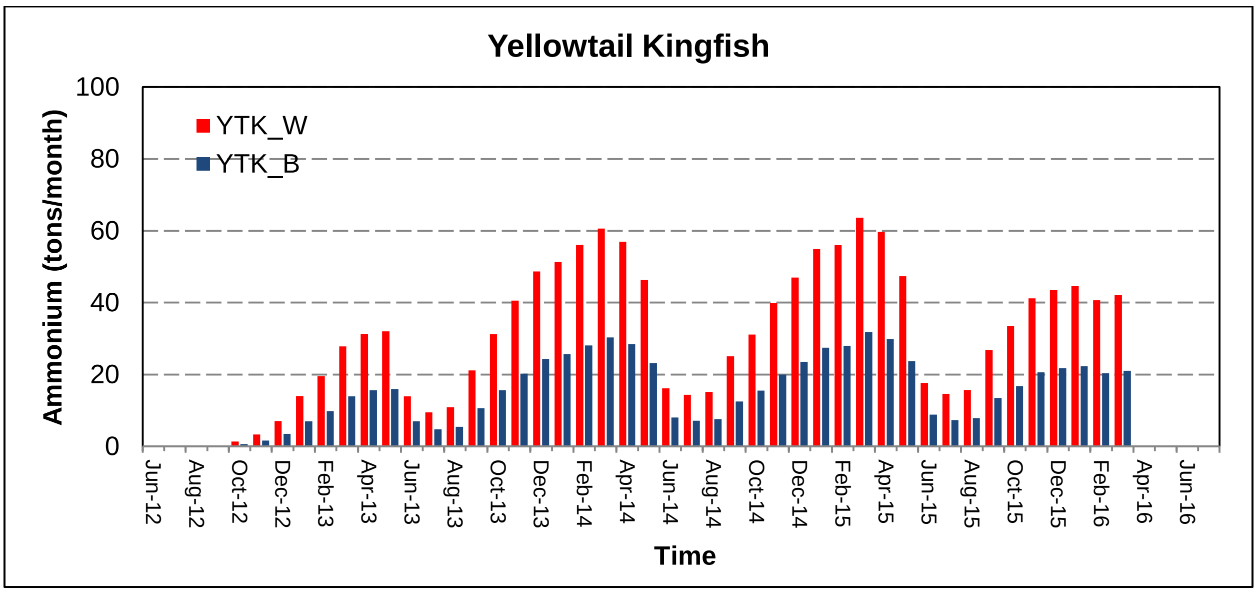


Figure 2.4.2. Estimated total monthly nutrients loads emitted from; (top) Southern Bluefin tuna aquaculture, (bottom) YTK leases in Wallaroo (red bars) and Boston Bay (blue bars) for the proposed 3-year feed schedule simulated in the second scenario study. The feed schedule undertaken in the second scenario study encompasses four June-to-July periods of model simulation. We assume the proposed feeding schedule commences in October 2012 and finishes in March 2016. Tuna emissions for June the 2012-to-July 2013 period are repeated for each successive year of the simulations.

3. RESULTS

3.1. Currents and Connectivity

3.1.1. Spencer Gulf Region

The annual circulation in Spencer Gulf is strongly influenced by seasonal weather variations. Throughout the year, evaporation exceeds precipitation across the Gulf leading to the formation of dense salty water in the shallow nearshore perimeter and upper half of the Gulf (Nunes and Lennon 1987). During summer, strong atmospheric heating and evaporation form warm, saline waters of a subtropical nature in the Gulf. Gulf waters remain largely separated from the cooler, fresher temperate continental shelf waters due to the formation of a front at the entrance to the Gulf (Petrusevics et al. 2011). Beginning in autumn and continuing through winter into early spring, atmospheric cooling and evaporation lead to the formation of cold, dense water. This dense water forms an outflow along the eastern side of the Gulf onto the shelf (Nunes Vaz et al. 1990). During the outflow, a corresponding inflow of relatively nutrient rich water occurs on the western side of the Gulf (Doubell et al. 2013).

The residual circulation within the Gulf is significantly influenced by the tides. Spencer Gulf experiences large sea-level displacements (1-2 m) and the resonant nature of the Gulf generates strong tidal currents of 0.5-1.5 m/s (Easton 1978). Spencer Gulf also experiences a 'dodge' neap tide where tidal amplitudes and associated velocities become very small approximately every 15 days. The tides are a major generator of strong horizontal mixing due to shear dispersion which significantly enhances the flushing and dilution of anthropogenic nutrients, such as those emitted from finfish aquaculture (Middleton and Doubell 2014, Middleton et al. 2014). Hydrodynamic models developed for the Gulf have good predictive ability for the tides (Herzfeld et al. 2009, Luick et al. 2013).

Wind-forced currents are important to transport, vertical mixing and current shear within the Gulf. It has been shown that seasonally varying mean winds can lead to currents that can largely modify and, at times, even cancel density currents (Bullock 1975, Nixon and Noye 1999). In addition, while mean wind-forced currents in the southern half of the Gulf may be small (~2 cm/s), they can be important to transport over longer time scales, with transport distances of 50 km expected on a monthly basis.

The seasonally forced horizontal variations in density described above lead to a general clockwise 'residual' circulation within the Gulf that is modulated by tidal and wind driven currents. Figure 3.1.1 shows the residual circulation patterns within the Gulf across the seasons. Mean residual current speeds (i.e. non tidal currents) are weak (typically in the order of 0.05 m/s). Common features of the surface circulation patterns throughout the year include a northward flow along the western side of the Gulf and southward return flow along the centre and lower eastern side of the Gulf. This circulation feature is most intense during cooler months (July, August, September; defined as the 1st Quarter in Figure 3.1.1) and weakest during warmer months (Jan, Feb, March; 3rd Quarter). During warmer months a northward wind-driven flow intensifies along the east coast of the Gulf. The northward inflow of waters from the shelf on the western side of the Gulf typically extends to Franklin Harbor and as far as Point Lowly in winter. This inflow is entrained into the outflow of dense water from northern Spencer Gulf and is subsequently drawn across into the central Gulf during warmer seasons and to the eastern side of the Gulf in cooler seasons.

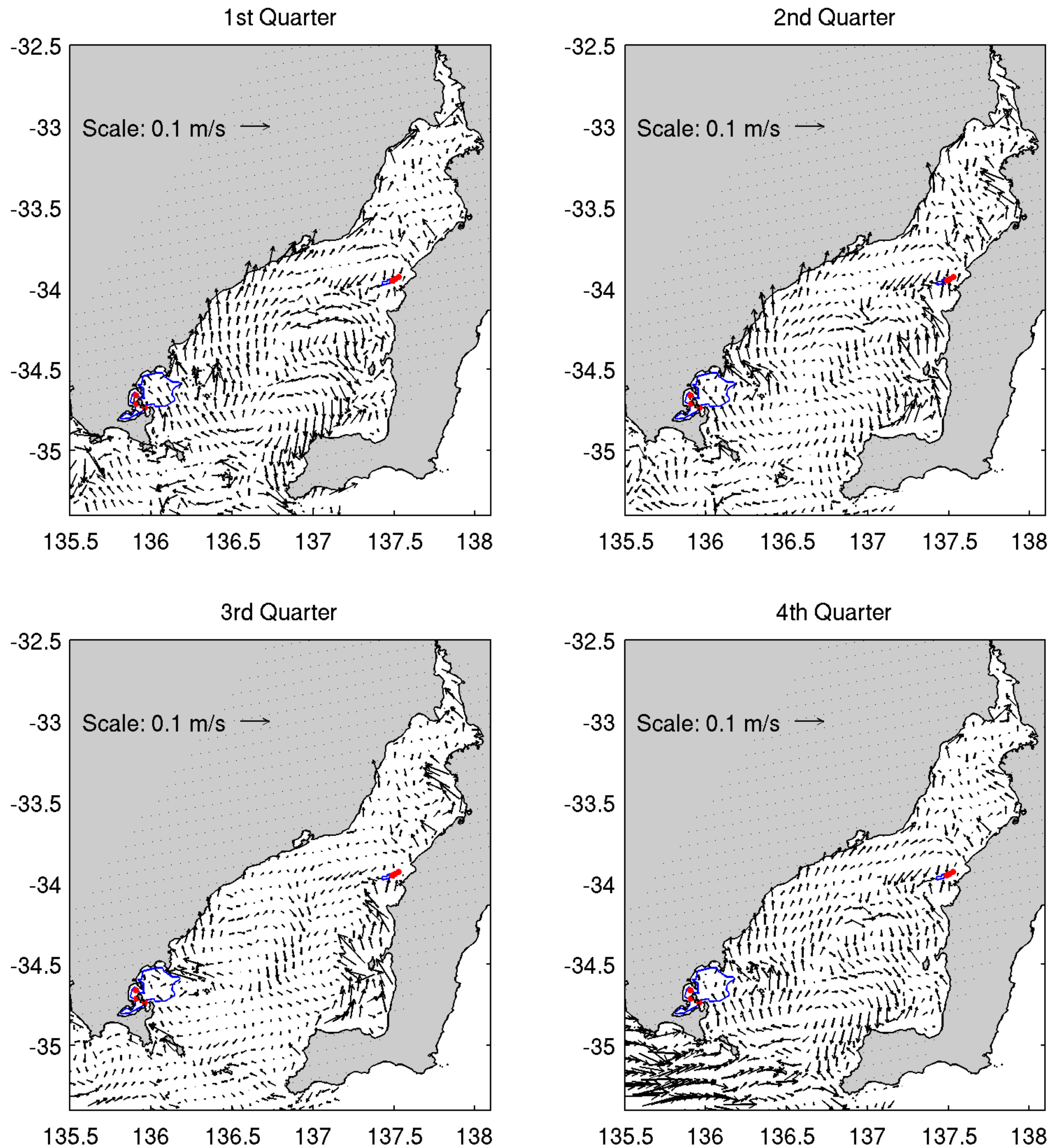


Figure 3.1.1. Mean depth-averaged oceanographic seasonal circulation pattern in Spencer Gulf for the 1st (July-August), 2nd (September-November), 3rd (December-March) and 4th (April-June) quarters of the hydrodynamic model run. Red circles show the location of proposed YTK lease sites within aquaculture zones (blue line) for each region.

3.1.2. Port Lincoln

Figure 3.1.2 shows the seasonal residual circulation in the Port Lincoln region. The inflow of water from the shelf is a persistent feature in offshore waters year round. Residual currents speeds reach up to 0.1 m/s offshore and, in part, drive an anticlockwise circulation of water around Boston Island. Inshore of Boston Island residual current speeds are reduced with a mean speed of approximately 0.01 - 0.02 m/s throughout the year. Flows to the north of Point Boston are generally into Louth Bay and show increased levels of seasonal variability in the magnitude and direction of currents relative to the currents in Boston Bay. Increased connectivity of waters from Boston Bay and from the shelf are observed with southern Louth Bay during spring and summer (2^{nd} and 3^{rd} quarters). This connectivity appears to be reduced during winter and autumn and shifts towards Peake Bay, particularly during winter (1^{st} quarter).

Figure 3.1.3 shows plots of current ellipses for each of the 3 new sites proposed in Boston Bay. The size of the current ellipse is proportional to the current strength and the alignment of the major axis indicates the direction of the dominant tidal flow at each site. For each site, the small black stick shows the direction of the mean residual current averaged over a model year. Mean and maximum current speeds at sites 1 and 3 are approximately 0.05 and 0.25 m/s, respectively. Compared to sites 1 and 3, lower currents speeds with mean and maximum values of approximately 0.02 and 0.10 m/s, respectively were modelled for site 2. Predicted directions for both the dominant currents (ellipses) and the residual current (black stick) across the three sites are consistent with the large-scale anticlockwise circulation observed around Boston Island (Figure 3.1.2). The reduced tidal currents for the area inshore of Boston Island result in a high flushing timescale of ~25 hours relative to waters further offshore and other regions within Spencer Gulf (Middleton et al. 2013, 2014).

Hourly predictions of current speed (m/s), direction (^{o}T) and the magnitude of both the east-west and north-south components the current are provided for each of the three proposed sites in an Excel file.

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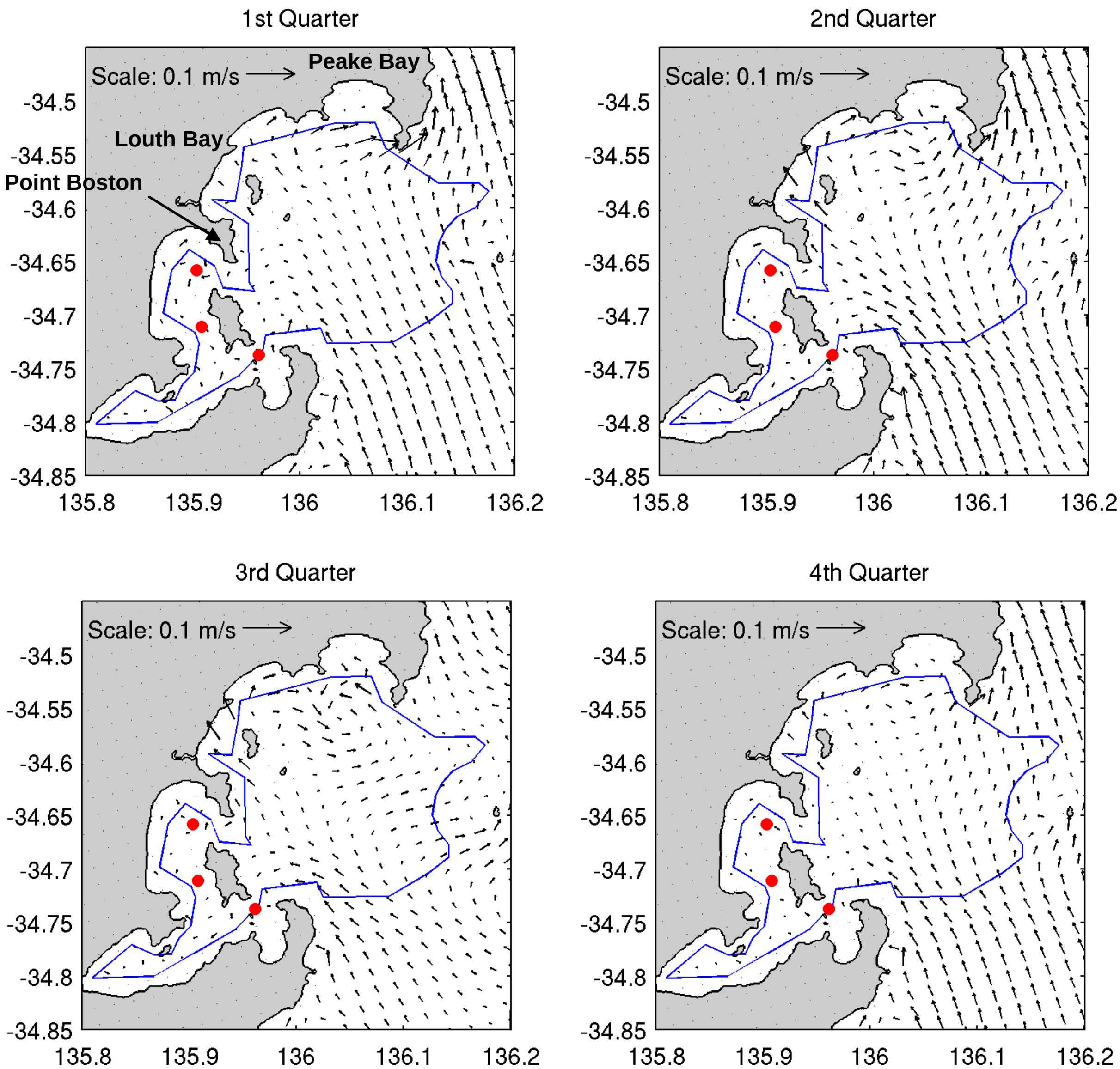

Figure 3.1.2. Zoom in of the mean depth-averaged oceanographic seasonal circulation pattern around Port Lincoln for the 1st (July-August), 2nd (September-November), 3rd (December-March) and 4th (April-June) quarters of the hydrodynamic model run. Red circles show the location of proposed YTK lease sites.

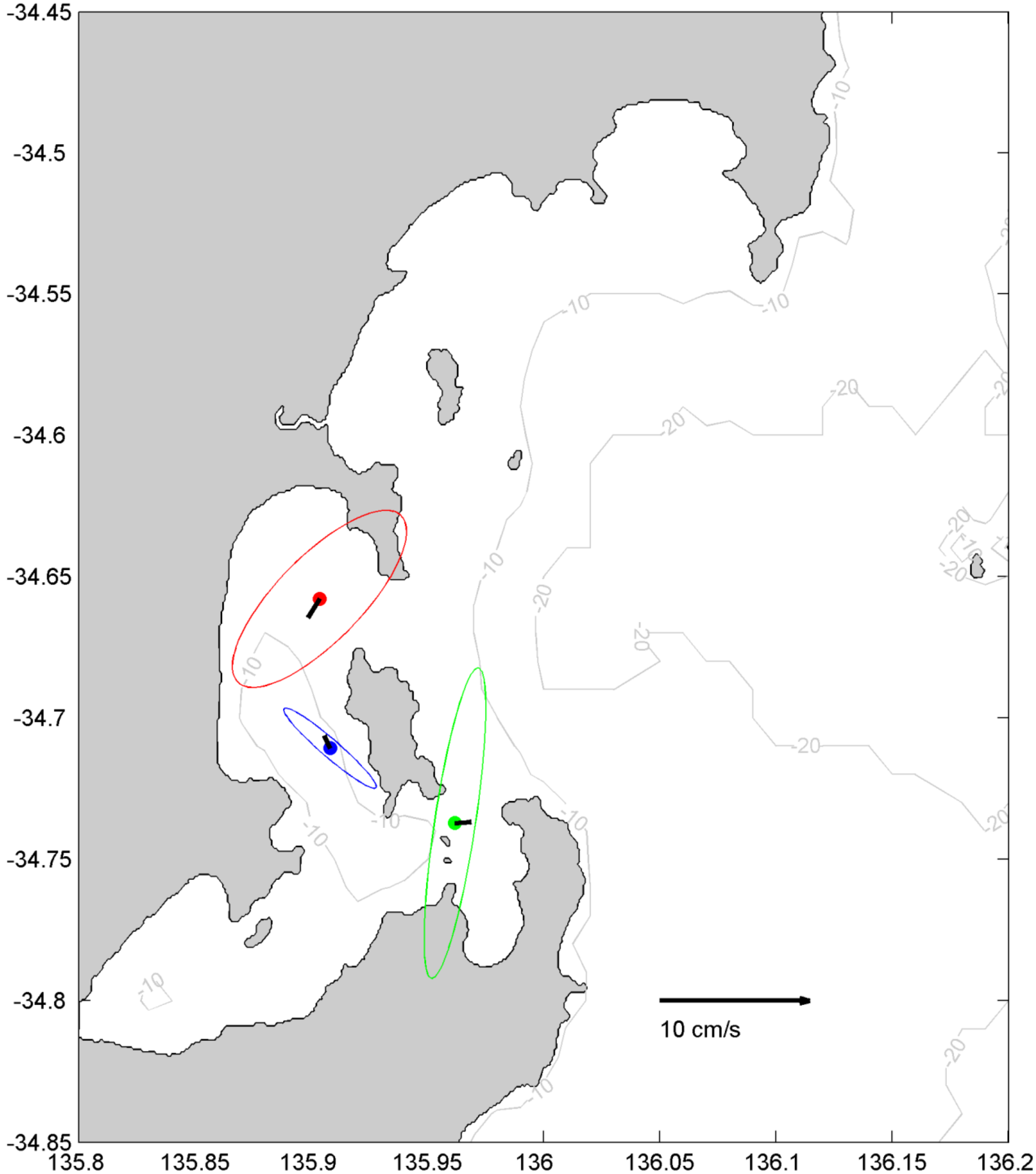

Figure 3.1.3. Surface current ellipses and residual current speed and direction (black tick) averaged over 1 year for each of the 3 new YTK sites proposed for Boston Bay; red ellipse (Site 1), blue ellipse (Site 2) and green ellipse (Site 3). The 10 and 20 m depth contours are plotted. Scale bar relates to the strength of dominant (ellipses) and residual (stick) currents.

