

Marine and Tropical Sciences Research Facility

Final Project Report

Project 2.5i.1 Milestone 15 June 2011

Title: Hydrodynamics at the whole of GBR scale

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Summary of Milestone report

This project has successfully developed pilot hydrodynamic models at two nested levels. A regional model covers the continental shelf from Moreton Bay to the mainland of Papua New Guinea, extending eastwards into the Coral Sea. This regional model is nested within an operational global circulation model. A more finely resolved model (the shelf model) is nested within the regional model to cover the continental shelf areas and the adjoining tract of the Coral Sea. By using operational models to provide ocean and atmospheric forcing data, the models have been implemented in a real-time operational capacity, and perform a routine near real-time/forecast cycle. The near real-time application of both models includes the input of river flows for a number of rivers with real-time gauging.

Model evaluation has been undertaken using the archive of results generated by the near real-time application of the regional model. Model results have been compared with observations of coastal sea levels and with current and temperature observations at scattered locations along the GBR collected as part of the Great Barrier Reef Ocean Observing System program. Given the proof of concept nature of the project, thorough calibration of the model was not undertaken, however comparison of predicted and observed features of the hydrodynamics indicate that the models perform well and capture the dominant tidal and large-scale features associated with the general circulation within the GBR.

The 2008-2009 wet season was chosen as the case study to demonstrate the utility of the models to simulate the spatial distribution and fate of freshwater inflows during a significant wet season. Model results compare well with observed plume characteristics for one major River which adds credibility to the models performance in simulating the synoptic distribution of freshwater plumes on the GBR.

The pilot hydrodynamic models developed through this project are the foundation elements upon which to build other components of future receiving water quality models for the GBR, capable of simulating the transport and transformation of terrestrially derived sediments, nutrients and pesticides through the GBR. A future modelling capability such as this could play a critical role in underpinning the development of Water Quality Improvement Plans by providing prediction of the likely impacts of alternative management strategies under prescribed scenarios, underpinning target-setting and strategy selection, and as such, the development of this capability remains a shared goal of CSIRO and AIMS.

For reference: Milestone extracted from Project Schedule

Project 2.5i.1

Date 15 June 2011

Description

Final project report

Final project report including analysis and interpretation of model performance and discussion on the suitability of sub-grid parameterization schemes for future incorporation into the whole of reef model. Final report will also present a strategy for the continued development of the hydrodynamic model as a fundamental component of a large scale water quality model, and the use of this modeling suite as a tool to inform catchment/coastal management. Will also include report on stakeholder workshop.

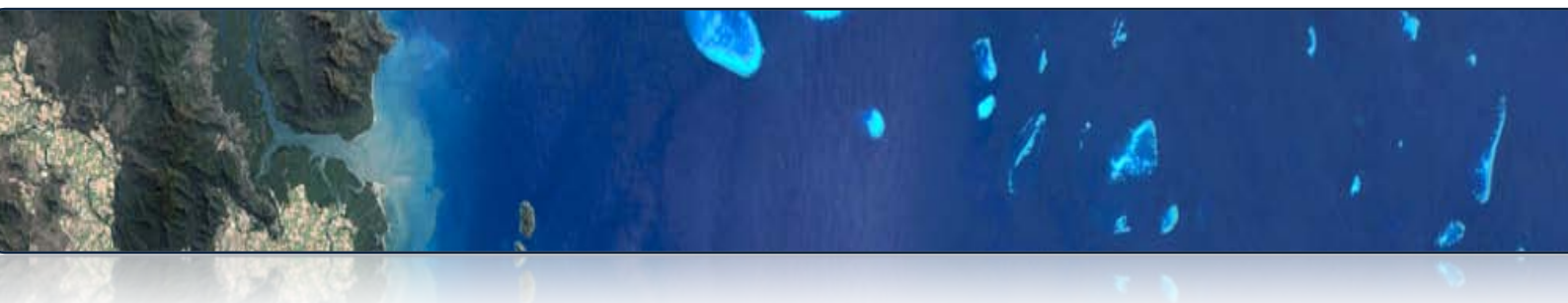
Hydrodynamics at the whole-of-GBR scale

A foundation for receiving water quality models

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Executive Summary

This project has successfully developed pilot hydrodynamic models at two nested levels. A regional model covers the continental shelf from Moreton Bay to the mainland of Papua New Guinea, extending eastwards into the Coral Sea. This regional model is nested within the OceanMAPS global circulation model. A more finely resolved model (the shelf model) is nested within the regional model to cover the continental shelf areas and the adjoining tract of the Coral Sea. By using operational models to provide ocean and atmospheric forcing data, the regional model has itself been implemented in a real-time operational capacity, and performs a routine near real-time/forecast cycle. The shelf model, due to slower run times, operates only in near real-time mode, and a forecast is not delivered. The near real-time application of both models includes the input of river flows for a number of rivers with real-time gauging.