3.1.3. Wallaroo Region

Figure 3.1.4 shows the seasonal residual circulation in the Wallaroo region. Similar circulation patterns are observed for each season. The patterns are characterised by a relatively strong (~0.1 m/s) northward flow along the shallow nearshore waters of the east coast. These coastal currents are steered westward by the headlands of Point Riley and Warburto Point, where they are then entrained into the offshore outflow of dense water from upper and western Spencer Gulf. This circulation gives rise to an anticlockwise eddy centred on the proposed lease sites where the residual currents are significantly reduced relative to the current speeds of approximately 0.1 m/s observed further inshore and offshore.

Figure 3.1.5 shows plots of current ellipses for each of the 3 sites proposed in Wallaroo. The size of the current ellipse is proportional to the current strength and the alignment of the major axis indicates the direction of the depth-averaged tidal currents over the course of a tidal period. Mean and maximum current speeds across the sites ranged between 0.20-0.25 and 0.60-0.70 m/s, respectively. Current speeds showed a general gradient from north to south; with currents slightly stronger in the south (i.e. Site 3) compared to those in the north (i.e. Site 1). The alignment of the major axis of the ellipses shows the main direction of the tidal flow at each site is predominantly alongshore. For each site, the small black stick shows the strength and direction of the mean residual current averaged over the modelled year were negligible. The strength and direction predicted for the depth-averaged currents (ellipses) due to tidal motions suggests nutrient emissions at these sites will be periodically diluted over the 12 hour tidal period.

Considering the small shift in the strength and orientation of the dominant tidal currents modelled between the three sites (Figure 3.1.5), shifts in the location of sites within the zone shows the potential for influencing the transport of dissolved and organic matter from sites. For example, the shoreward and then northward transport of water within the nearshore coastal flow (Figure 3.1.4) modelled under the current simulation could be potentially minimized by locating leases in the south-western most limits of the zone.

Hourly predictions of current speed (m/s), direction (^{o}T) and the magnitude of both the east-west and north-south components of the current are provided for each of the three proposed sites in an Excel file.

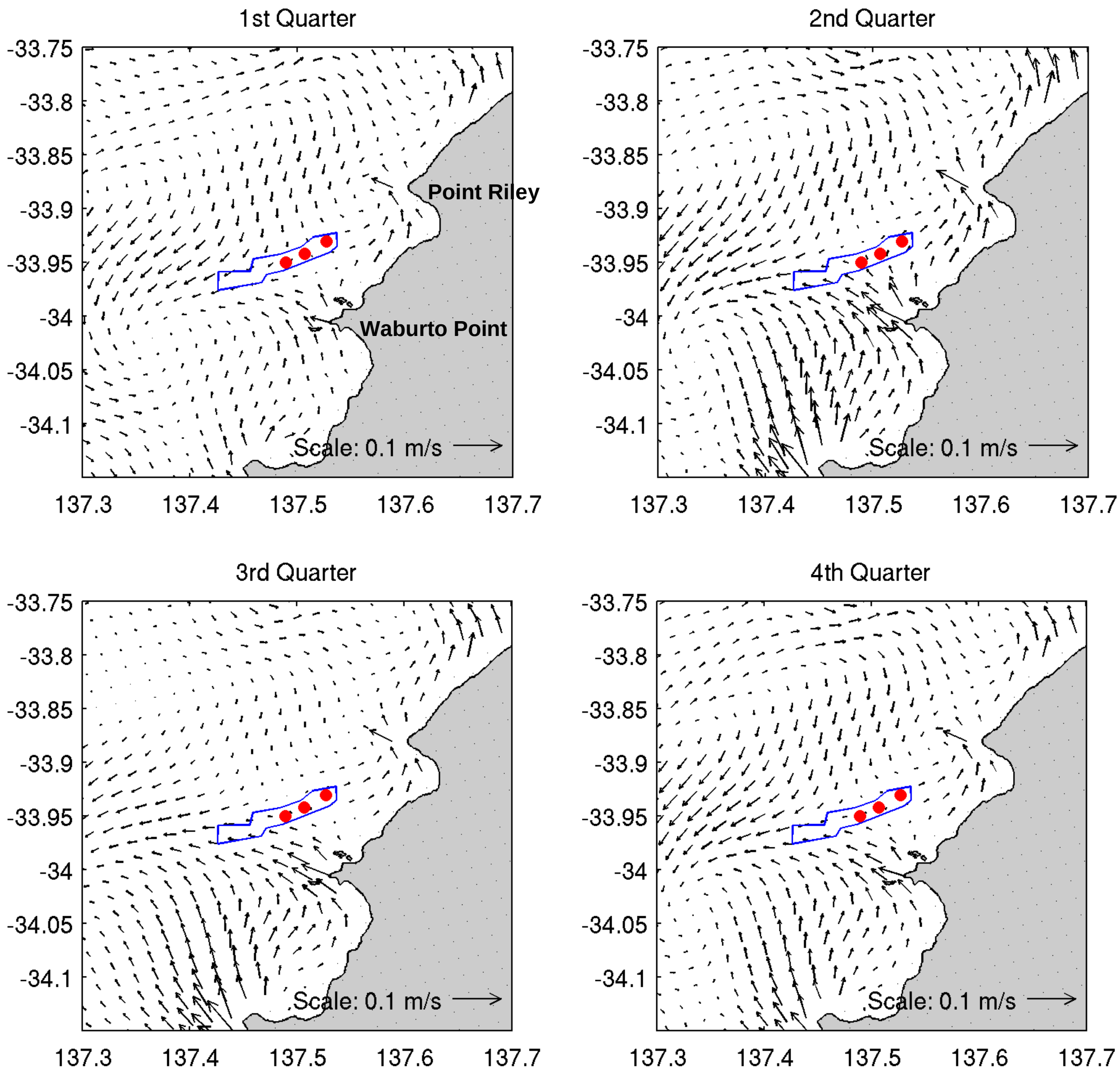

Figure 3.1.4. Zoom in of the mean depth-averaged oceanographic seasonal circulation pattern around Wallaroo for the 1st (July-August), 2nd (September-November), 3rd (December-March) and 4th (April-June) quarters of the hydrodynamic model run. Red circles show the location of proposed YTK lease sites.

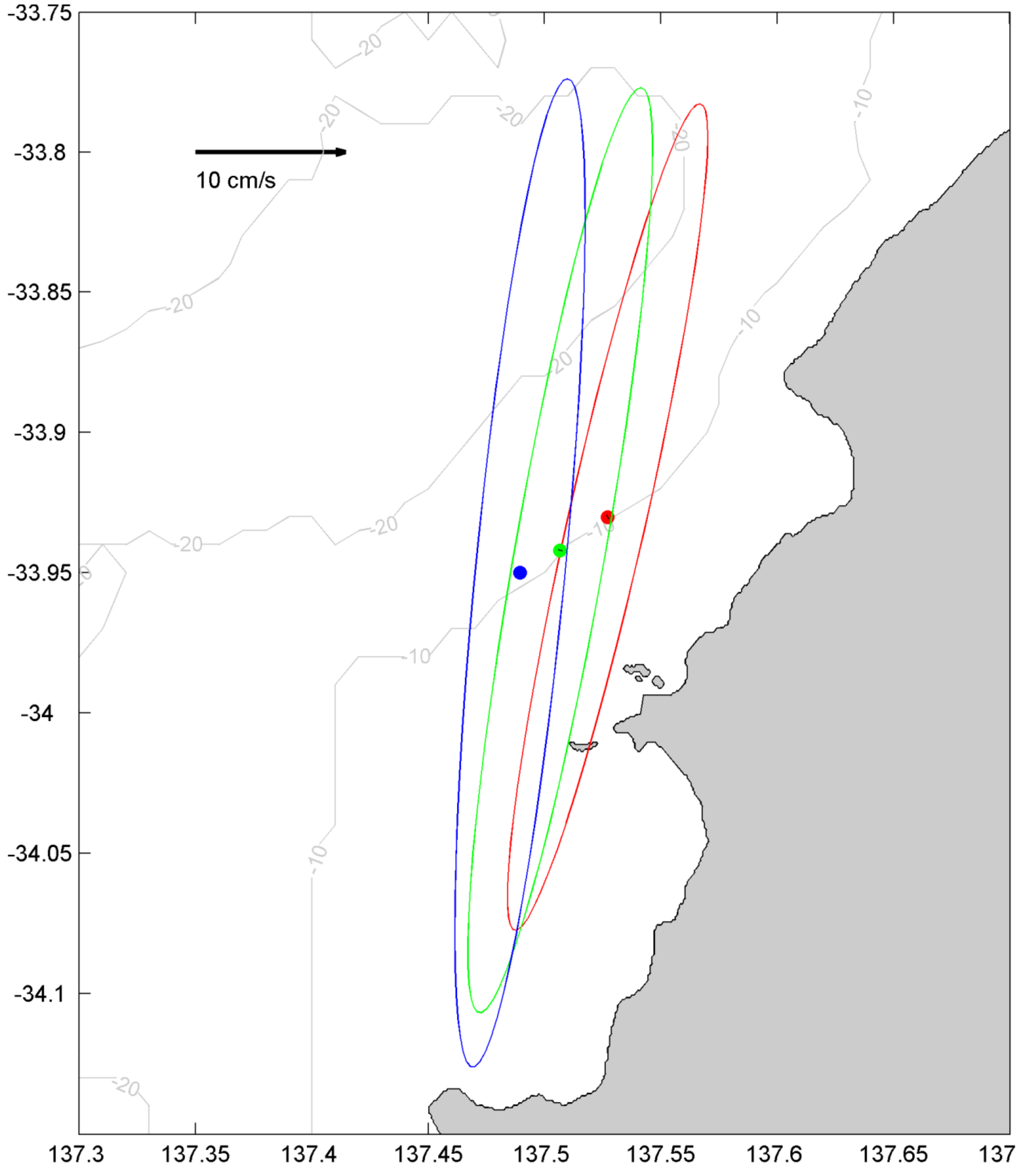

Figure 3.1.5. Surface current ellipses and residual current speed and direction (black stick) averaged over 1 year for each of the 3 new YTK sites proposed for Boston Bay; red ellipse (Site 1), green ellipse (Site 2) and blue ellipse (Site 3). The 10 and 20 m depth contours are plotted. Scale bar relates to the strength of dominant (ellipses) and residual (stick) currents.

3.2. Spatial and temporal temperature variability

3.2.1. Spencer Gulf

The annual seasonal cycle in Spencer Gulf drives changes in water temperatures typically in excess of 10 ^{o}C throughout the Gulf. Seasonal temperature variability is generally greater in the shallow nearshore perimeter and upper half of the Gulf and less near the Gulf's entrance that is adjacent to the deeper, cooler waters of the continental shelf. Figure 3.2.1 demonstrates the seasonal shifts in water temperatures experienced across the Gulf using monthly-averaged maps of modelled sea surface temperature (SST). The maps clearly show SST during the cooler months of June through September remains below 15 ^{o}C. From October, shallower regions of the Gulf, particularly in the north, begin to warm. Seasonal heating leads to the establishment of a strong north-south temperature gradient through November to April. Water temperatures peak in the Gulf during late January with SST generally in excess of 24 ^{o}C.

From December to April the development of an east-west temperature gradient across the southern region of Spencer Gulf can be observed (Figure 3.2.1). This gradient is characterised by lower SST in the south-western corner of the Gulf relative to water further to the east. During the peak summer months, Gulf waters remain largely separated from the cooler temperate continental shelf waters due to the formation of a thermohaline front at the entrance to the Gulf. The front limits exchange with the shelf and results in a build-up of warm water within the Gulf. During this period the spatial extent of cooler water in the west becomes increasingly restricted to the Port Lincoln region. The strong temperature difference between Gulf and shelf waters modelled during summer is consistent with satellite observations presented by Petrusivics (2011). Model simulations suggest the formation of the front may significantly reduce nutrient and biological exchange between the shelf and Gulf and is likely to have a range of implications for ecology of the Gulf.

Beginning in late March and continuing through winter into early spring, atmospheric cooling and evaporation lead to the formation of dense water in the Gulf. This dense water forms an outflow along the eastern side of the Gulf onto the shelf (Nunes Vaz et al. 1990; also Figure 3.1.1, 3.2.1). During the outflow, a corresponding inflow of relatively cooler, nutrient rich water occurs on the western side of the Gulf (Doubell et al. 2013).

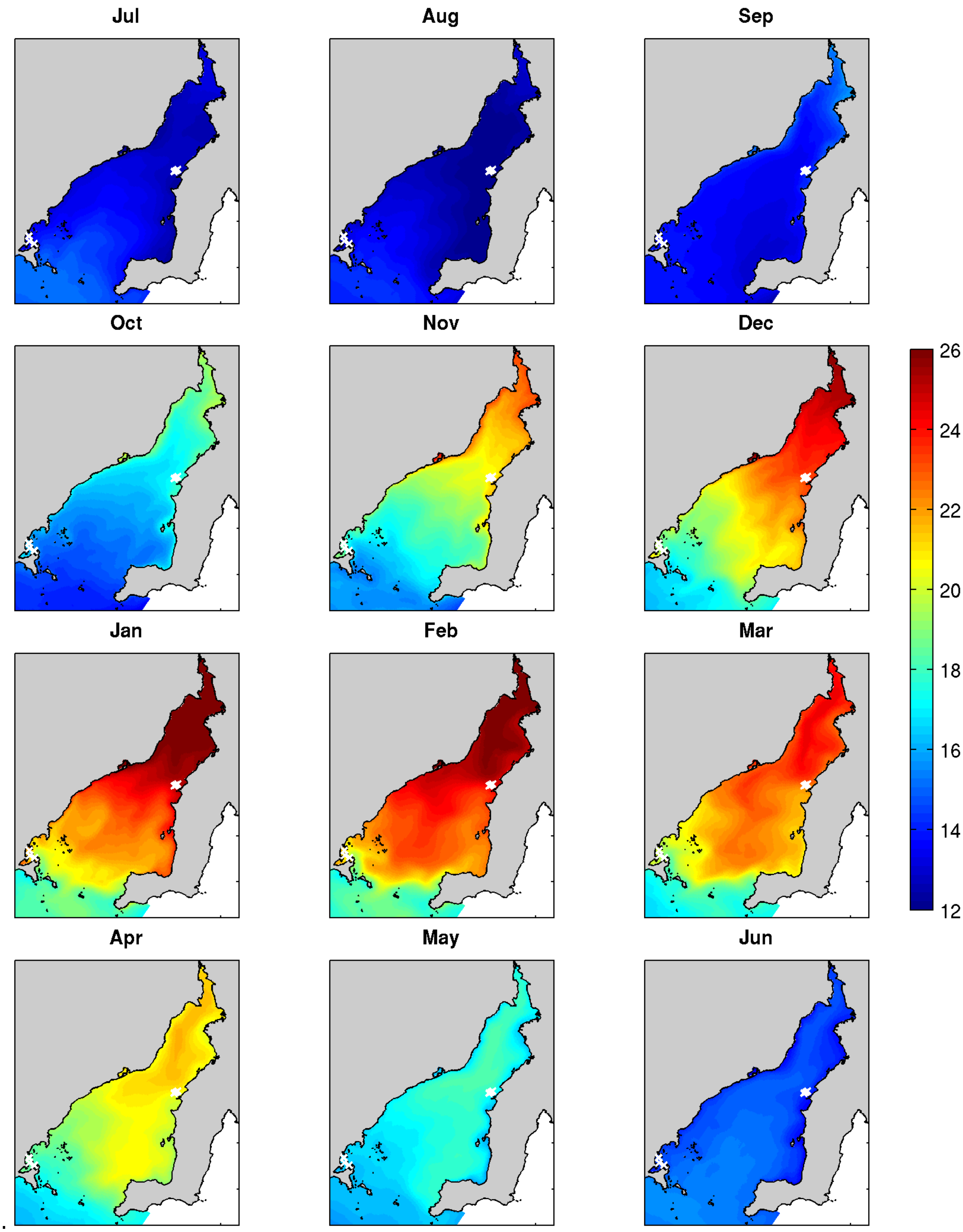

Figure 3.2.1. Modelled monthly-average sea-surface temperature (^oC) across Spencer Gulf. The location of proposed YTK sites in Boston Bay and Wallaroo are marked with white crosses.

3.2.2. Port Lincoln

Maps of the model monthly-averaged SST for the Port Lincoln aquaculture region are shown in Figure 3.2.2. Seasonal changes in water temperatures in this region are slightly less than that experienced further north due the close proximity of, and exchange with, cooler shelf waters. The spatial distribution of SST in the region ranges from a relatively homogenous distribution of water below 15 ^{o}C during winter months (June-September) up to 23 ^{o}C during late summer in the inshore regions of Proper, Boston, and Peake Bays. Temporal variations in temperature are greater in the shallower bay regions relative to deeper waters offshore. During warmer months (November to April) cooler SSTs, driven by the influx of water from the shelf through Thorny Passage, are a consistent feature of deeper waters adjacent to Cape Donnington and to the east of Boston Island. Consistent with the circulation (Figure 3.1.2), cooler waters typically extend from around Cape Donnington through to Louth Bay through November to February and give rise to persistent temperature gradient of between 1-3 ^{o}C between the inner bays and offshore waters.

Animations of daily-averaged SST across the mapped region shown in Figure 3.2.2 have been provided to CS to show the extent of daily spatial variability throughout the year. Figure 3.2.3 shows a comparison of simulated hourly-averaged SST for the three sites proposed for YTK farming in Boston Bay. The temperature time-series have been smoothed with a low-pass filter to suppress tidal variability (Thompson 1983). Minimum SST of approximately 13 ^{o}C occurs in late August across all sites and temperature differences between sites remain small during the cooler months (May-October). From late September, water temperatures steadily increase at all stations peaking at approximately 21-22 ^{o}C in late January. Notably, the model results suggest temperature increases occur more rapidly at Sites 1 and 2. SST at these sites are consistently up to 1-1.5 ^{o}C greater than those simulated at Site 3 through November to March.

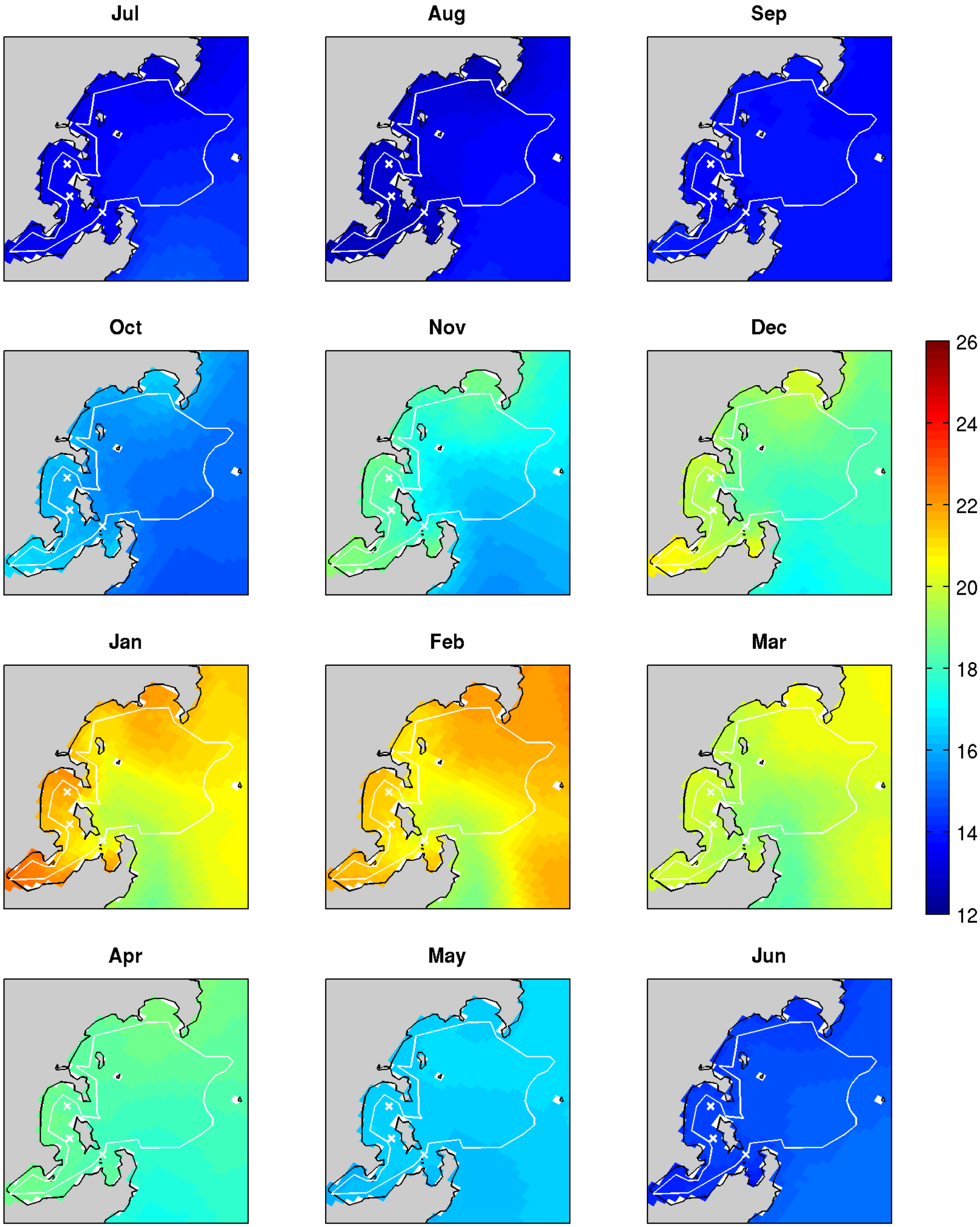

Figure 3.2.2. Modelled monthly-averaged sea-surface temperature (^{o}C) in the Port Lincoln region. White crosses indicate the location of proposed YTK aquaculture leases and the white line denotes the outer limits of the aquaculture zone.

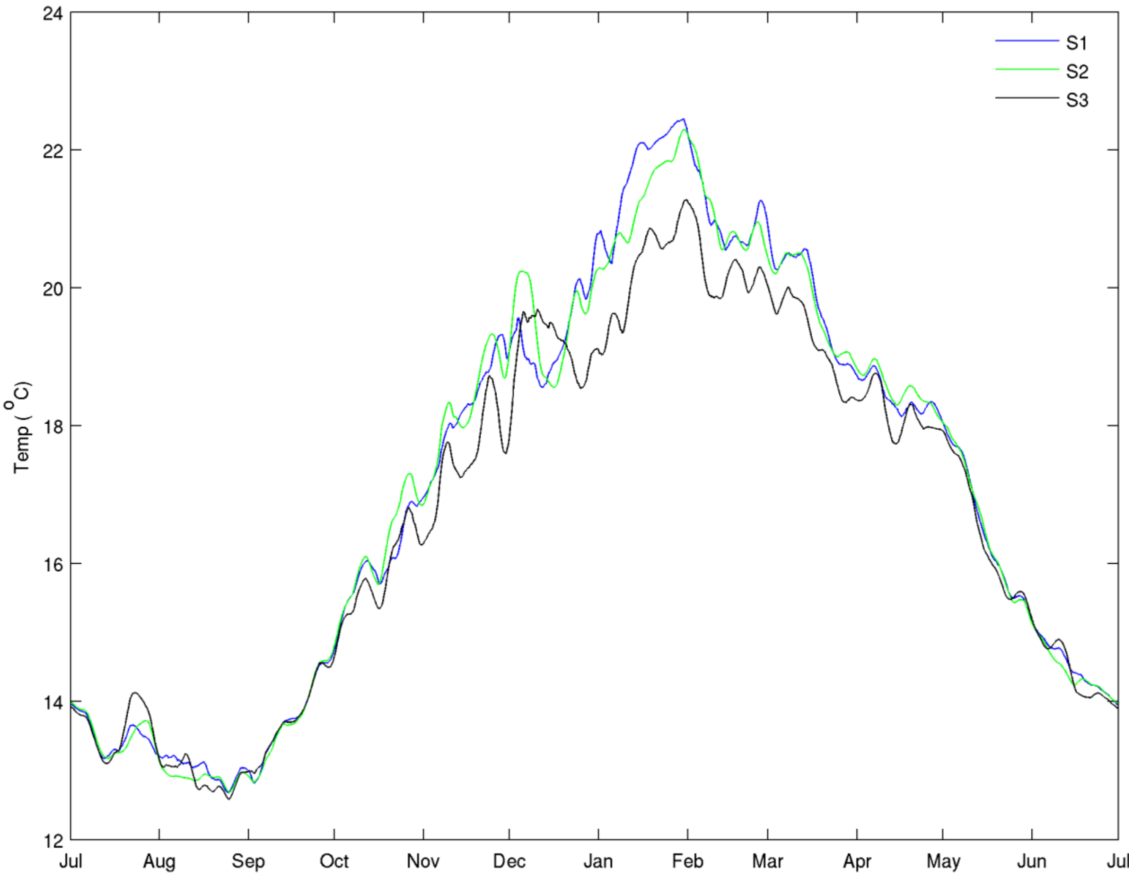

Figure 3.2.3. Simulated sea-surface temperature (^oC) at the three sites proposed for YTK aquaculture in Boston Bay (see Figure 2.3 for site locations).

3.2.3. Wallaroo

Maps of model monthly-averaged SST for the Wallaroo region are shown in Figure 3.2.4. Seasonal changes in SST greater than 12 ^{o}C are greater than those observed in southern Spencer Gulf. Similar to other regions of Spencer Gulf, variations in temperature are larger in the shallow nearshore waters relative to deeper offshore waters throughout the year. The spatial distribution of SST in the region ranges from a relatively homogenous distribution of water below 15 ^{o}C during winter months (June-September) up to approximately 25 ^{o}C during late summer. During spring (October, November), atmospheric heating in shallow coastal waters leads to the development of an inshore-offshore temperature gradient, with SST along the coast approximately 1-2 ^{o}C warmer than those at the proposed lease sites. This trend reverses during autumn (March, April, and May) as atmospheric cooling leads to cooler SST inshore relative to offshore waters. During warmer months (December to March), a weak north-south gradient centred on the proposed YTK lease sites is observed, although temperature differences over the mapped region are generally less than 1 ^{o}C.

Animations of daily-averaged SST across the mapped region shown in Figure 3.2.4 have been provided to CS to show the extent of daily SST spatial variability throughout the year. Figure 3.2.5 shows a comparison of simulated hourly-averaged SST for the three sites proposed for YTK farming off Wallaroo. The temperature time-series have been smoothed with a low-pass filter to suppress tidal variability (Thompson 1983). Minimum SST's of approximately 12 ^{o}C occur during August and with maximum SST peaking at approximately 26 ^{o}C during late January, early February across all sites. Temperature differences between sites are negligible for the months of May through November. Small differences in SST are modelled for the warmer months of January through April, with SST approximately 0.5 ^{o}C greater at the Site 1 in the north relative to Site 3 in the south.

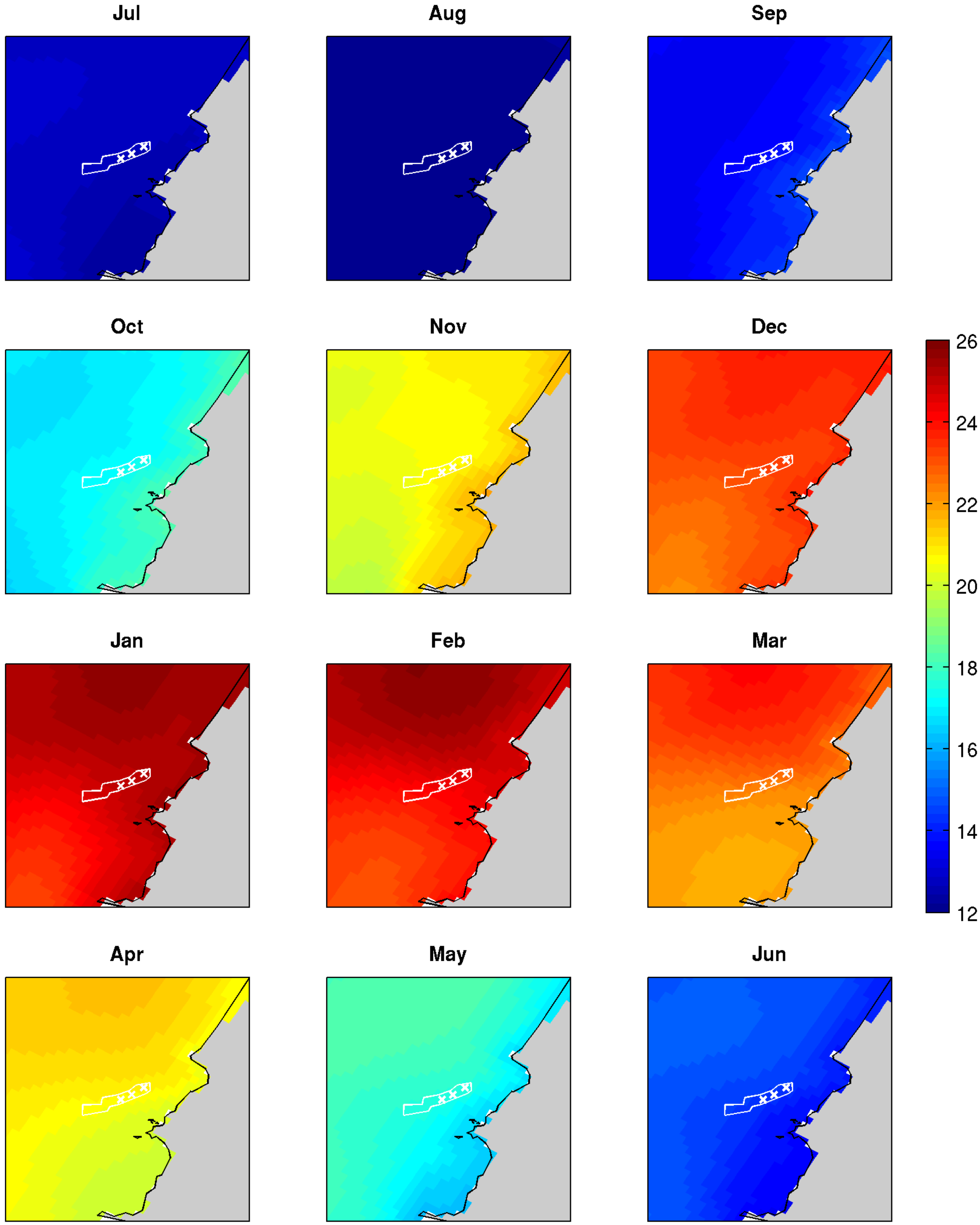

Figure 3.2.4. Modelled monthly-averaged sea-surface temperature (^{o}C) in the Wallaroo region. The White crosses indicate the location of proposed YTK aquaculture leases and the white line denotes the outer limits of the aquaculture zone.

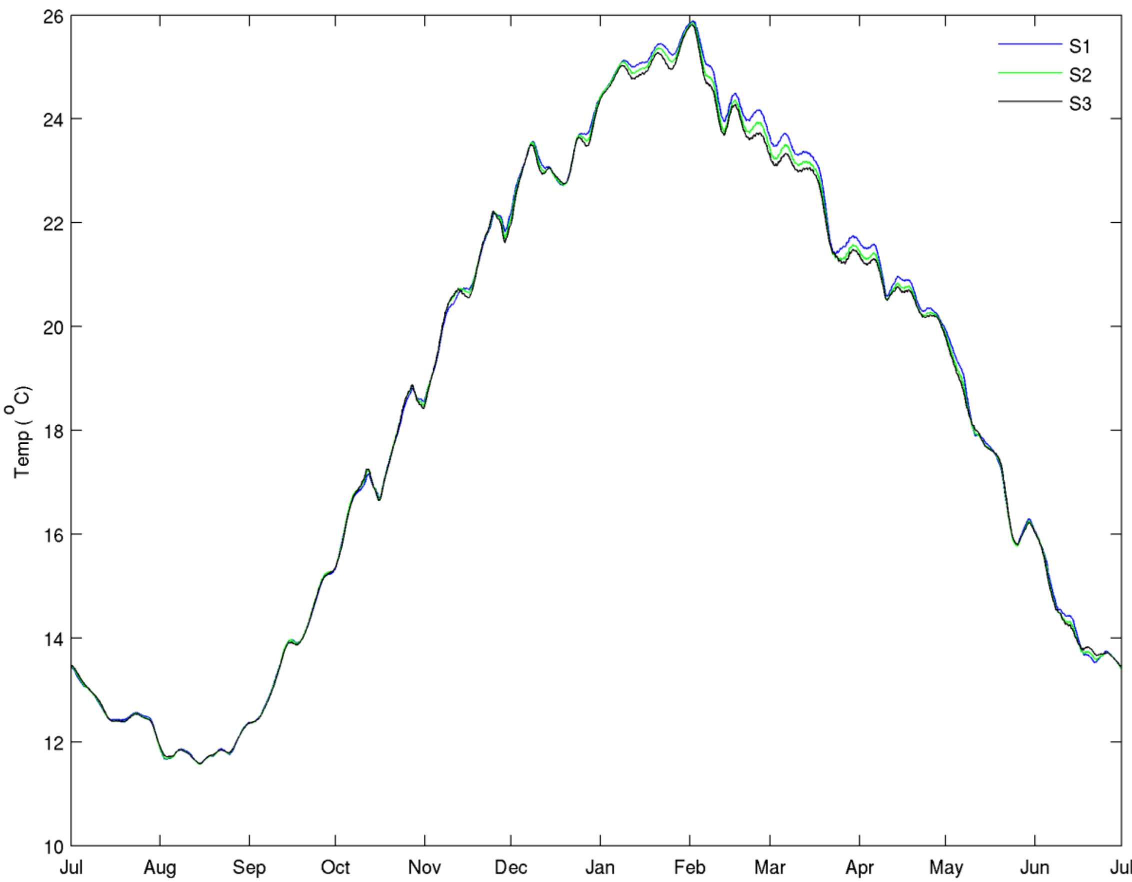

Figure 3.2.5. Simulated sea-surface temperature (°C) at the three sites proposed for YTK aquaculture in Wallaroo. See Figure 2.3 for site locations.

3.3. Waves

3.3.1. Spencer Gulf Region

The entrance of Spencer Gulf is open to wave energy from the Southern Ocean and the incoming wave direction is generally from the south to southwest. Waves entering Spencer Gulf are refracted shoreward by the bottom topography and wave height and energy dissipates with distance from the Gulf's entrance and as water column depth decreases. A snapshot of validated model results for 9 August (2010) is shown in Figure 3.3.1. Significant wave heights, defined as the mean of the highest third of waves, diminish from about 3 m at the Gulf mouth to values of less than 0.5 m at the head of the Gulf. Swell propagates into the Gulf generally from the south-west and then towards the coasts due to interaction with the seafloor in shallower areas. Consequently, for much of the Spencer Gulf wave activity away from its southern entrance is typically modulated by local winds. The resultant wind waves are of low to medium energy due to the limited fetch within Spencer Gulf.

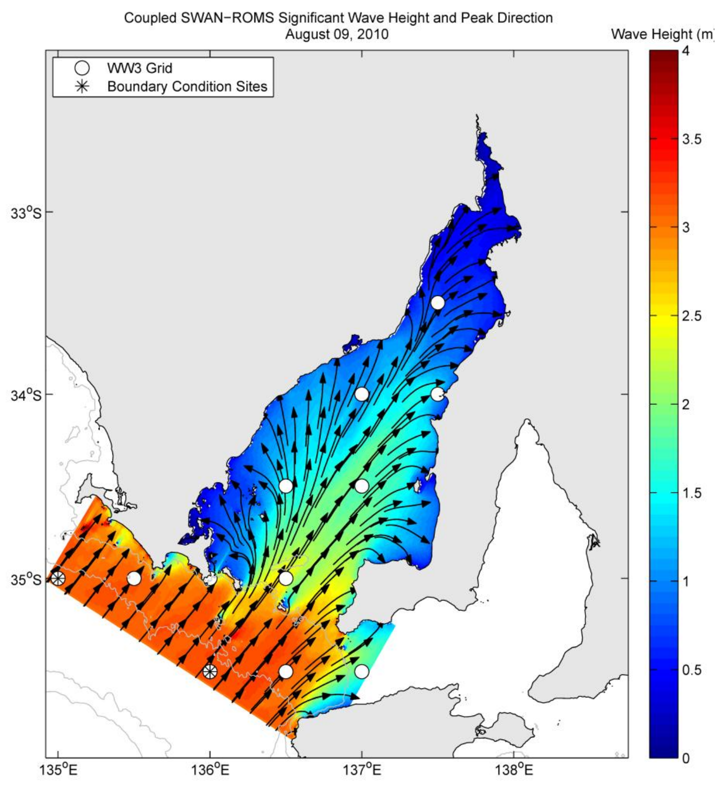

Figure 3.3.1. Results for the coupled SWAN output are shown for 9th August 2010: the vectors shown indicate wave direction and the colour bar indicates significant wave height in meters. The location of Wavewatch III grid points around Spencer Gulf are shown as white circles. The two points used to generate the SWAN boundary conditions are indicated by the white starred circles.

3.3.2. Boston Bay Region

Modelled wave activity inshore of Boston Bay was low due to protection by Boston Island and the shape of the coastline. Table 3.3.1 shows seasonal changes in model estimates of wave heights, periods and bottom orbital velocity (BOV). BOV is the current velocity associated with the ellipse/orbital motion of waves felt at the seafloor. The variability of all statistical wave parameters across the proposed lease sites and seasons was small. Figure 3.3.2 shows the corresponding time-series plot for Sites 1 and 2; which showed the highest and lowest amount of wave activity of the three sites (Table 3.3.1).

Across seasons and sites mean and maximum significant wave heights were less than 0.5 m and 1.5 m, respectively (Table 3.3.1). Similarly, mean wave periods were generally low with values <6.6 s indicating the dominance of local winds for wave generation (Table 3.3.1). The increased frequency of high period waves (>10 s) predicted at site 1 during cooler months (April-October) is a result of the site being more open to the effect of ocean swell relative to other sites 2 and 3. Modelled peak wave directions showed strong variability within and between sites. Results indicated approximately 60% of the peak wave direction across the year were from the north at Site 1 and 50% from the west to northwest at site 2. For Site 3, over 50% of the modelled peak wave directions were from the east to north-east.