Model evaluation has been undertaken using the archive of results generated by the near real-time application of the regional model. Model results have been compared with observations of coastal sea levels and with current and temperature observations at scattered locations along the GBR collected as part of the Great Barrier Reef Ocean Observing System program. Given the proof of concept nature of the project, thorough calibration of the model was not undertaken, however comparison of predicted and observed features of the hydrodynamics indicate that the models perform well and capture the dominant tidal and large-scale features associated with the general circulation within the GBR.

The 2008-2009 wet season was chosen as the case study to demonstrate the utility of the models to simulate the spatial distribution and fate of freshwater inflows during a significant wet season. For the hindcast period, model results were compared with limited sub-surface salinity observations and remote sensing imagery. Simulated surface salinity distributions showed qualitative agreement with observations of the extent and timing of the predicted surface fresh water plume, and predicted sub-surface salinity time series compared well with observed salinity time series that captured the propagation of Burdekin River plume. The models performance for this test case adds credibility to the models performance in simulating the synoptic distribution of freshwater plumes on the GBR.

The pilot hydrodynamic models developed through this project are the foundation elements upon which to build other components of future receiving water quality models for the GBR, capable of simulating the transport and transformation of terrestrially derived sediments, nutrients and pesticides through the GBR. A future modelling capability such as this could play a critical role in underpinning the development of Water Quality Improvement Plans by providing prediction of the likely impacts of alternative management strategies under prescribed scenarios, underpinning target-setting and strategy selection, and as such, the development of this capability remains a shared goal of CSIRO and AIMS.

Introduction

A modelling framework that links the management of agricultural activities in catchments that drain into the Great Barrier Reef (GBR) to water quality and ecological responses in receiving waters has been recommended as an approach to support the design and implementation of water quality improvement plans (Webster et al 2008). Such a framework would link models of land use and contaminant supply to the transport of these contaminants down rivers and through estuaries and ultimately to the transport and transformation of this material in marine systems. The conceptual linkages between agricultural activities in catchments and receiving water quality targets are illustrated in Figure 1.



Figure 1 Conceptual linkages between management action targets and targets/objectives for receiving waters water quality and ecosystem health (from Webster et al. 2008)

The fate of material delivered to the marine environment can be simulated through the application of materials transport and transformation models, the foundation of which is a robust and validated 3-dimensional hydrodynamic model (see Figure 2). Hydrodynamic models simulate the advection and mixing of water and as such are a necessary precursor to the development of water quality and ecological response models that can be applied generically in the GBR lagoon to support Water Quality Improvement Plan (WQIP) development and implementation (Webster et al. 2008).