BOV is important in influencing the net transport of water and sediment shoreward. Consequently, BOV is of relevance to resuspension, flushing and potentially stresses felt by fish in cages. Mean BOV across the three sites are negligible with maximum velocities of 0.15 m/s measured at the relatively more exposed Sites 1 and 3. Overall the low wave activity predicted across all sites demonstrates the inshore region of Boston Bay is well sheltered from long period ocean swells.

Table 3.3.1. Summary wave statistics estimated across seasons at Sites 1, 2 and 3 in Boston Bay. Calculated values show the mean, standard deviation (s. d.) and maximum (max) predicted values of significant wave height, period and bottom orbital velocity (BOV). See Figure 2.3 for site locations.

Site	Period	Height (m)			Period (s)			BOV(m/s)		
		mean	s.d	max	mean	s.d	max	mean	s.d	max
1	Jul-Sep	0.46	0.25	1.25	6.43	5.02	18.31	0.03	0.01	0.11
	Oct-Dec	0.48	0.25	1.41	4.80	3.48	16.50	0.03	0.02	0.15
	Jan-Mar	0.61	0.28	1.31	4.75	1.92	14.88	0.04	0.03	0.14
	Apr-Jun	0.43	0.22	1.10	5.80	4.40	18.31	0.02	0.01	0.07
2	Jul-Sep	0.32	0.22	1.16	2.29	0.94	13.41	0.00	0.01	0.05
	Oct-Dec	0.29	0.17	0.93	2.22	0.59	3.86	0.00	0.00	0.03
	Jan-Mar	0.30	0.14	0.76	2.22	0.61	10.89	0.00	0.00	0.02
	Apr-Jun	0.27	0.19	0.94	2.34	1.66	14.88	0.00	0.00	0.03
3	Jul-Sep	0.40	0.23	1.51	3.62	2.77	14.88	0.01	0.01	0.15
	Oct-Dec	0.37	0.17	0.84	3.09	1.82	16.50	0.01	0.01	0.05
	Jan-Mar	0.42	0.18	0.85	3.28	1.48	16.50	0.02	0.01	0.06
	Apr-Jun	0.36	0.18	0.94	3.55	2.53	16.50	0.01	0.01	0.05

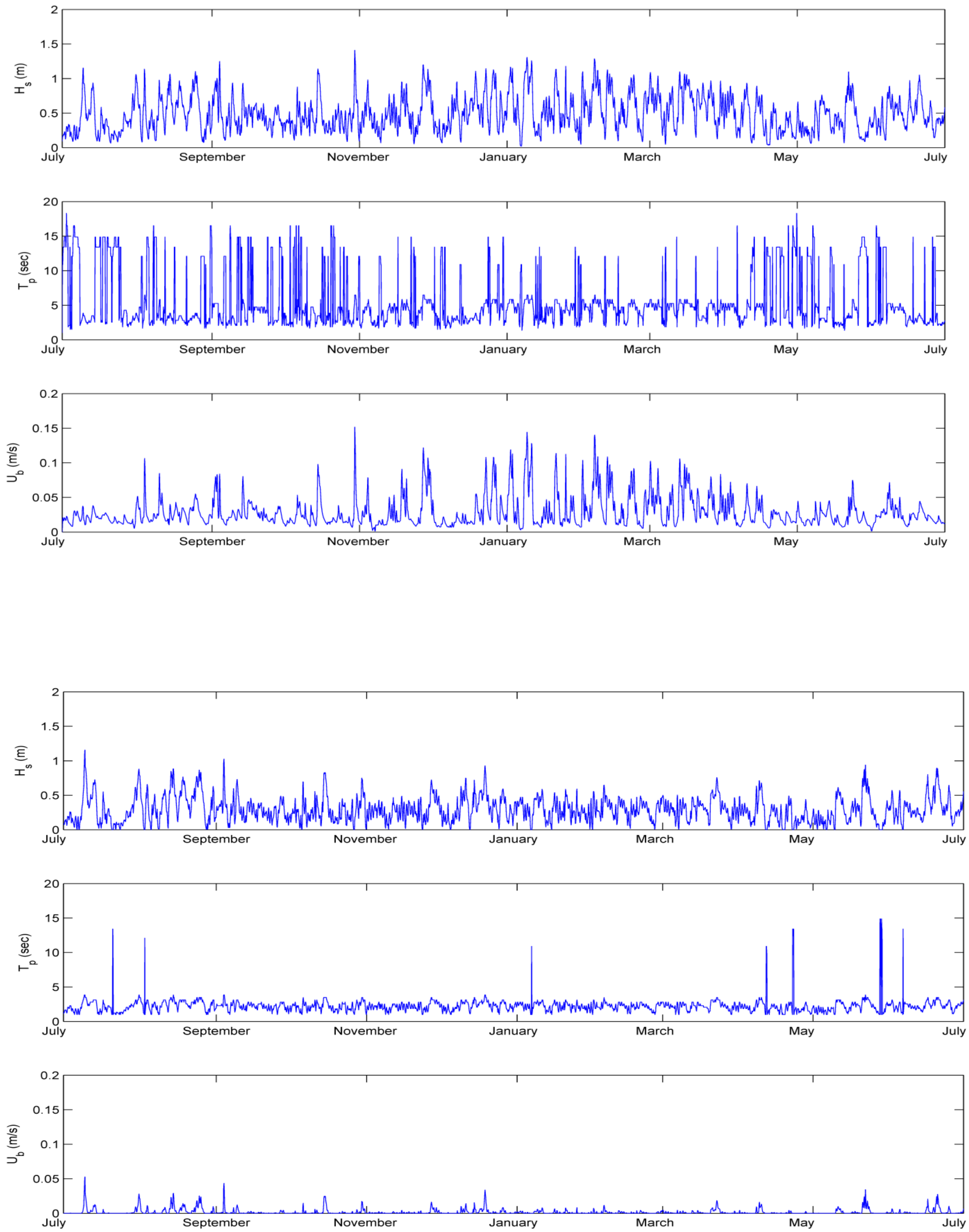

Figure 3.3.2. Time series of 3-hourly wave model predictions of significant wave height (H_s; m), period (T_p; s) and bottom orbital velocity (U_b; m/s) at (top panels) Site 1 and (bottom panels) Site 3.

3.3.3. Wallaroo Region

Wave activity at Wallaroo is generally higher than at the sheltered location of Boston Bay, although conditions are still diminished compared to wave activity experienced at the mouth of the Gulf.

Table 3.3.2 shows changes in model estimates of wave heights, periods and BOV for each of the proposed lease sites across the seasons. Figure 3.3.3 shows the corresponding time-series plot for Sites 1 and 3; which showed the highest and lowest amount of wave activity of the three sites (Table 3.3.2).

Across seasons and sites mean and maximum significant wave heights were typically less than 1.0 m and 2.4 m, respectively (Table 3.3.2). Mean periods were between 7 s and 10.5 s with maximum periods experienced up to 20.3 s. The modelled increase in mean and maximum wave heights, periods and associated variability (Table 3.3.2) relative to Boston Bay demonstrates that a mixture of local wind-generated waves and ocean swells affect the region. Local wind waves dominated the warmer months (i.e. November – April) as indicated by the increased frequency of low period waves (<9 s) (Figure 3.3.3) and peak wave directions from the east. During this period, wave heights were generally less than 1.5 m (Figure 3.3.2). For cooler months (May-Sept) an increased frequency of longer period waves (>9 s) and wave heights over 1.5 m was modelled. The influence of swell on the Wallaroo aquaculture zone is reflected in the strong dominance of waves from the southwest which accounted for over 50% of the modelled peak annual wave directions. Increases in wave activity were associated with increases in mean (0.1 m/s) and maximum BOV (0.5 m/s) (Table 3.3.2). BOV greater than 0.2 m/s were typically associated with wave heights greater than 1.5 m (Figure 3.3.3).

Table 3.3.2. Summary wave statistics estimated across the oceanographic seasons at Sites 1, 2 and 3 in Wallaroo. Calculated values show the mean, standard deviation (s.d) and maximum (max) predicted significant wave height, period and bottom orbital velocity (BOV). See Figure 2.3 for site locations.

Site	Period	Height (m)			Period (s)			BOV(m/s)		
		mean	s.d	max	mean	s.d	max	mean	s.d	max
1	Jul-Sep	0.91	0.41	2.36	10.09	4.40	18.31	0.15	0.07	0.46
	Oct-Dec	0.78	0.27	1.93	8.40	4.63	16.50	0.11	0.04	0.38
	Jan-Mar	0.73	0.21	1.72	7.03	4.66	18.31	0.09	0.03	0.32
	Apr-Jun	0.77	0.32	2.09	9.69	4.69	20.31	0.12	0.05	0.41
2	Jul-Sep	0.95	0.42	2.38	10.36	4.28	18.31	0.16	0.07	0.45
	Oct-Dec	0.82	0.28	2.00	8.72	4.55	16.50	0.12	0.05	0.39
	Jan-Mar	0.77	0.21	1.80	7.56	4.65	18.31	0.10	0.03	0.34
	Apr-Jun	0.81	0.33	2.13	10.12	4.56	20.31	0.13	0.06	0.42
3	Jul-Sep	0.99	0.43	2.41	10.50	4.21	18.31	0.16	0.07	0.45
	Oct-Dec	0.86	0.29	2.08	8.87	4.48	16.50	0.12	0.05	0.40
	Jan-Mar	0.81	0.23	1.89	7.94	4.60	18.31	0.10	0.03	0.35
	Apr-Jun	0.84	0.34	2.20	10.43	4.43	20.31	0.13	0.06	0.42

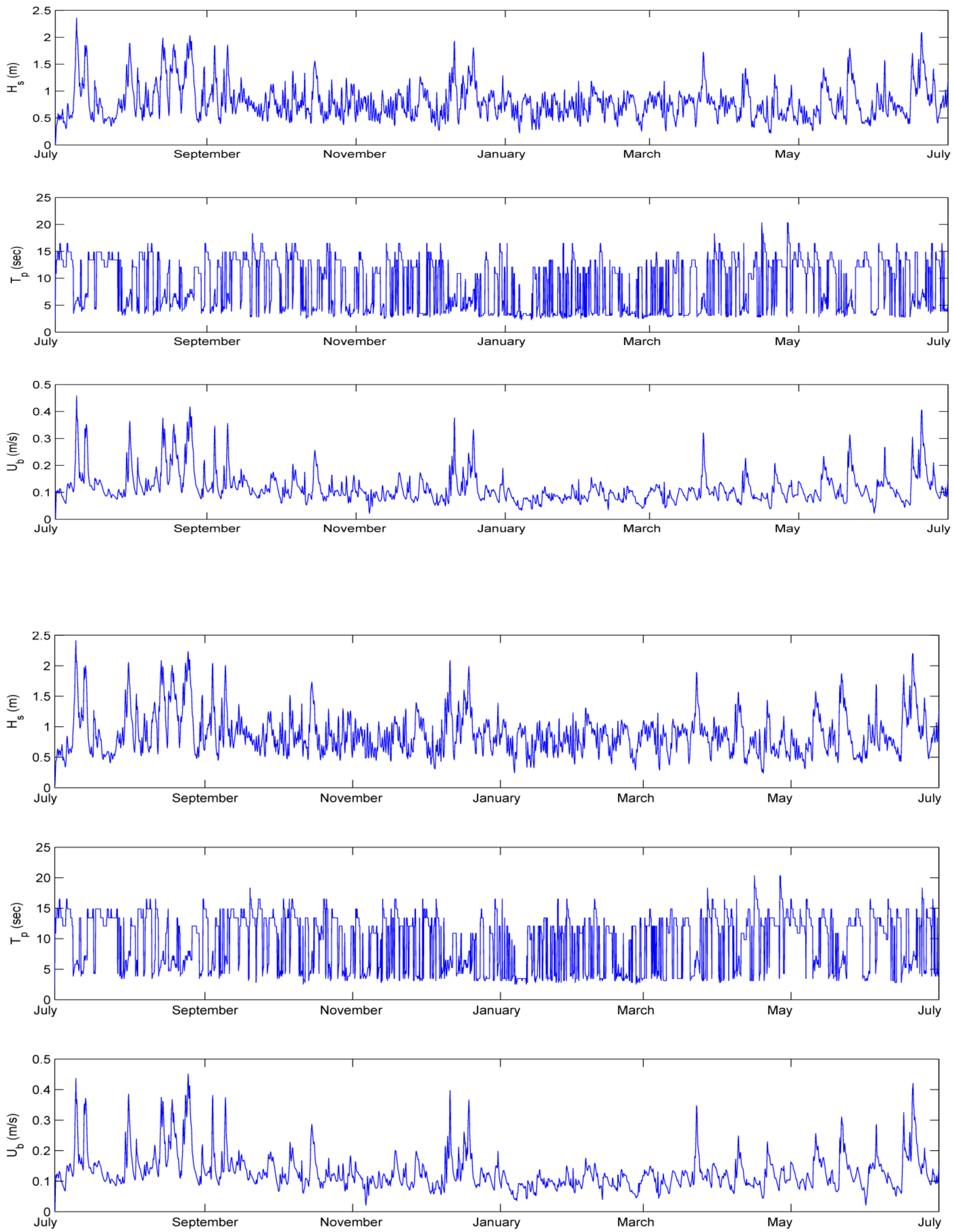

Figure 3.3.3. Time series of 3-hourly wave model predictions of significant wave height ($H_{s;}$ m), period (T_p; s) and bottom orbital velocity ($U_{b;}$ m/s) at (top panels) Site 1 and (bottom panels) Site 3.

3.4. Water quality

3.4.1. Spencer Gulf Region

Seasonal variations in meteorological conditions and oceanographic circulation strongly influence the dynamics of nutrient transport and their assimilation into the pelagic ecosystem (Doubell et al 2013, van Ruth and Doubell 2013). Recent 'whole of Gulf' biogeochemical modelling studies indicated that the largest source of dissolved inorganic nitrogen into the Gulf was natural exchange processes with adjacent shelf waters (Doubell et al. 2013). Natural exchange is strongest during the late autumn/winter flushing period and provides a source of nitrate to fuel primary production. During late spring and summer, ecosystem recycling processes and anthropogenic sources supply nutrients (mainly ammonium) which sustain productivity in the Gulf. Observed background concentrations of ammonium outside aquaculture zones are generally low throughout the Gulf over the annual seasonal cycle (<5 µg N /L; van Ruth and Doubell 2013) and show good predictive skill, typically within a factor of 2, with modelled concentrations (Doubell et al. 2013). For this reason, elevated concentrations of ammonium arising from point sources, such as finfish aquaculture, in the current modelling studies provide a good trace to visualize the transport and dilution of nutrients.

Figure 3.4.1 demonstrates the modelled monthly averaged surface distribution of ammonium in Spencer Gulf across a year for the 3rd year (2014/15) of the second scenario study which includes the newly proposed feeding schedules for YTK aquaculture. At the scale of the Gulf, the distribution of ammonium is very low across October to January. Emissions from finfish aquaculture increase from February to April and are generally restricted to source regions. During May, elevated ammonium concentrations associated with SBT farming offshore near Port Lincoln (Figure 2.4.2) are advected northwards along the western side of the Gulf and become mixed and diluted. Consistent with the Gulf's winter circulation, this ammonium enriched water is then entrained away from the west coast near Franklin Harbor as it is drawn into the dense water outflow from upper Spencer Gulf. Further dilution and uptake of ammonium occurs as these waters are transported eastwards and south into southern Spencer Gulf.

Figure 3.4.2 shows the corresponding monthly averaged distribution of surface chlorophyll. Phytoplankton assimilate nutrients over timescales of several hours to days and chlorophyll typically shows an inverse distribution to nutrients over these temporal scales. However, when chlorophyll concentrations are averaged over longer time scales (i.e. weeks to months) the spatial distribution of chlorophyll provides an indication of the phytoplankton response relative to changes in the spatial and temporal distribution of nutrients. Model results (Figure 3.4.2) show elevated concentrations of chlorophyll are maintained in the south-west around Port Lincoln throughout the year. The elevated concentrations and seasonal variations in modelled chlorophyll are consistent with observations in this region (Bierman et al. 2009). During autumn and winter, the characteristic clockwise circulation pattern which drives the distribution of natural and anthropogenic nutrients within the Gulf results in increases in chlorophyll concentrations (~0.5 -1.0 µg/L) across much of southern Spencer Gulf. In early spring (September-November), chlorophyll concentrations throughout the Gulf begin to decrease in response to seasonal reduction in the nutrients from the shelf and finfish aquaculture (Figure 2.4.2). In summer (January-March), the import of nutrients (i.e. nitrate) from the shelf is lowest due to the blocking effect of a strong temperature front which establishes across the Gulf's entrance (Figure 3.2.1). Correspondingly, chlorophyll concentrations are generally at their lowest, except in the vicinity of nutrient inputs from anthropogenic sources such as finfish aquaculture.

Figure 3.4.3 shows the corresponding monthly averaged bottom distribution of large detritus. Large detritus is formed through the coagulation of smaller non-living particulate organic matter (Figure 2.3.1) and has a higher sinking speed than small detritus. This component of the model has not been validated and no water quality values are available under the ANZECC/ARCMANZ (2000) guidelines. Nonetheless, the modelled distribution patterns provide an indicator of the potential transport pathways and resulting spatial distribution of organic matter deposited to the sea floor. Modelled biomass distribution patterns are strongly linked to the major circulation pathways. Areas of higher bottom detritus concentrations occur at distance downstream from the source regions of natural and anthropogenic nutrients (i.e. south-western Spencer Gulf) which drive productivity. The footprint of large detritus is greatest throughout southern Spencer Gulf during late winter and spring when biomass levels are higher (Figure 3.4.3). During summer, when nutrient and phytoplankton biomass levels (i.e. chlorophyll) are generally lower throughout the Gulf, the footprint of large detritus is significantly reduced.