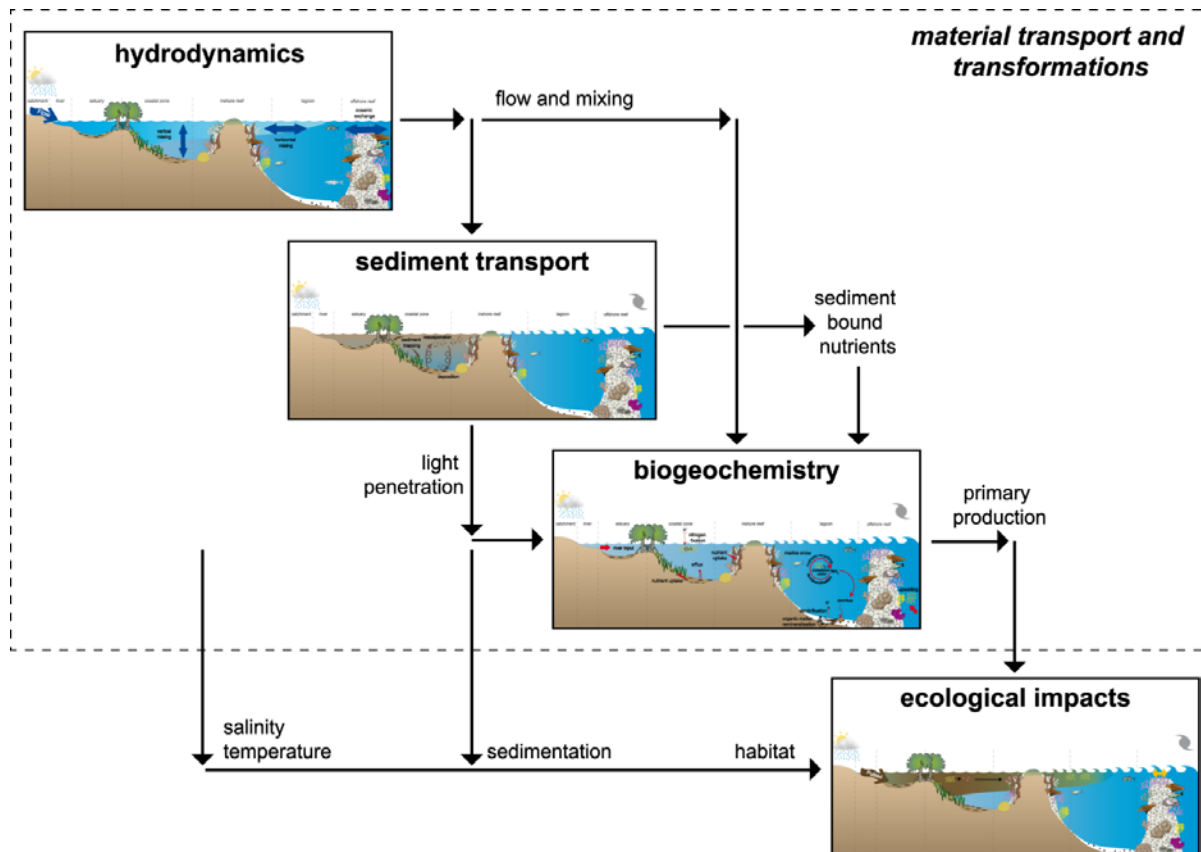


Figure 2 Primary components of a material transport and transformation models (inside box), and showing internal linkages between sub models and linkage to ecological impacts models (from Webster et al. 2008).

This project has successfully developed a nested suites of 3-dimensional baroclinic hydrodynamic models of the entire GBR at spatial resolution capable of capturing the key oceanographic processes impacting the region. The models adequately represent the dominant physical processes that control currents, mixing, temperature and salinity within the GBR lagoon and exchanges with the adjacent Coral Sea. These models have been developed as a 'proof of concept' to demonstrate the feasibility of modelling such a large and complex domain, acknowledging that a 3-dimensional hydrodynamic model is a necessary precursor to the development of sediment dynamics and biogeochemical components of a whole of GBR Water Quality Model.

This document reports on the development of the models and their deployment in a near real-time operational mode, and describes the preliminary validation of the model against observational data and a case study involving a hindcast simulation of 3-dimensional hydrodynamics during the 2008-2009 wet season.

Methodology

Modelling framework

The modelling framework adopted for this study involves nesting a regional hydrodynamic model within a global circulation model, in order to provide accurate forcing data along the boundary with the Coral Sea, where mesoscale oceanographic processes strongly affect exchange between the Coral Sea and the GBR Lagoon. The regional model covers the continental shelf from Moreton Bay to the mainland of Papua New Guinea, extending eastwards into the Coral Sea Territories a sufficient distance to avoid the topographical complexities of the Queensland and Marion plateaus (see Figure 3). The regional model is intended to simulate the dominant oceanographic processes impacting on the GBR shelf, including the significant mesoscale features of the South Equatorial Current (SEC) and the current jets that result from the interactions of the SEC with the Queensland and Marion Plateaus. The average resolution of the regional model is 4 km. Within this regional grid, a more finely resolved model (the shelf model) with resolution of 1 km is nested to cover the continental shelf areas and the adjoining tract of the Coral Sea. Output from the regional model is used to force the boundaries of the shelf model.