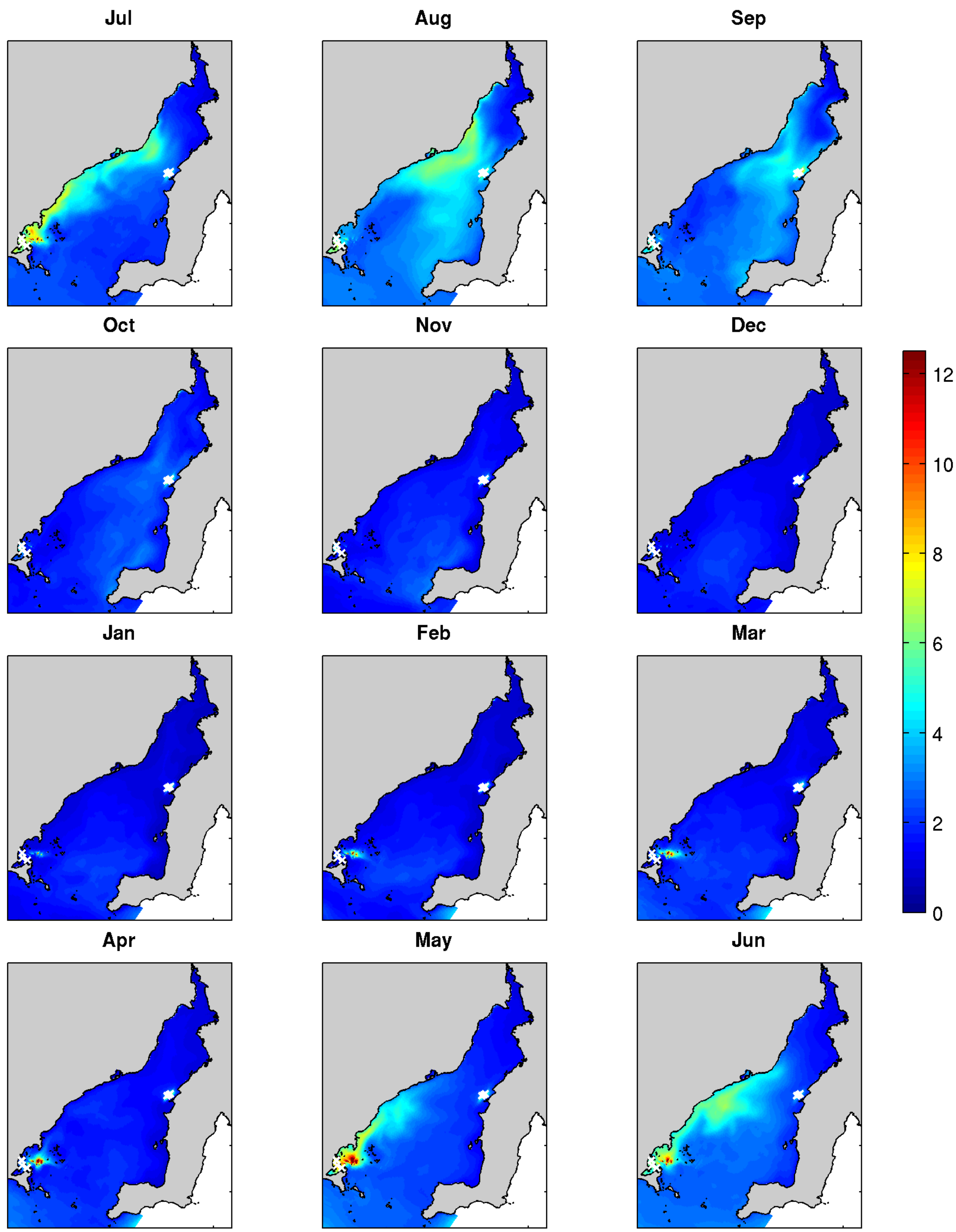

Figure 3.4.1. Monthly-averaged surface ammonium concentrations (µg/L) predicted for the third year (2014/15) of the second scenario study which included proposed YTK aquaculture. To aid visualisation the colorbar scale is set to 1/4 the ANZECC water quality values recommended for marine waters in South Australia. White crosses indicate the location of proposed YTK aquaculture leases.

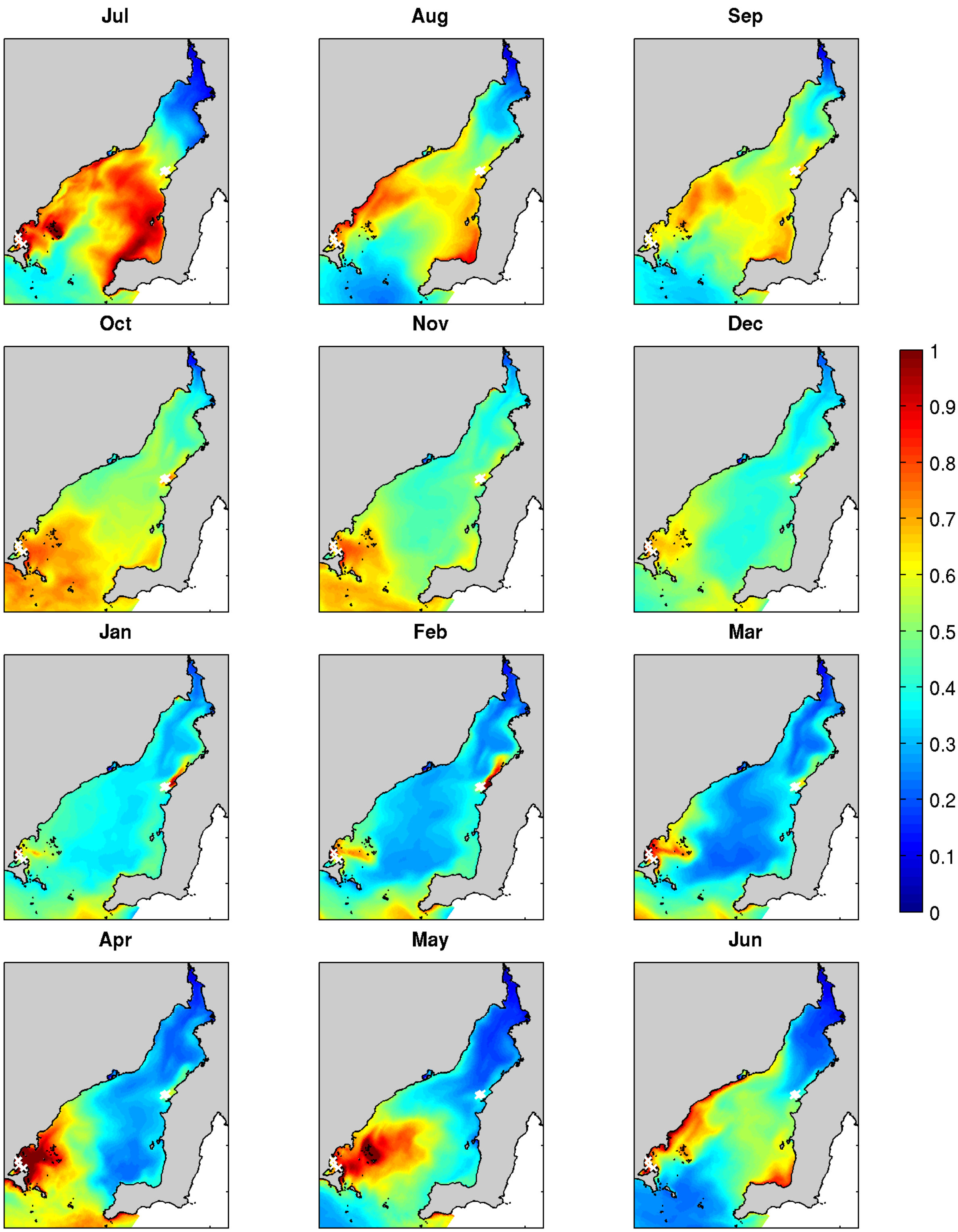

Figure 3.4.2. Monthly-averaged surface chlorophyll (µg/L) predicted for the third year (2014/15) of the second scenario study which included proposed YTK aquaculture. The colorbar scale is set to the ANZECC water quality values recommended for marine waters in South Australia. White crosses indicate the location of proposed YTK aquaculture leases.

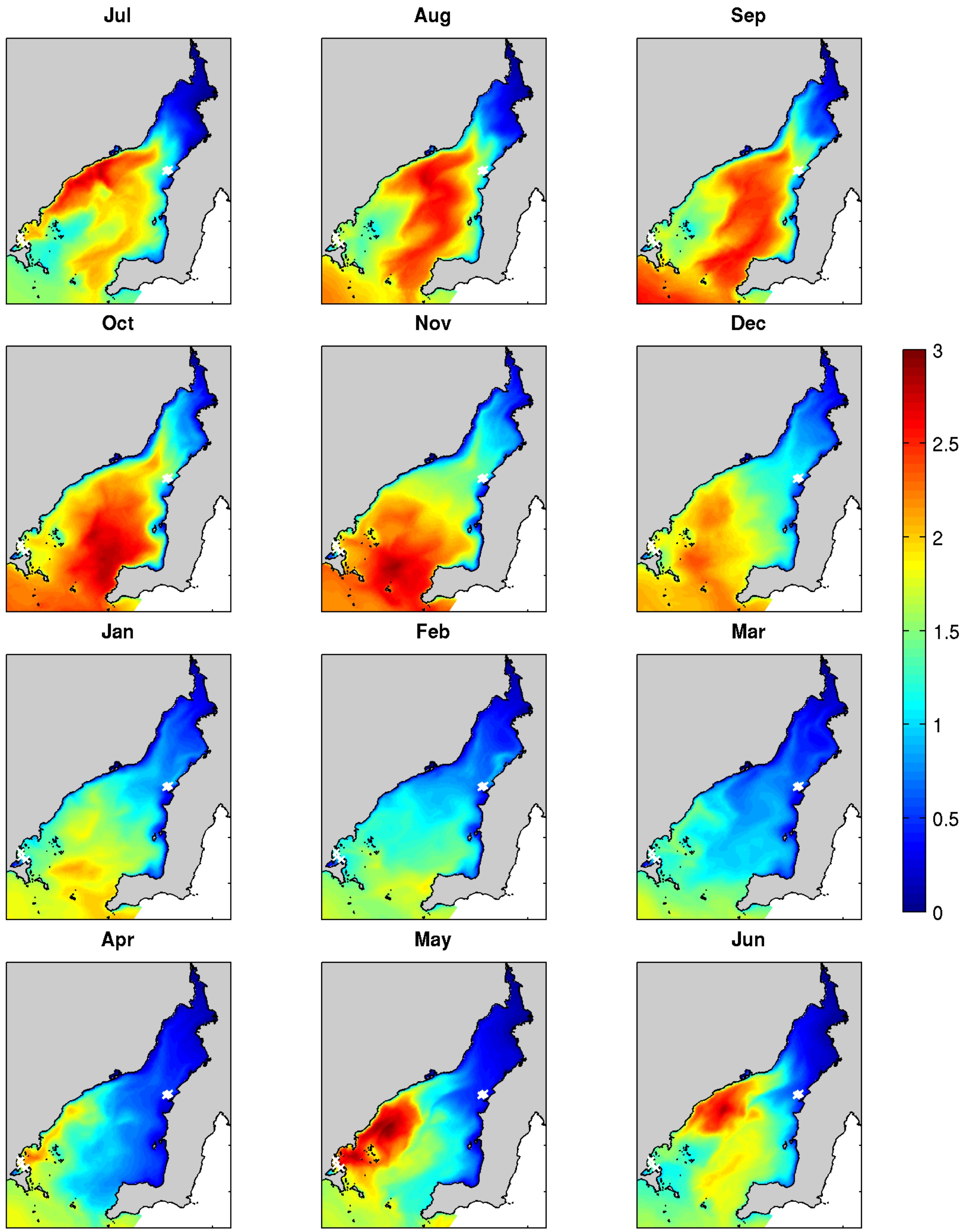

Figure 3.4.3. Monthly-averaged bottom large detritus (µg N /L) predicted for the 3rd year of the second scenario study which included proposed YTK aquaculture. White crosses indicate the location of proposed YTK aquaculture leases.

3.4.2. Boston Bay Region

Figures 3.4.4 and 3.4.5 show the monthly-averaged distribution of ammonium and chlorophyll in the Port Lincoln region. During periods of peak SBT (March–August) ammonium loading, emissions from offshore leases are primarily transported inshore to Boston and Louth Bays and northwards past Point Bolingbroke along the west coast (Figure 3.1.2). Chlorophyll concentrations in excess of 0.6 µg/L are maintained throughout the region during this period due to nutrients sourced from both natural processes and finfish aquaculture. In late spring/summer, both SBT ammonium emissions and the natural import of nutrients from the shelf are reduced and offshore chlorophyll concentrations are lower. The distribution of elevated ammonium concentrations from SBT aquaculture becomes restricted to the areas surrounding lease sites. YTK aquaculture ammonium emissions in Boston Bay increase, but elevated concentrations of ammonium are largely confined within Boston Bay. The distribution of large detritus on the seafloor (Figure 3.4.6) further demonstrates the potential effect of hydrodynamics and circulation (Figure 3.1.2) in this region on the transport and deposition of organic matter resulting from increased primary and secondary productivity. Higher levels of bottom detritus concentrations are indicated for the inshore regions of Boston and Louth Bays, as well as offshore and to the north of the SBT farms. Detrital levels are reduced during peak YTK feeding periods in summer when nutrient and chlorophyll levels are significantly lower relative to the other seasons.

The temporal averaging used to produce the monthly maps of key water quality parameters at the Gulf scale (Figures 3.3.4 to 3.4.6) smooth's out variability found at shorter temporal scales. This variability may be important when monitoring and assessing the potential impact of natural and anthropogenic nutrients on water quality and their cumulative effect on marine ecosystems. Figure 3.4.7 presents a comparison of the time-series of ammonium and chlorophyll concentrations for each the two scenario studies at the three proposed YTK sites. For both scenario studies ammonium concentrations never exceed the ANZECCC/ARMCANZ (2000) water quality guideline value of 50 µg N/L. However, an increase in ammonium concentration associated with the proposed YTK feed schedules in Scenario 2 is observed across sites, particularly during summer when YTK nutrient emissions are highest and elevated relative to the control scenario at Sites 2 and 3. This result is consistent with the poor flushing expected at these sheltered sites (Middleton et al. 2013) and may indicate that Site 2 is less suitable than the other proposed lease sites in the Boston Bay region.

Chlorophyll increases relative to the control study were generally small and within the levels of variability expected currently under the control study. Maximum chlorophyll concentrations typically did not exceed those modelled under the control scenario, although small shifts in the baseline chlorophyll levels during warmer months are apparent due to differences in the feeding schedules between the scenario studies. While the ANZECCC/ARMCANZ (2000) water quality guideline value for chlorophyll in marine waters is 1.0 µg/L, model values rarely exceeded the range of chlorophyll concentrations (i.e. 0.2 – 1.4 µg/L) observed in this region (Bierman et al. 2009, Thompson et al. 2009, Doubell et al. 2013).

A further comparison of modelled ammonium and chlorophyll concentrations at each of the four virtual monitoring stations under each scenario is presented in Figures 3.4.8 and 3.4.9, respectively. These results demonstrate that the effects of YTK aquaculture at the proposed sites on the ammonium and chlorophyll concentrations at offshore monitoring stations situated to the north and east of Boston Island are minimal. Consistent with the flushing and circulation of Boston Bay small increases in ammonium and chlorophyll were modelled at the southern, and to a lesser extent, western monitoring stations.

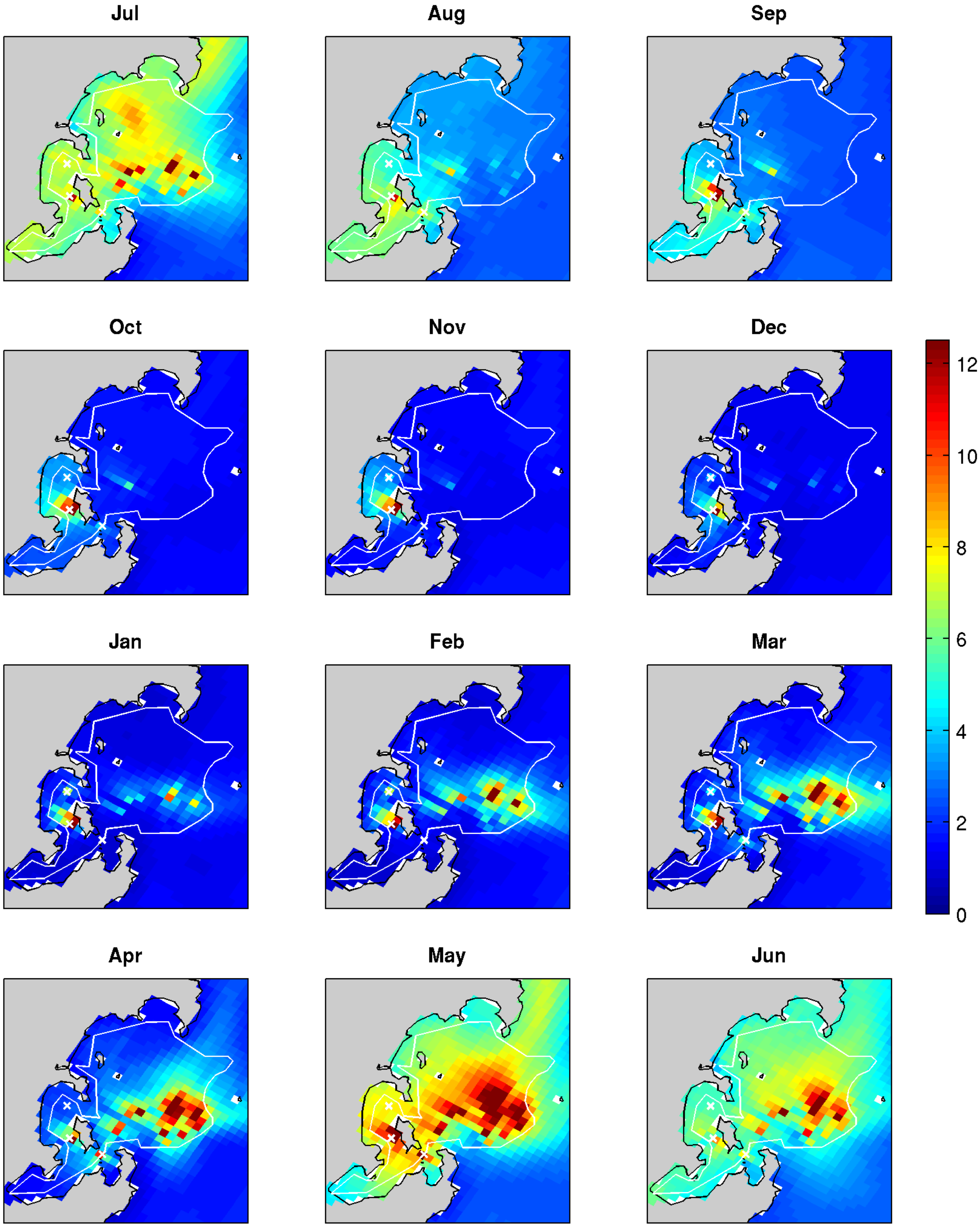

Figure 3.4.4. Monthly-averaged surface ammonium concentrations (µg/L) predicted for the third year (2014/15) of the second scenario study which included proposed YTK aquaculture. To aid visualisation the colorbar scale is set to 1/2 the ANZECC water quality values recommended for marine waters in South Australia. White crosses indicate the location of proposed YTK aquaculture leases and the white line denotes the outer limits of the aquaculture zone.

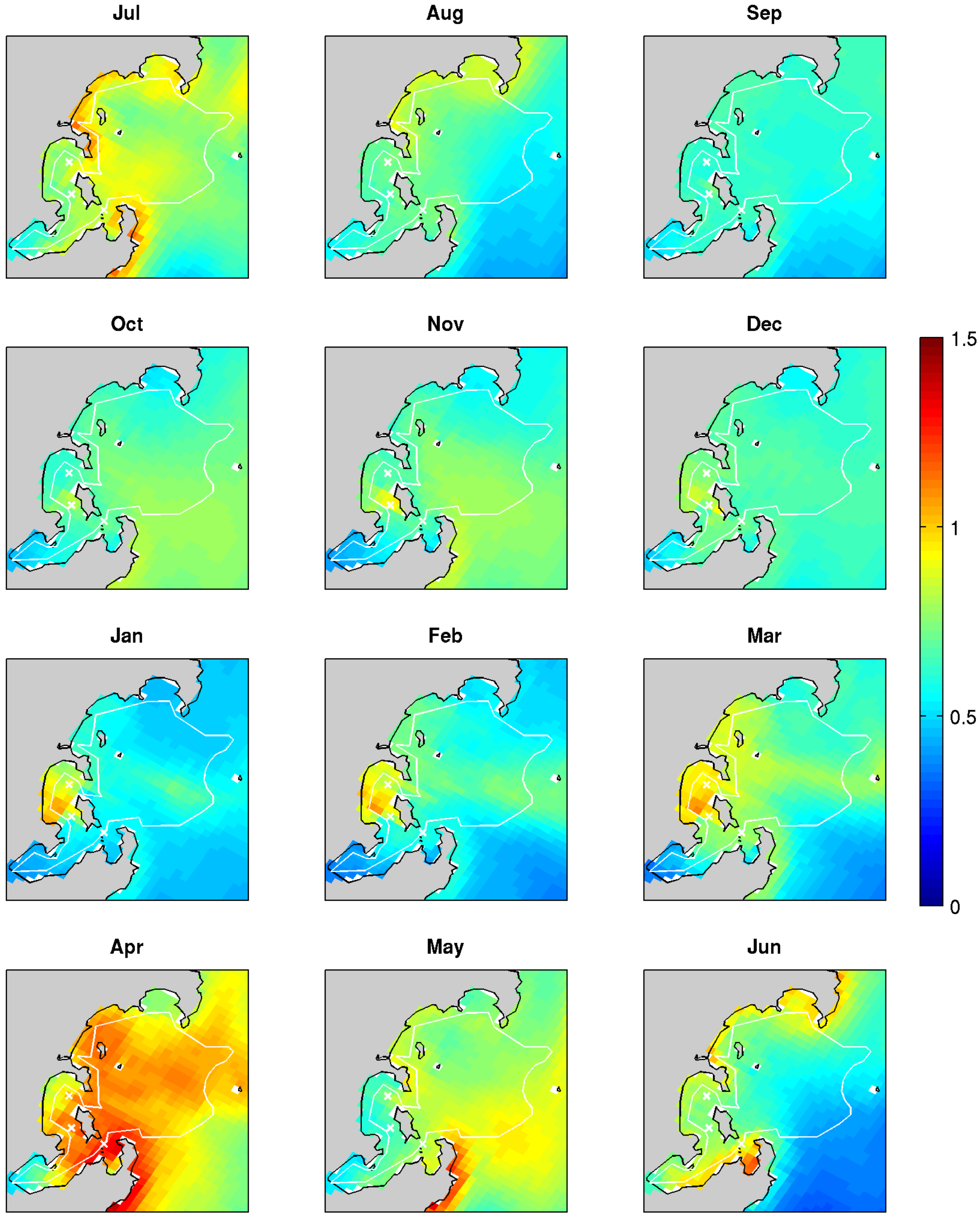

Figure 3.4.5. Monthly-averaged surface chlorophyll (µg/L) predicted for the third year (2014/15) of the second scenario study which included proposed YTK aquaculture. White crosses indicate the location of proposed YTK aquaculture leases and the white line denotes the outer limits of the aquaculture zone.

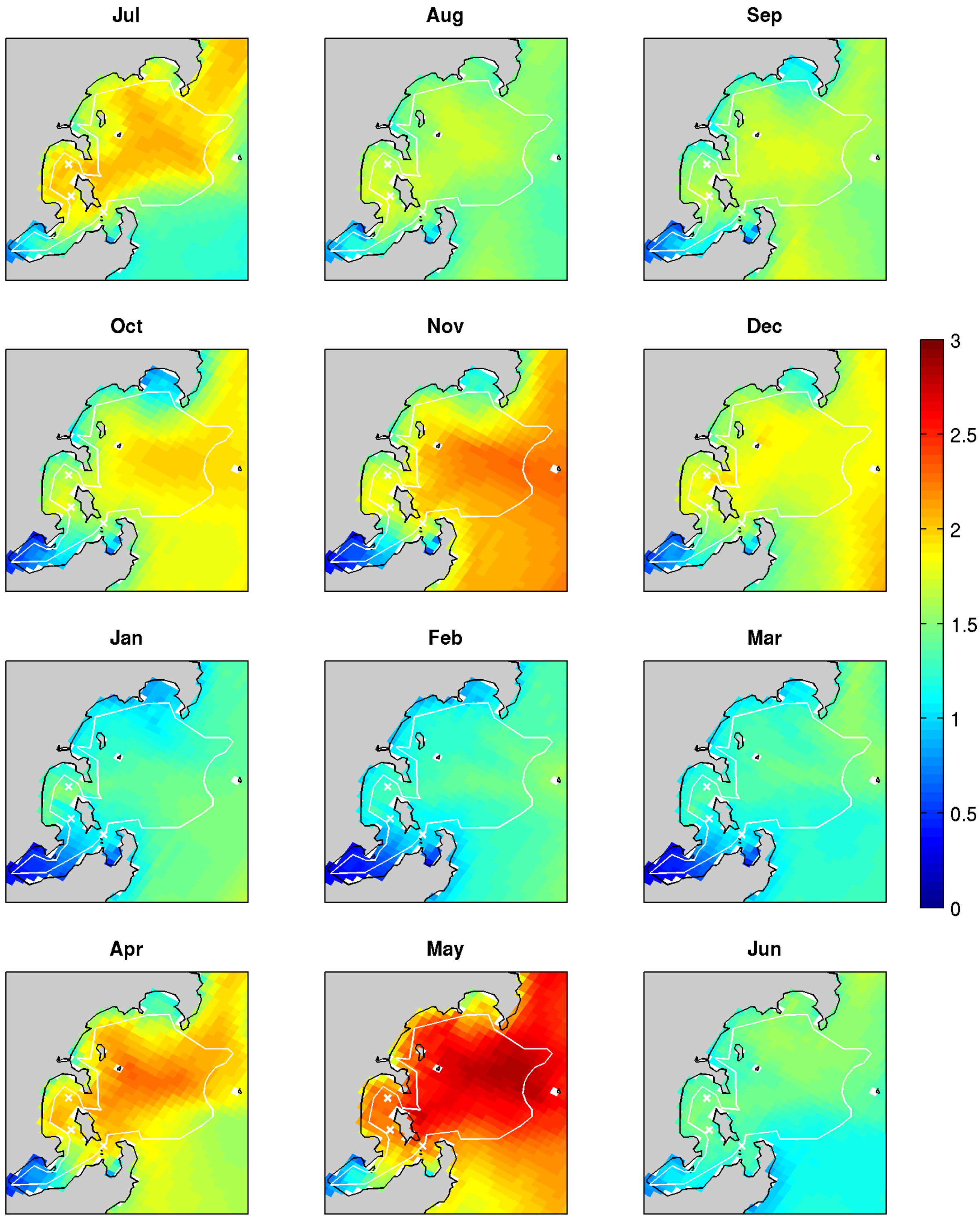

Figure 3.4.6. Monthly averaged bottom detritus concentrations (µg N /L) predicted for the third year (2014/15) of the second scenario which included proposed YTK aquaculture. White crosses indicate the location of proposed YTK aquaculture leases and the white line denotes the outer limits of the aquaculture zone.

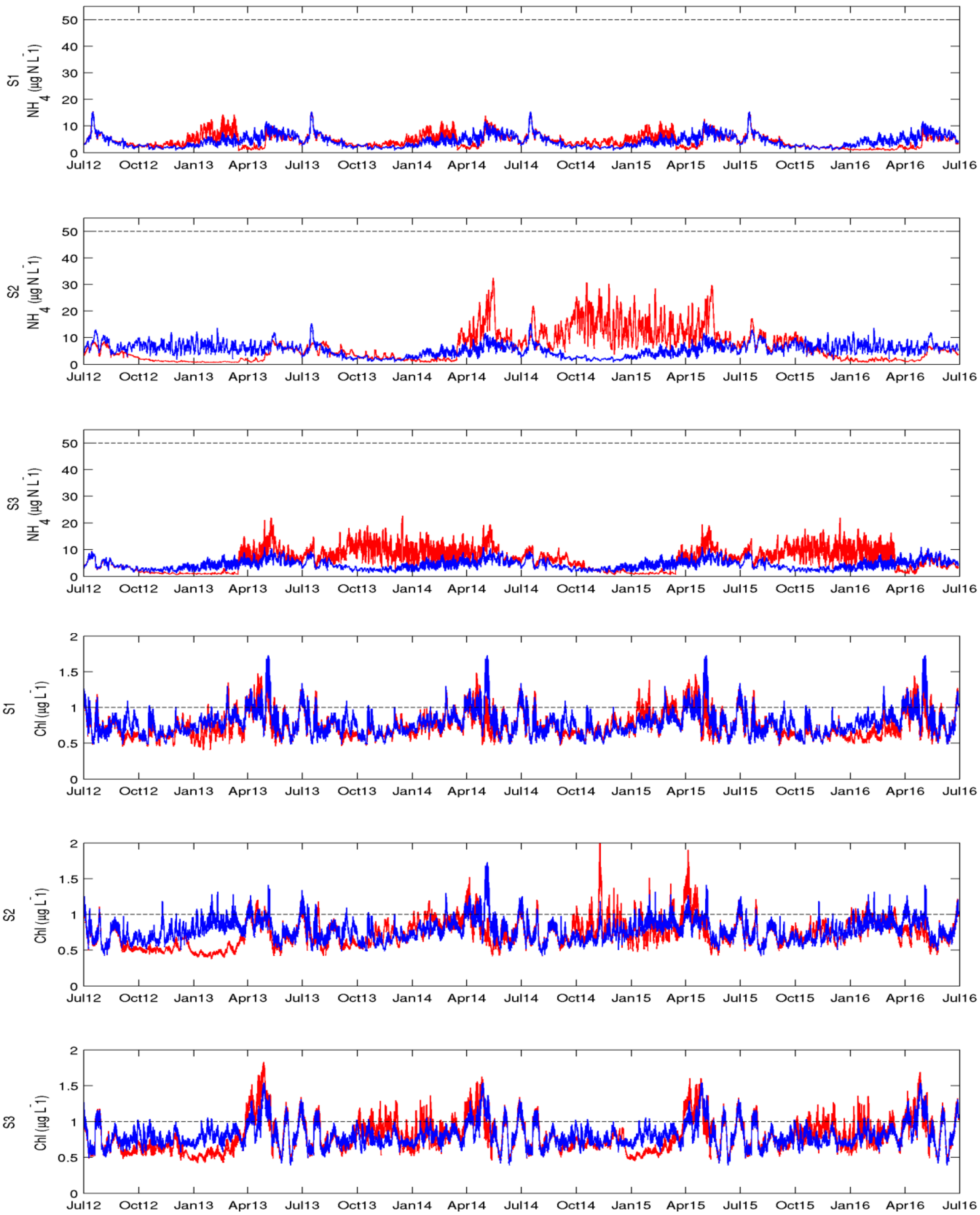

Figure 3.4.7. Time-series modelled ammonium (top panels) and chlorophyll (bottom panels) concentrations at each of the proposed YTK lease sites across the 3-year production cycle. The blue line shows the model results from the control Scenario 1 (i.e. assumed current situation) and the red line shows results for Scenario 2 which includes the newly proposed YTK aquaculture feed schedules. Dashed lines indicate the recommended ANZECC/ARCMANZ (2000) guideline values.

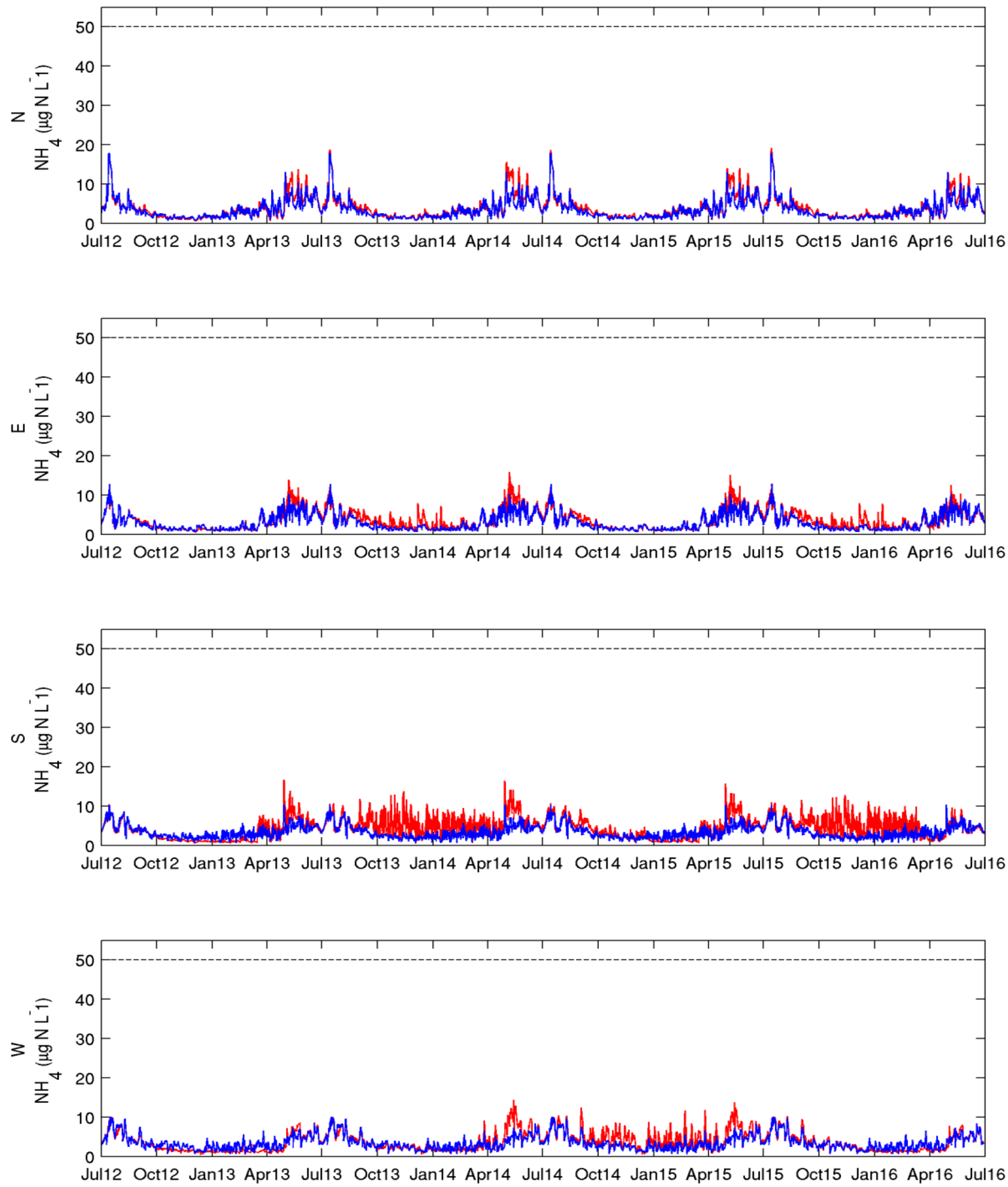

Figure 3.4.8. Time-series modelled ammonium concentrations at each of the virtual monitoring stations positioned to the north (N), east (E), south (S) and west (W) of the proposed YTK lease sites. The blue line shows the model results from the control Scenario 1 (i.e. assumed current situation) and the red line shows results for Scenario 2 which includes the newly proposed YTK aquaculture feed schedules. Dashed lines indicate the recommended ANZECC/ARCMANZ (2000) guideline values.

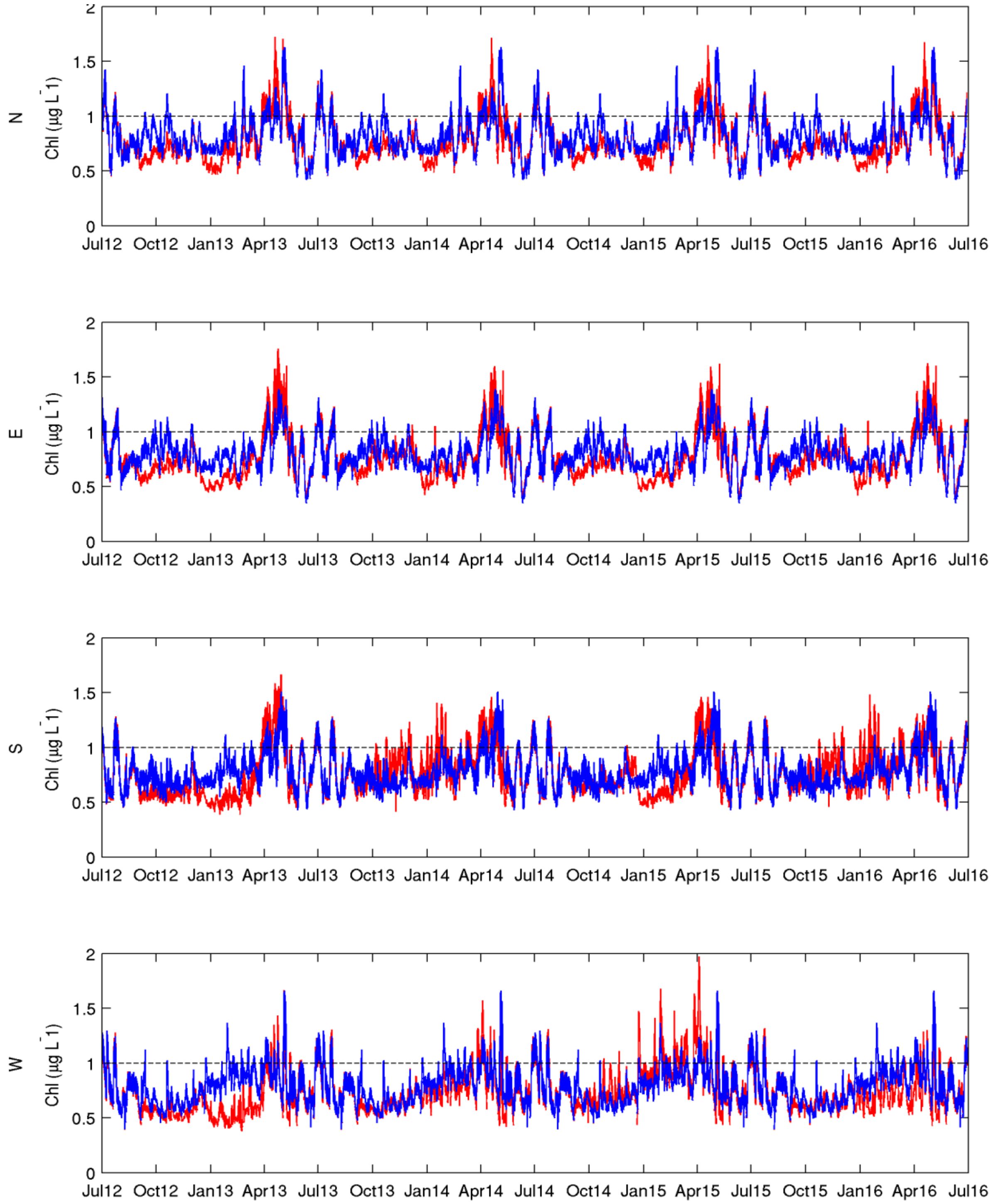

Figure 3.4.9. Time-series modelled chlorophyll concentrations at each of the virtual monitoring stations positioned to the north (N), east (E), south (S) and west (W) of the proposed YTK lease sites. The blue line shows the model results from the control Scenario 1 (i.e. assumed current situation) and the red line shows results for Scenario 2 which includes the newly proposed YTK aquaculture feed schedules. Dashed lines indicate the recommended ANZECC/ARCMANZ (2000) guideline values.