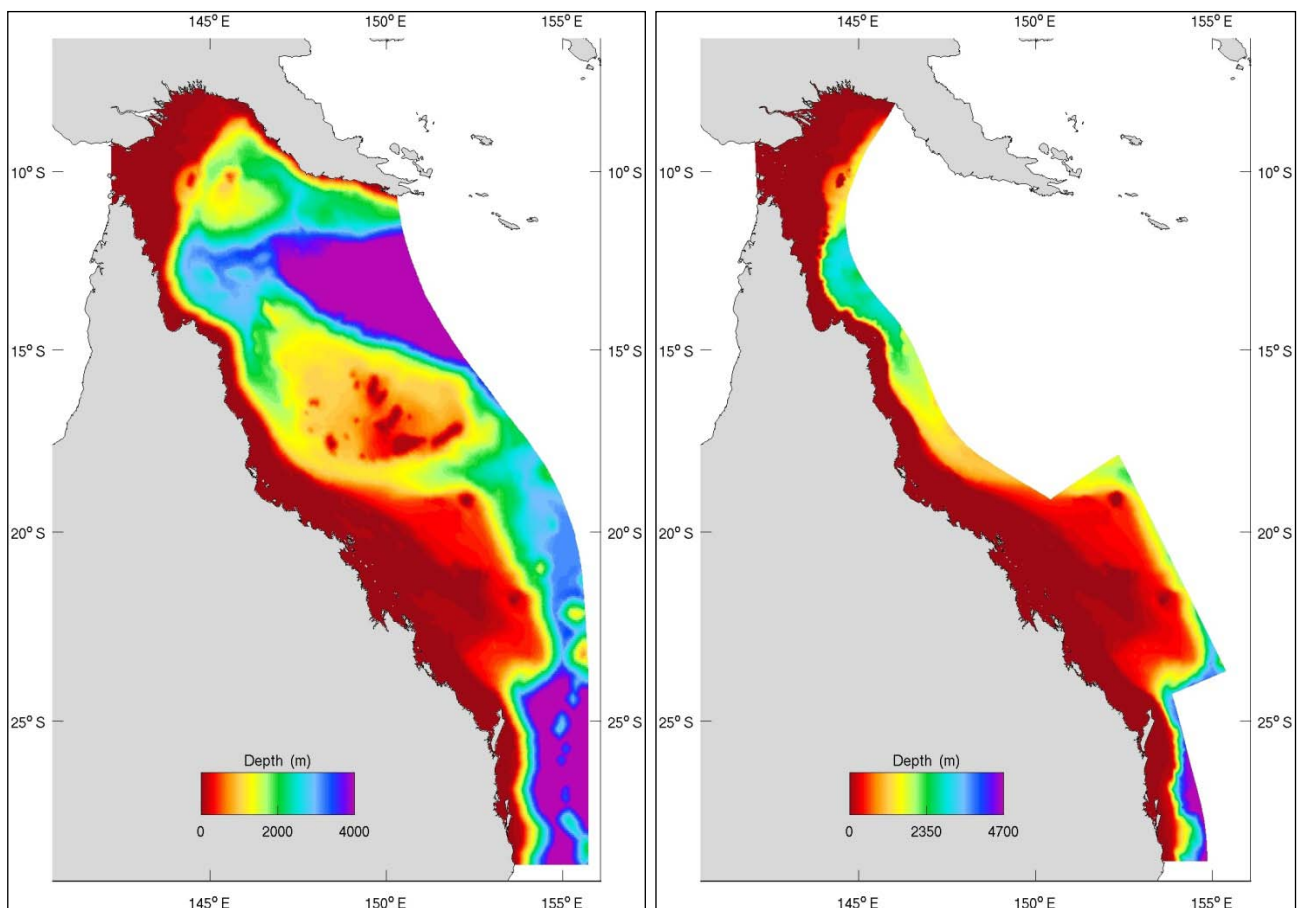


Figure 3 Model domains and bathymetry established for regional (left) and shelf (right) models.

Model Description

The hydrodynamic model SHOC (Sparse Hydrodynamic Ocean Code; Herzfeld et al., 2006) is employed for this study for both the regional and shelf model applications. SHOC is a general purpose model (Herzfeld, 2006) based on the paper of Blumberg and Herring (1987), applicable on spatial scales ranging from estuaries to regional ocean domains. It is a three-dimensional finite-difference hydrodynamic model, based on the primitive equations. Outputs from the model include three-dimensional distributions of velocity, temperature, salinity, density, passive tracers, mixing coefficients and sea-level. Inputs required by the model include forcing due to wind, atmospheric pressure gradients, surface heat and water fluxes and open-boundary conditions such as tides and low frequency ocean currents (Figure 4). The model is based on the equations of momentum, continuity and conservation of heat and salt, employing the hydrostatic and Boussinesq assumptions. The equations of motion are discretized on a finite difference stencil corresponding to the Arakawa C grid.

The model uses a curvilinear orthogonal grid in the horizontal and a choice of fixed 'z' coordinates or terrain-following σ coordinates in the vertical. The 'z' vertical system allows for wetting and drying of surface cells, useful for modelling regions such as tidal flats where large areas are periodically dry. The current implementation of the model uses z-coordinates. The bottom topography is represented using partial cells. SHOC has a free surface and uses mode splitting to separate the two dimensional (2D) mode from the three dimensional (3D) mode. This allows fast moving gravity waves to be solved independently from the slower moving internal waves allowing the 2D and 3D modes to operate on different time-steps, resulting in a considerable contribution to computational efficiency. The model uses explicit time-stepping throughout except for the vertical diffusion scheme which is implicit. A Laplacian diffusion scheme is employed in the horizontal on geopotential surfaces. Smagorinsky mixing coefficients may be utilized in the horizontal. The ocean model can invoke several turbulence closure schemes, including k- ϵ , k- ω , Mellor-Yamada 2.0 & 2.5 and Csanady type parameterizations. A variety of advection schemes may be used on tracers and 1st or 2nd order can be used for momentum. The model also contains a suite of open boundary conditions, including radiation, extrapolation, sponge and direct data-forcing. A generous suite of diagnostics is included in the model.

The equations of motion SHOC are based upon are similar to those described in Blumberg and Herring (1987).

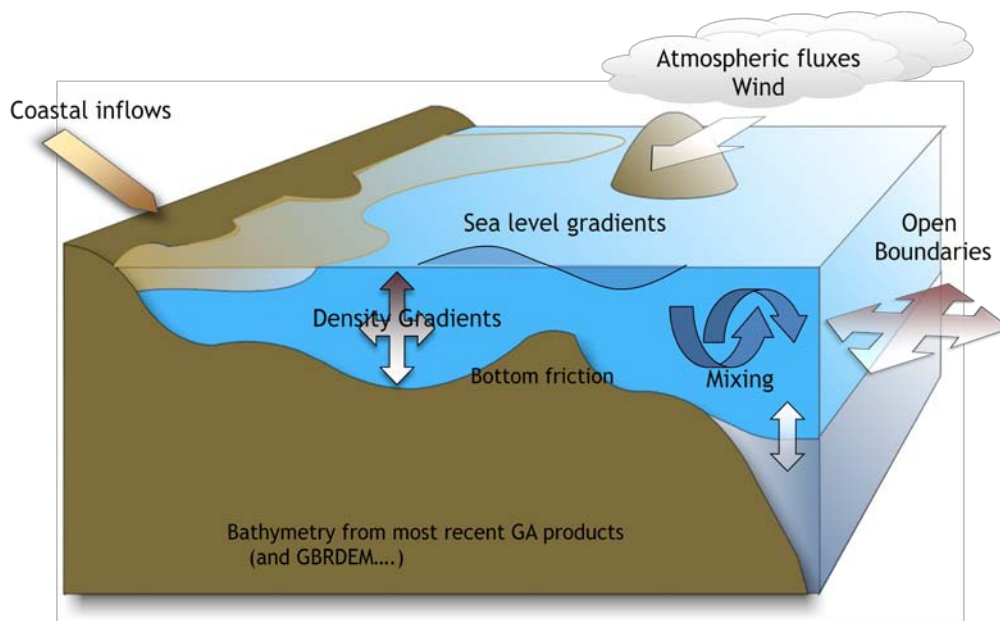


Figure 4. Schematic representation of major forcing inputs for the SHOC hydrodynamic model.

Model Grids – regional and shelf models

The regional application of SHOC has a horizontal resolution ranging from 3 km to 7 km, with a large proportion of the model domain having a resolution of approximately 4 km (Figure 5). The grid established for the shelf model has a horizontal resolution of approximately 1 km for the majority of the GBR shelf (Figure 5).

The regional grid size is 220 x 500 horizontally with 45 vertical layers; the shelf grid size is 510 x 2389 horizontally with 49 layers in the vertical. Both grids have a minimum depth of 1 m, and maximum depths of 4000 m and 4790 m for the regional and shelf grids, respectively. The depth of the vertical layers map identically between the two grids, except for depths greater than 3780 m that are not resolved by the regional grid. Both model grids include 14 layers in surface 100m depth, with 4 layers in the surface 11 m, to enable adequate resolution of any vertical structure in the water column, particularly buoyant freshwater plumes that are associated with wet season flood events.

Time steps for the regional model are 90 s and 5 s respectively for the 3D and 2D modes, giving a runtime ratio of ~31:1. For the shelf model, 3D/2D time steps and runtime ratios are 60 s/1 s and 1:1 respectively

Bathymetry data for the regional grid was derived primarily from the Geoscience Australia - Australian bathymetry and topography grid (Geoscience Australia, 2009), which had a spatial resolution of ~250m. Vertical datum for this data was Mean Sea Level (MSL). The coastline was determined by using MSL and the bathymetry data set to delineate the boundary between wet and dry cells. The shelf model used the Digital Elevation Model of the GBR produced at 100 m spatial resolution (Beaman, 2010), <http://www.deepreef.org/>.

The model grids did not explicitly describe the river mouths and estuaries. River flows were prescribed as inflows to coastal cells at locations of river mouths, with the flow velocity decreasing in a parabolic fashion from a maximum value at the surface to zero at a depth of the bottom, such that the flow rate over the entire open boundary corresponds to a user specified rate.