3.4.3. Wallaroo Region

Figures 3.4.10 and 3.4.11 show the monthly averaged surface distribution of ammonium and chlorophyll in the Wallaroo region expected under Scenario 2. Throughout the year the footprint of elevated ammonium concentrations surrounding the proposed lease sites remains relatively constant and is aligned alongshore. This result is consistent with the direction and strength of the dominant currents (Figure 3.1.5) and demonstrates the dominant and efficient role of tidal currents in dispersing ammonium emissions from the proposed lease sites. YTK nutrient loads are lowest in winter (June-August) and correspond with low ammonium concentrations (<10 µg N/L) within the emission footprint. Across late winter/early spring (July-October), the Gulfs' annual circulation drives an increase in the background level of ammonium and chlorophyll in the region. Ammonium, largely transported from the Port Lincoln aquaculture zone, and to a lesser extent from non-aquaculture related sources in upper Spencer Gulf, is observed to gradually impinge on the Wallaroo aquaculture zone. The influence of this externally sourced ammonium is greatest in the Wallaroo region during August and September and leads to increases in the background concentration of ammonium by ~2-4 µg/L. Similarly, small increases in chlorophyll concentrations modelled in the immediate vicinity of lease sites (<0.1-0.2 µg chl/L) are further accompanied by an increase in the background level of chlorophyll transported from other regions in Spencer Gulf. Nutrient loads from YTK aquaculture peak over the warmer months (January-April, Figure 2.4.2) and, while leading to a substantial increase in the ammonium concentration at the lease sites, only small changes are observed in the spatial extent of the overall ammonium footprint. The corresponding spatial distribution and concentration of chlorophyll during these months shows that the additional nutrients emitted from lease sites may be readily assimilated by phytoplankton. Consistent with the broader circulation features (Figure 3.1.4) localised increases in chlorophyll are observed to extend inshore while being transported and diluted primarily northwards along the east coast with the coastal flow. Figure 3.4.12 shows the corresponding monthly averaged bottom detritus concentration. Across late winter/early spring (July-October), the Gulfs annual circulation drives an increase in the background concentration of detritus which gradually encroaches on the Wallaroo aquaculture zone. The detrital footprint across months is consistent with the regional circulation features with increased detrital concentrations extending northwards with the coastal flow, as well as southwards and offshore during cooler months. During the summer period, when YTK feeding/nutrient emissions peak, the detrital footprint extends predominantly northwards along the coast and is associated with marginal increases in the concentration above background levels. This is probably due to the action of the strong tidal and wind driven currents (Figure 3.1.5) that are characteristic of this region in summer and which limit the deposition of organic matter. Consequently, the detrital matter is eventually transported offshore and to the south by the local anticlockwise eddy field in this region (Figure 3.1.4).

The monthly averaging of concentrations presented in Figures 3.4.10 to 3.4.12 smooth out variability found at shorter temporal scales which may be important when monitoring and assessing the impact of water quality on marine ecosystems. Figure 3.4.13 presents time-series of ammonium and chlorophyll concentrations for the two scenario studies at the three proposed YTK sites. For both scenario studies, ammonium concentrations never exceeded the ANZECCC/ARMCANZ (2000) water quality guideline values. Comparison of the modelled ammonium and chlorophyll concentrations show a clear increase in ammonium concentration associated with the YTK feed schedules; particularly during peak summer periods. Both ammonium and chlorophyll levels showed high levels of variability due to tidal modulation, with peak concentrations occurring periodically around high and dodge tides. Notably, the concentrations of both variables periodically return to values close to the baseline concentrations modelled under the control scenario (i.e. no YTK aquaculture) every 12 hours during ebb tides and when nutrient inputs cease. This feature is consistent with the strong periodic tidal currents and associated flushing expected in this region (Figure 3.1.5).

A further comparison of modelled ammonium and chlorophyll concentrations at each of the four virtual monitoring stations under each scenario is presented in Figures 3.4.14 and 3.4.15, respectively. Notwithstanding the proximity of the monitoring sites to lease sites, significant reductions in the concentration of ammonium and chlorophyll, approximately half of that observed at lease sites and monitoring stations to the north and east, were observed at monitoring sites positioned to the south and west showing. These results further demonstrate the strong influence of tidal currents and the local circulation in diluting and dispersing aquaculture related inputs away from lease sites, with the dominant local connectivity to the north and east of the Wallaroo aquaculture zone.

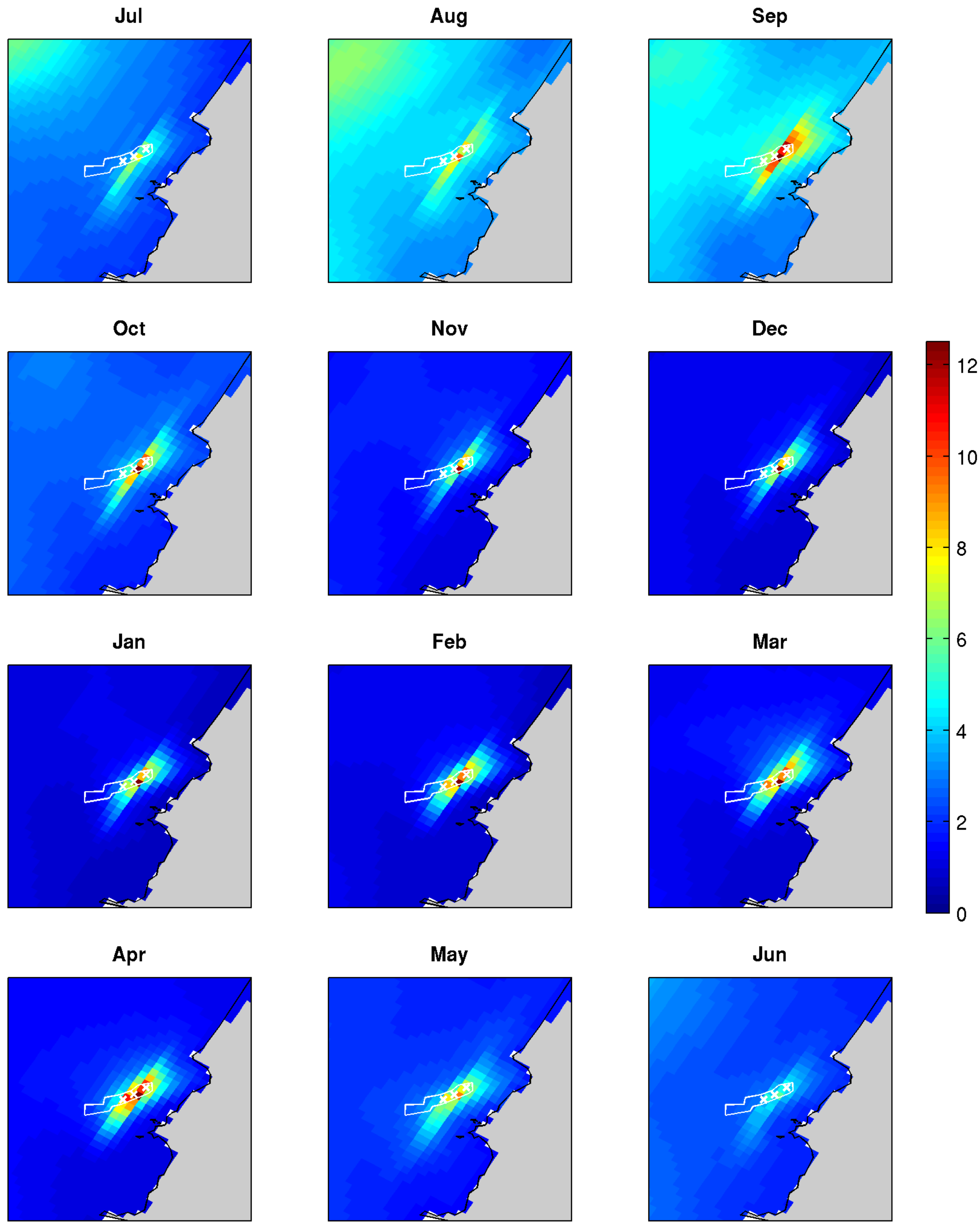

Figure 3.4.10. Monthly-averaged surface ammonium concentrations (µg/L) predicted for the third year (2014/15) of the second scenario study which included proposed YTK aquaculture. To aid visualisation the colorbar scale is set to 1/4 the ANZECC water quality values recommended for marine waters in South Australia. White crosses indicate the location of proposed YTK aquaculture leases and the white line denotes the outer limits of the aquaculture zone.

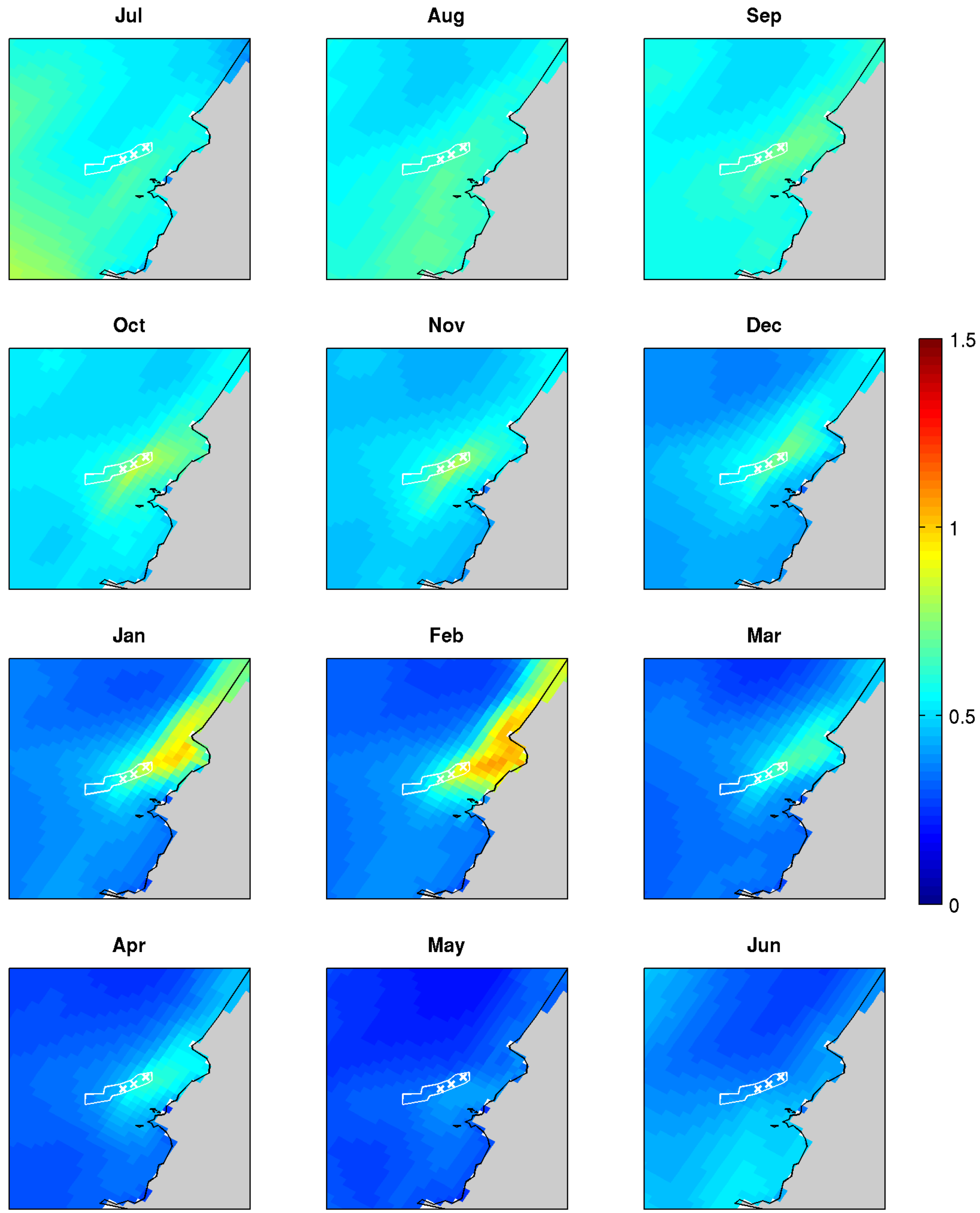

Figure 3.4.11. Monthly-averaged surface chlorophyll (µg/L) predicted for the third year (2014/15) of the second scenario study which included proposed YTK aquaculture. White crosses indicate the location of proposed YTK aquaculture leases and the white line denotes the outer limits of the aquaculture zone.

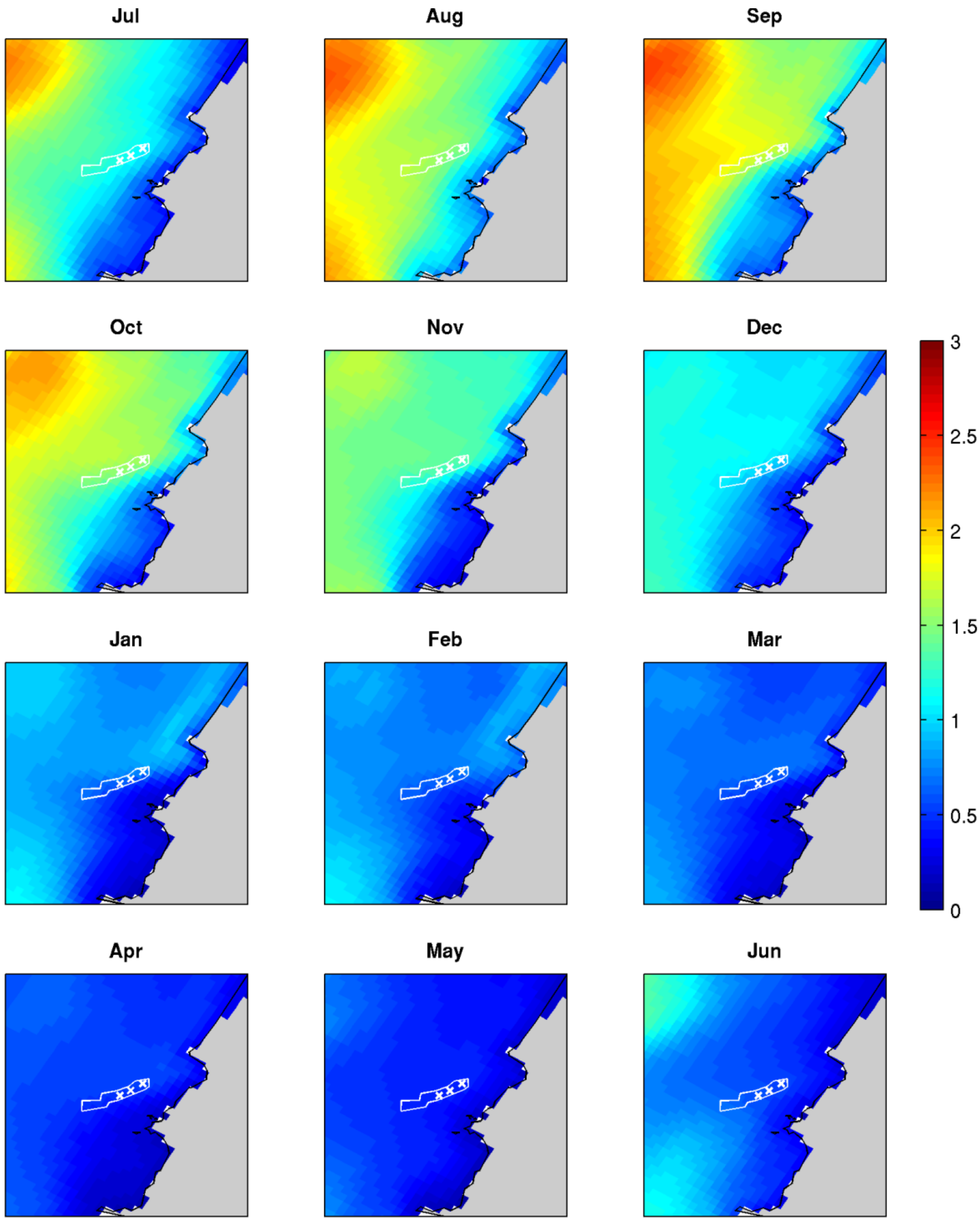

Figure 3.4.12. Monthly-averaged bottom detritus concentrations (µg N /L) predicted for the third year (2014/15) of the second scenario study which included proposed YTK aquaculture. White crosses indicate the location of proposed YTK aquaculture leases and the white line denotes the outer limits of the aquaculture zone.

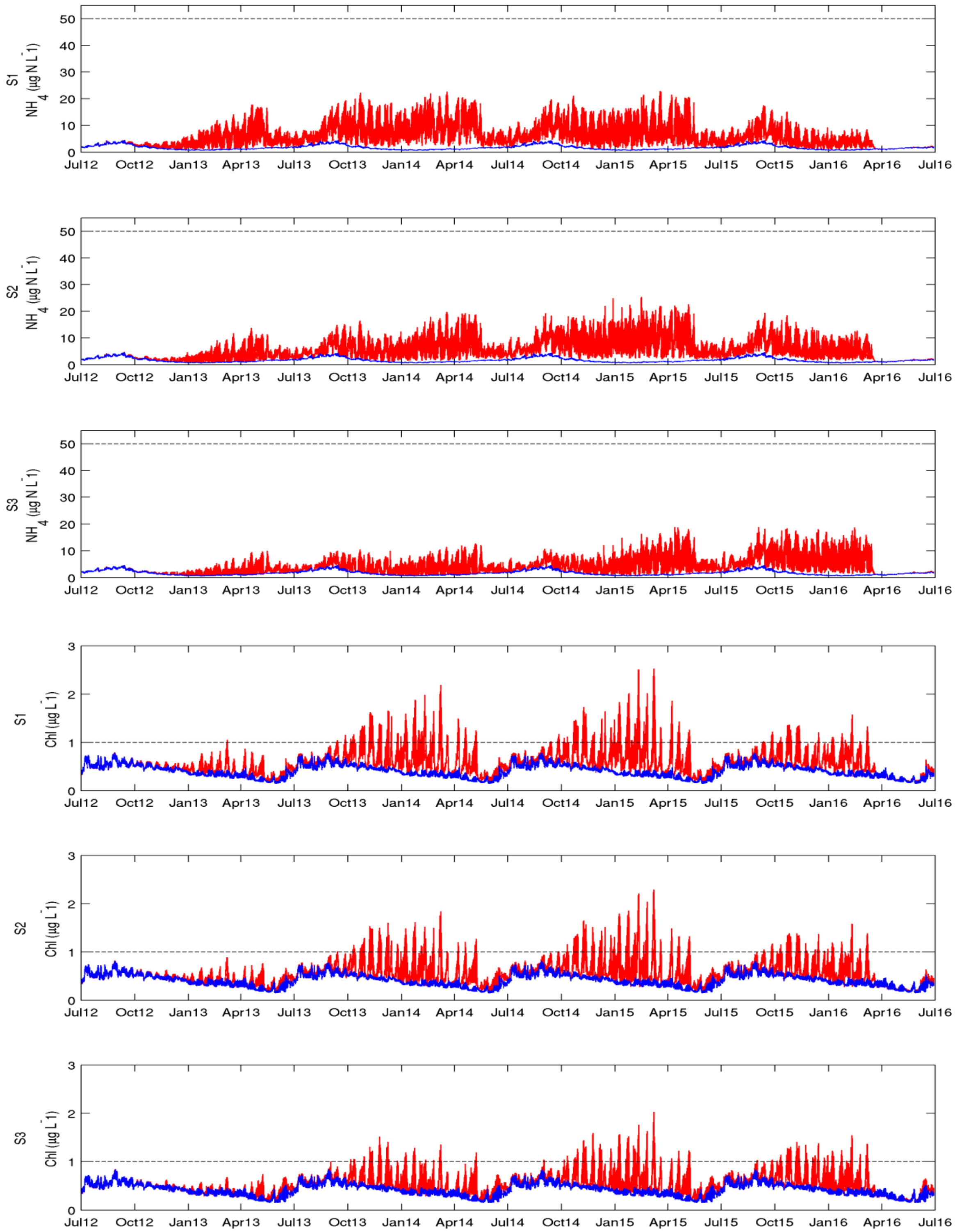

Figure 3.4.13. Time-series modelled ammonium (top panels) and chlorophyll (bottom panels) concentrations at each of the proposed YTK lease sites across the 3-year production cycle. The blue line shows the model results from the control Scenario 1 (i.e. assumed current situation) and the red line shows results for Scenario 2 which includes the newly proposed YTK aquaculture feed schedules. Dashed lines indicate the recommended ANZECC/ARCMANZ (2000) guideline values.