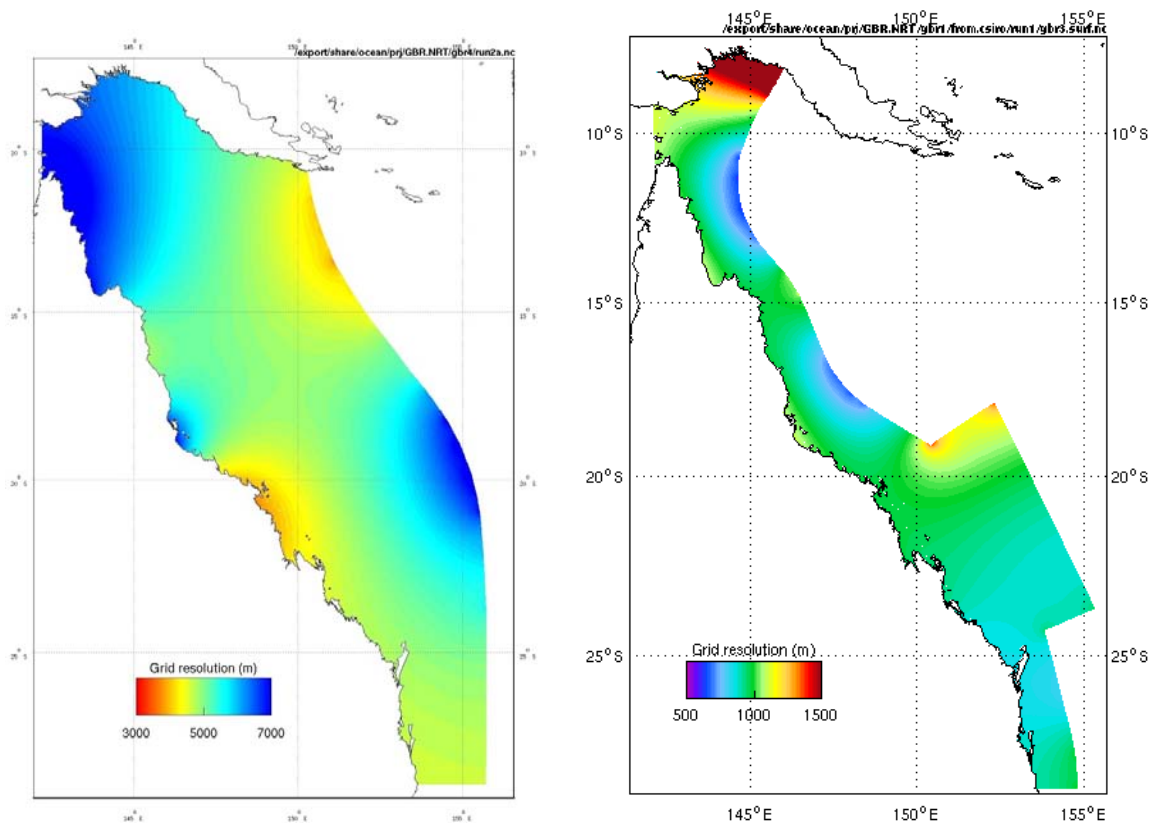


Figure 5. Grid resolution for regional (left) and shelf (right) models.

Examples of how the regional and shelf scale grids resolve the topographic features on the GBR shelf are presented in Figure 6. It must be recognized that the 4-km regional model is an intermediate step required to downscale the larger ocean model to the shelf scale 1-km resolution model, and as such, the regional model does not attempt to reproduce the fine bathymetric and topographic detail inherent in the GBR bathymetry. However, the higher spatial resolution of the 1-km grid more realistically captures the individual reefs and passages that are ubiquitous features of the GBR bathymetry (Figure 6). The difference between the 4- and 1-km grids, and the subsequent description of the bathymetry is highlighted around the Capricorn Bunker Group of Islands (bottom middle and bottom left panel of Figure 6). At 4-km resolution, the various reefs, islands and shoals display very little definition, and are represented in the model as relatively smooth feature, or in some cases, not represented at all. At 1-km resolution, there is a much higher level of description of the islands, reefs

and shoals, and importantly, passage between reefs that are likely conduits for ocean-shelf exchange, are much more highly resolved.

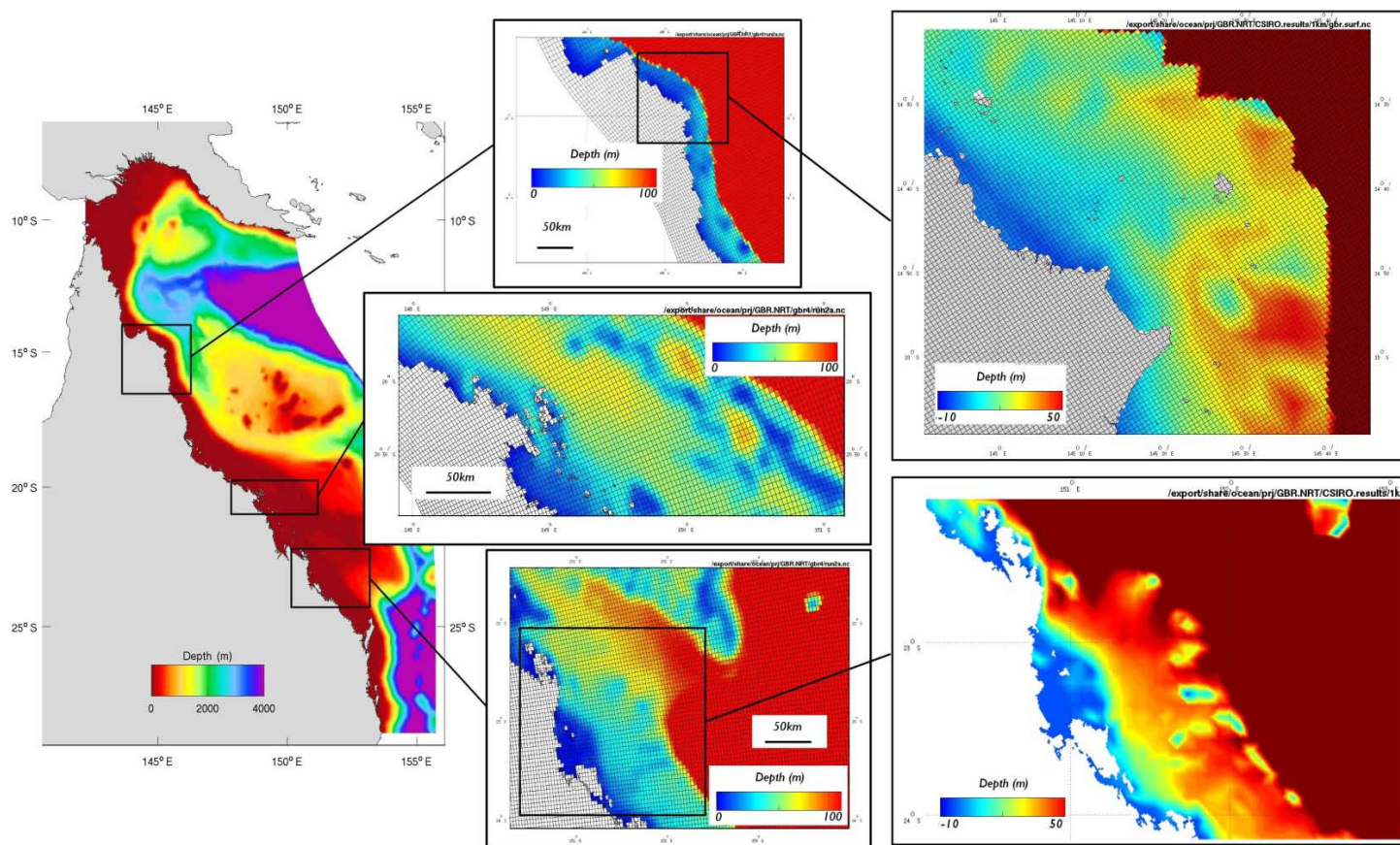


Figure 6 Domain and bathymetry of the regional (left and centre) and 1-km shelf (right) model grids, and examples of grid resolution at various subregions within the domain. Note change in depth colour scale between full domain and regional subset images.

Model forcing

Oceanic forcing for the regional model was provided by the global ocean operational model OceanMAPS, operated by the Bureau of Meteorology (BOM). OceanMAPS is a data assimilating global model with 10 km horizontal resolution in the Australasian region, using the MOM4p1 ocean model as the code base. OceanMAPS provides time evolving fields of currents, temperature, salinity and sea level for use in forcing the regional model. Global model outputs are considered the best product suitable for forcing the nested models, due to their superior temporal and spatial resolution compared to observational data or climatologies. Tidal forcing is included via the OTIS tidal model superimposed on the low frequency sea level oscillation provided by OceanMAPS on the regional grid open boundary. This tidal signal was introduced via a local flux adjustment (Herzfeld, 2009). Forcing for the shelf model is provided by output from the 4km regional model,

Atmospheric forcing products (wind, pressure, heatflux, precipitation, evaporation) are supplied by the ACCESS atmospheric model at 1/8 degree resolution. This modeled product is preferable to

spatially interpolated meteorological data supplied by BOM weather stations for surface forcing, since its spatial detail is superior. ACCESS provides wind, mean sea level pressure, cloud amount, air temperature and dew point temperature. From these variables, bulk schemes (Kondo, 1975) are used to compute sensible and latent heat fluxes, and black body radiation may be used to compute long wave radiation (Zillman, 1972). The sum of these and computed short wave input provides a net heat budget.

By using operational near real-time models to provide ocean and atmospheric forcing data, the regional model has itself been implemented in a near real-time operational capacity, with the operational cycle governed primarily by the operational cycle of OceanMAPS. OceanMAPS produces a near real-time analysis and seven day forecast twice per week on Mondays and Thursdays. The analysis is performed five days behind real-time to make use of satellite altimetry which arrives 3 days behind real-time together with available in situ observations. The ocean model is then integrated for a further four days up to real-time and then an additional seven days for the forecast period. The regional model utilizes this output to produce a weekly near real-time nowcast and forecast, twice per week. Output from the sequence of nowcasts are then joined to construct a single model time series which is archived as 3-dimensional fields of currents, salinity and temperature and 2-dimensional fields of sea-surface elevation. The archive of the regional model extends from March 2010 to the present, currently providing 15 months of output data.

The near real-time implementation also includes real-time information on river flows for rivers shown in Table 1. These river streamflow data are obtained from the Queensland Government Department of Environment and Resource Management, described at http://www.derm.qld.gov.au/water/monitoring/current_data.

Normanby River	Daintree River
Barron River	Mulgrave-Russell Rivers
Johnstone River	Tully River
Herbert River	Haughton River
Burdekin River	Don River
O'Connell River	Pioneer River
Fitzroy River	Burnett River
Mary River	

Table 1: Rivers included in the regional and shelf models, and the 2008-2009 wet season hindcast.

Results

Results presented in the following section represent output from the pilot implementation of both the regional and shelf models. It should be stressed that given the 'proof of concept' nature of the project, the model has not been fully calibrated, and as such only a preliminary evaluation of model performance has been undertaken.

Regional Model

The general synoptic circulation produced by the regional model shows encouraging agreement with major circulation features of the Coral Sea circulation adjacent to the GBR, and tidal dynamics on the GBR shelf. The model resolves important meso-scale circulation features (Figure 7) such as the poleward flowing East Australian Current and the equatorward flowing Hiri Current that are known to impact low frequency currents on the GBR shelf (Brinkman *et al*, 2002).