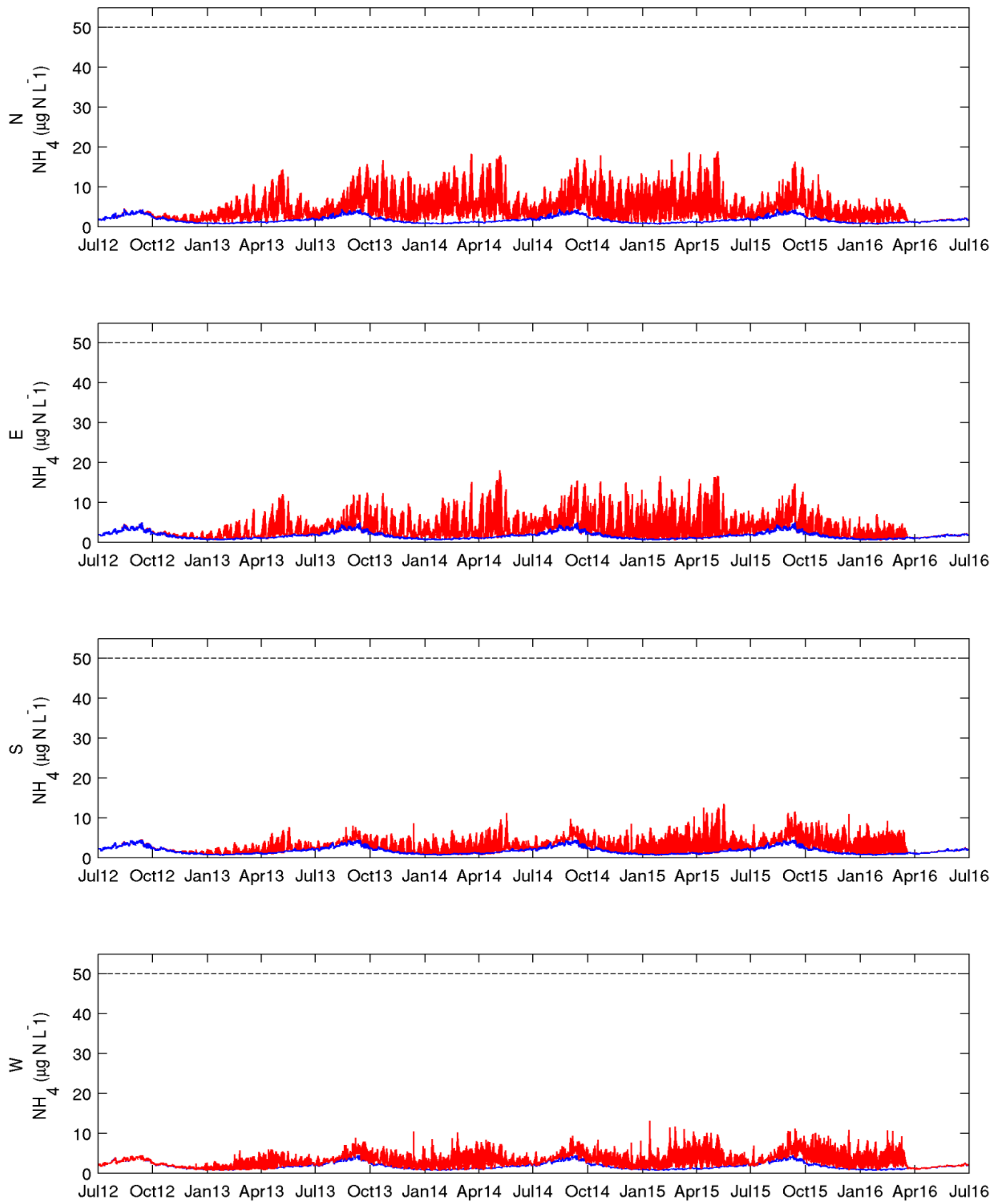

Figure 3.4.14. Time-series modelled ammonium concentrations at each of the virtual monitoring stations positioned to the north (N), east (E), south (S) and west (W) of the proposed YTK lease sites. The blue line shows the model results from the control Scenario 1 (i.e. assumed current situation) and the red line shows results for Scenario 2 which includes the newly proposed YTK aquaculture feed schedules. Dashed lines indicate the recommended ANZECC/ARCMANZ (2000) guideline values.

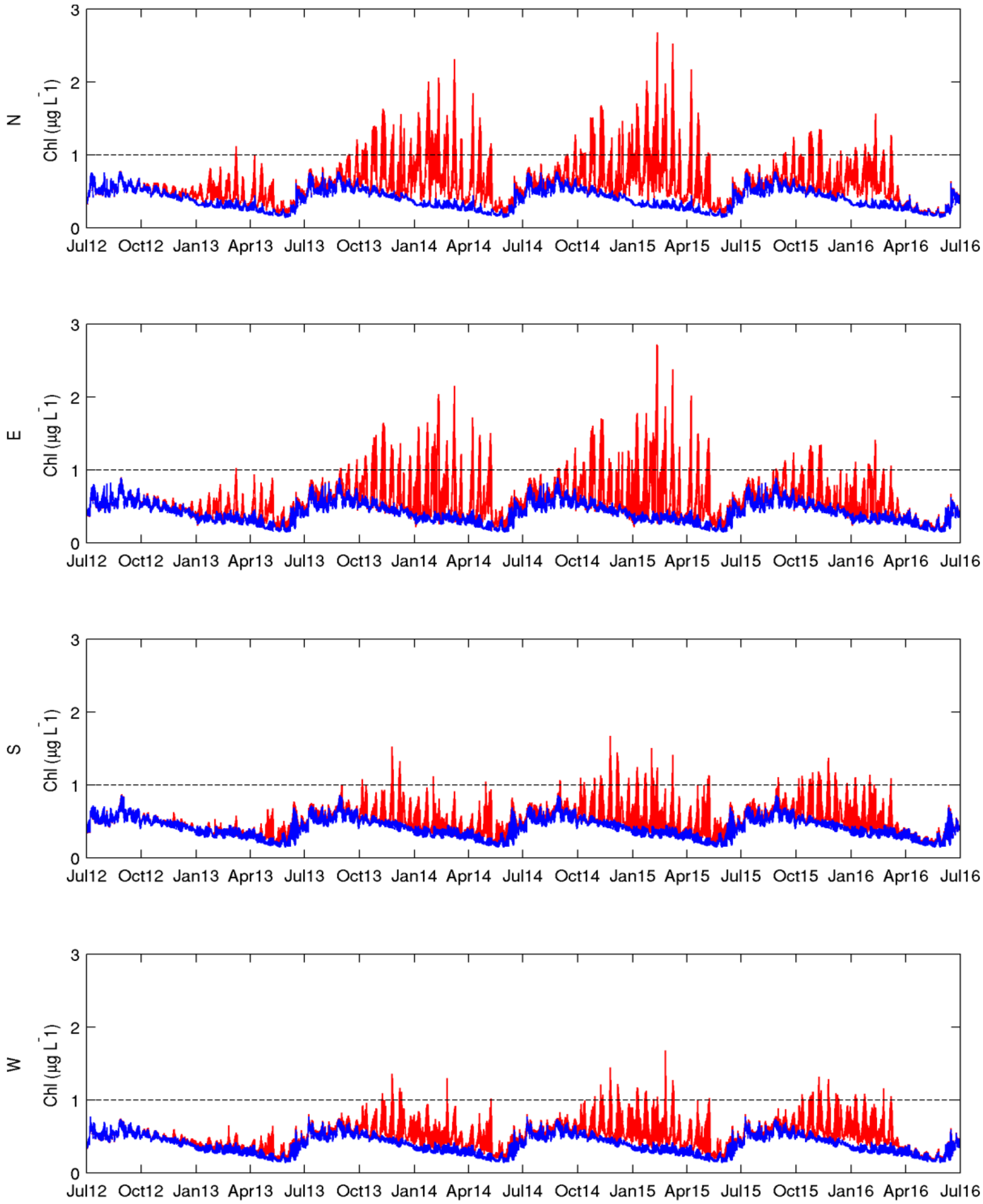

Figure 3.4.15. Time-series modelled chlorophyll concentrations at each of the virtual monitoring stations positioned to the north (N), east (E), south (S) and west (W) of the proposed YTK lease sites. The blue line shows the model results from the control Scenario 1 (i.e. assumed current situation) and the red line shows results for Scenario 2 which includes the newly proposed YTK aquaculture feed schedules. Dashed lines indicate the recommended ANZECC/ARCMANZ (2000) guideline values.

4. CONCLUSION

Oceanographic information was requested by CS to assist in the sustainable development of YTK aquaculture. A suite of previously validated oceanographic models for Spencer Gulf (Middleton et al. 2013) are used to provide estimates of the spatial and temporal variability of key physical, chemical and biological variables for new and existing YTK sites and production strategies proposed for the Wallaroo and Boston Bay aquaculture zones. Modelling scenario studies are used to compare the integrated effect of realistic hydrodynamics and key biological processes on the assimilative capacity of the pelagic ecosystem to nutrient (i.e. ammonium) inputs arising from YTK aquaculture.

For the Boston Bay region, seasonal changes in temperature of up to 9 ^{o}C were modelled across the year, with differences of up to 1.5 ^{o}C occurring between sites during warmer months. Throughout the year, the flow of water around Boston Island follows a general anticlockwise circulation. Offshore residual currents speeds of up to 0.1 m/s are reduced to less than 0.02 m/s inshore from Boston Island. Mean and maximum current speeds ranged between 0.02-0.05 m/s and 0.10-0.25 m/s across sites, with smaller values predicted for the sheltered waters in the lee of Boston Island. Wave activity in the area is low, with mean and maximum significant wave heights less than 0.32 and 1.16 m, respectively. Nutrient concentrations at leases sites under the proposed feeding strategies were predicted to increase by up to a factor of 10 during peak feeding periods compared to the control study. Phytoplankton biomass levels largely remained within the levels of intra-annual variability simulated in the control study which is assumed to be representative of the status quo.

For the Wallaroo region, seasonal changes in temperatures of up to 12 ^{o}C were modelled across the year, with differences of less than 1.0 ^{o}C predicted between sites. Wallaroo experiences increased current and wave activity relative to the Boston Bay region. Largely driven by tides, mean and maximum current speeds at sites ranged between 0.20-0.25 and 0.60-0.70 m/s, respectively. Mean and maximum significant wave heights ranged between 0.80 and 2.4 m, respectively. Nutrient emissions at proposed lease sites were found to be strongly modulated by the tides and showed high variability over the tidal cycle. Peak nutrient and chlorophyll concentrations occurred during high and ‘dodge’ neap tides. In comparison with the control study, nutrient and chlorophyll concentrations during the summertime peak feeding period were intermittently increased by factors of approximately 10 and 2, respectively. Tidal mixing generally acted to periodically lower nutrient and chlorophyll concentrations baseline levels consistent with the control study.

For all modelling studies, finfish aquaculture related nutrient emission (i.e. ammonium) remained below the current recommended ANZECC/ARCMANZ (2000) guideline levels for marine waters. The results for each scenario study have been included in an update of the CarCap software (Middleton et al. 2013). CarCap has been provided to PIRSA Fisheries and Aquaculture for assessing the location and production strategies of the proposed finfish aquaculture sites. CarCap allows managers to assess transport pathways and the concentrations of nutrients and phytoplankton across a range of spatial and temporal scales and to relate these concentrations, through estimates of flushing times (Middleton et al. 2013, Middleton and Doubell 2014, Middleton et al. 2014), to feed levels and published (ANZECC/ARCMANZ 2000), or user-defined, water quality guidelines.

REFERENCES

Alves, J. H. G. M., Chao Y. Y. and Tolman H. L. (2005) The Operational North Atlantic Hurricane Wind-Wave Forecasting System at NOAA/NCEP. NOAA / NWS / NCEP / MMAB Technical Note Nr. 244, 59 pp.

ANZECC/ARMCANZ (2000) Australian and New Zealand guidelines for fresh and marine water ecology. Canberra, ACT.

Avnimelech Y. (1999) Carbon nitrogen ratio as a control element in aquaculture systems. Aquaculture, 176: 227-235.

Bianucci L., Fennel K. and Denman K.L. (2012) Role of sediment denitrification in water column oxygen dynamics: comparison of the North American East and West Coasts. Bio geoscience 9: 2673-2682.

Booij N, Ris R.C. and Holthuijsen L.H. (1999) A third-generation wave model for coastal regions, Part I, Model description and validation. J. Geophys. Res., 104, (C4): 7649-7666.

Burkholder J.M.,Tomasko D.A., Touchette B.W. (2007) Seagrasses and eutrophication, Journal of Experimental Marine Biology and Ecology, 350:46-72.

Doubell M.J., James C., van Ruth P.D., Luick J., Middleton J.F. (2013) Modelling biogeochemical cycles in Spencer Gulf: development of a nitrogen based ecosystem model and implications for aquaculture. In: Middleton, J.F. (Ed.), PIRSA Initiative II: Carrying Capacity of Spencer Gulf: Hydrodynamic and Biogeochemical Measurement, Modelling and Performance Monitoring. FRDC Project No.2009/046. SARDI Publication. South Australian Research and Development Institute (Aquatic Sciences), Adelaide, SARDI Publication No. F2013/000311-1. SARDI Research Report Series No. 705. 97 pp. ISBN: 978-1-921563-51-5, Australian National Library.

Easton, A.K. (1978) A Reappraisal of the Tides in Spencer Gulf, South Australia. Aust. J. Mar. Freshwater Res., 29, 467-477.

Egbert G.D., Bennett A.F., Foreman M.C.G. (1994) Topex/Poseidon tides estimated using a global inverse model, *J. Geophys. Res., 99,* 24821-52.

Fennel K., Wilkin J., Levin J., Moisan M. O'Reilly J. and Haidvogel D. (2006) Nitrogen cycling in the Middle Atlantic Bight: Results from a three-dimensional model and implications for the North Atlantic nitrogen budget. Global Biogeochemical Cycles, Vol 20: GB03007, doi:10.1029/2005GB002456.

Fernandes M., Angove M., Sedawie T., and Cheshire A. (2007) Dissolved nutrient release from solid wastes of southern bluefin tuna (Thunnus Maccoyii, Castelnau) aquaculture.

Fernandes M. and Tanner J.E. (2008) Modelling of nitrogen loads from the farming of yellowtail kingfish Seriola lalandi (Valenciennes, 1833). Aquaculture Research 39, 1328–1338.

Gaylard S. (2014) Marine Pollution within Spencer Gulf. In Natural History of Spencer Gulf, Shepherd S.A., Madigan S., Gillanders B., Murray-Jones S. and Wiltshire D. Roy. Soc. Sth. Aust., Adelaide,432pp.

Howarth R.W. and Marino R. (2006) Nitrogen as the limiting nutrient for eutrophication in coastal marine systems: Evolving views over three decades. Limnol. Oceanogr., 51(1,part2): 364-376.

James, C. 2013. The wave model, In: Middleton, J.F., Wada, K. (Eds.), PIRSA Initiative II: Carrying Capacity of Spencer Gulf: Hydrodynamic and Biogeochemical Measurement, Modelling and Performance Monitoring. FRDC Project No. 2009/046.SARDI Publication. South Australian Research and Development Institute(Aquatic Sciences), Adelaide, 97 pp., SARDI Publication No. F2013/000311-1.SARDI Research Report Series No. 705. ISBN: 978-1-921563-51-5, Australian National Library.

Nixon S. W. (1995) Coastal Marine Eutrophication - a Definition, Social Causes, and Future Concerns. Ophelia, 41: 199-219.

Middleton, J.F., Doubell, M. (2014) Carrying capacity for finfish aquaculture. Part I—Near-field semi-analytic solutions. Aquacult. Eng., (in press), http://dx.doi.org/10.1016/j.aquaeng.2014.07.005

Middleton J.F. J. Luick and James, C. (2014) Carrying Capacity for Aquaculture. Part II – rapid assessment using hydrodynamic and near-field semi-analytic solutions. Aquacult. Eng., (in press), http://dx.doi.org/10.1016/j.aquaeng.2014.07.006

Middleton, J. F., M. Doubell, C. James, J. Luick, and P. van Ruth. (2013) PIRSA Initiative II: carrying capacity of Spencer Gulf: hydrodynamic and biogeochemical measurement, modelling and monitoring. Final report for the Fisheries Research and Development Corporation. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2013/000311-1. SARDI Research Report Series No 705. 97 pp.

Nixon S.W. and Pilson M.E.Q. (1983) Nitrogen in estuarine and coastal marine ecosystems, in Nitrogen in the Marine Environment, edited by E.J. Carpenter and D.G. Capone, pp. 565-648, Elsevier, New York.

Nunes Vaz, R., Lennon, G. & Bowers, D., 1990. Physical behaviour of a large, negative or inverse estuary. Continental Shelf Research, 10(3), pp.277–304.

Olsen Y. and Olsen L.M. (2008) Environmental impact of aquaculture on coastal plank-tonic ecosystems. In: Tsukamoto, K., Kawamura, T., Takeuchi, T., Beard Jr., T.D.,Kaiser, M.J. (Eds.), Fisheries for Global Welfare and Environment, 5th WorldFisheries Congress 2008. TERRAPUB, Tokyo, pp. 181–196.

Petrusevics P., Bye J., Luick J., Teixeira C.E.P.(2011) Summer sea surface temperature fronts and elevated chlorophyllorophyll-a in the entrance to Spencer Gulf, South Australia, Continental Shelf Research, 31:849-856.

Schendel E.K., Nordstrom S.E., Lavkulich L. M. (2004) Floc and sediment properties and their environmental distribution from a marine fish farm. Aquaculture Research, 35: 483-493.

Shchepetkin A.F. and McWilliams J.C. (2005) The regional oceanic modelling system (ROMS): a split-explcit, free-surface, topography-following-coordinate oceanic model, Oceanic Modelling, 9:347-404, doi:10.1016/j.ocemod.2004.08.002

Tanner, J.E., Clark, T.D., Fernandes, M. and Fitzgibbon, Q. (2007) Innovative Solutions for Aquaculture: Spatial Impacts and Carrying Capacity – Further Developing, Refining and Validating Existing Models of Environmental Effects of Finfish Farming. South Australian Research and Development Institute (Aquatic Sciences), Adelaide, 126pp. SARDI Aquatic Sciences Publication Number F2007/000537.

Thompson, R. (1983) Low-Pass Filters to Suppress Inertial and Tidal Frequencies. J. Phys. Oceanogr., 13, 1077-1083

van Ruth, P.D., Doubell, M.J. (2013) Spatial and temporal variation in primary and secondary productivity and lower trophic ecosystem function in Spencer Gulf, South Australia. In: Middleton, J.F., Wada, K. (Eds.), PIRSA Initiative II: Carrying Capacity of Spencer Gulf: Hydrodynamic and Biogeochemical Measurement, Modelling and Performance Monitoring. FRDC Project No. 2009/046.SARDI Publication. South Australian Research and Development Institute (Aquatic Sciences), Adelaide, 97 pp., SARDI Publication No. F2013/000311-1.SARDI Research Report Series No. 705. ISBN: 978-1-921563-51-5, Australian National Library.

Wild-Allen K., Herzfeld, M., Thompson, P.A., Rosebrock, U., Parslow, J., Volkman, J.K. (2009). Applied coastal biogeochemical modelling to quantify the environmental impact of fish farm nutrients and inform managers. *Journal of Marine Systems 81 (1–2)*: 134–147.