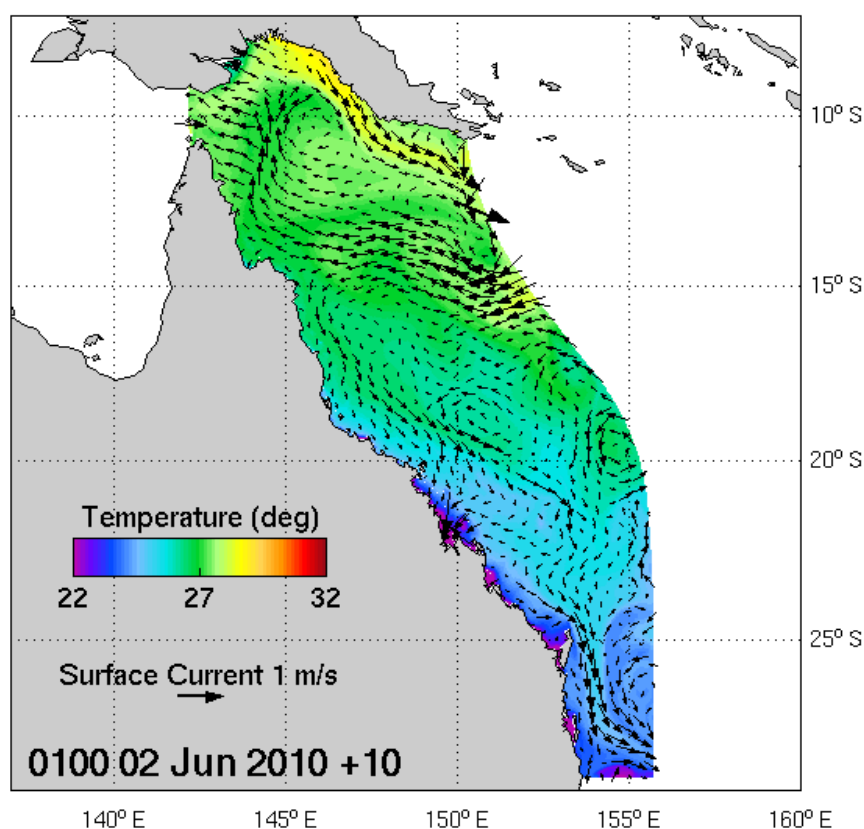


Figure 7 Snapshot of surface velocity vectors and sea surface temperature from the regional resolution model.

The coarse resolution of the model relative to the topographical complexity of the reef systems on many parts the GBR shelf implies that the model simulations will not resolve the fine-scale circulation features at the scale of individual reefs below the resolution of the model. However, large scale

motions such as the propagation of tides and sub-tidal motion in response to oceanic and atmospheric forcing are well captured in the modelled sea levels. Inter-comparison between observed and predicted tidal sea levels, which drive the general circulation, are a powerful verification of a model's performance, and the general agreement of both magnitude and phasing of tidal water level fluctuations at coastal stations throughout the GBR (Figure 8) gives confidence in the accuracy of the model's simulation of a dominant hydrodynamic process.

The magnitude and temporal trends of modelled low frequency sea levels show good agreement with observations (Figure 9). Offsets in the low frequency sea level predictions compared to observations are due to an offset in the horizontal datum used in the regional model and that used for observations. Sea levels in OceanMAPS are relative to the geoid whereas the measurements are relative to mean sea level. The offset between predicted and observed is not critical, but the magnitude and temporal trends are important as they drive, and respond to, low frequency circulation.

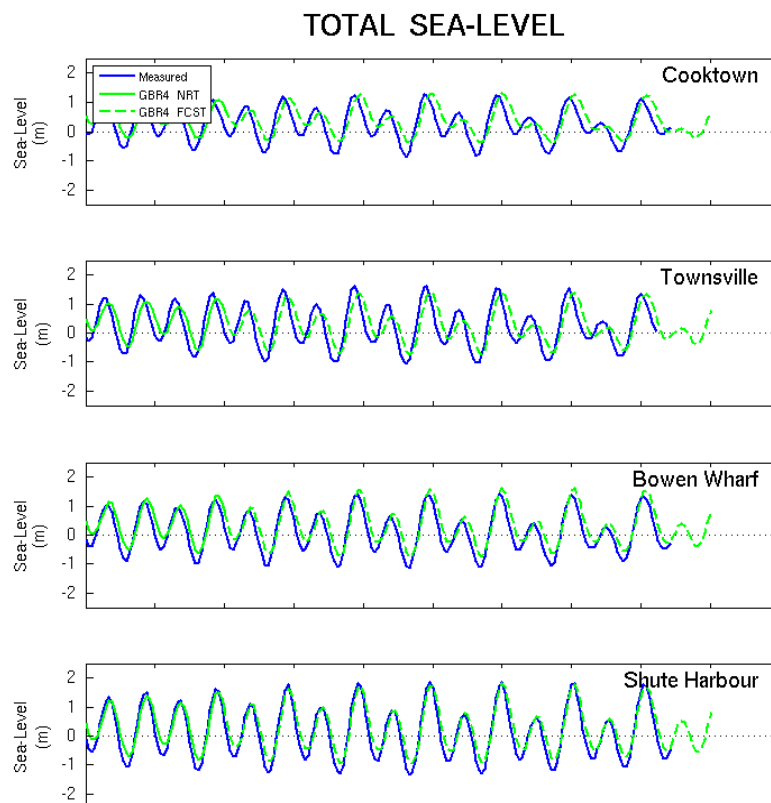


Figure 8 Observed and predicted sea-levels at coast stations within the domain of the GBR regional model.

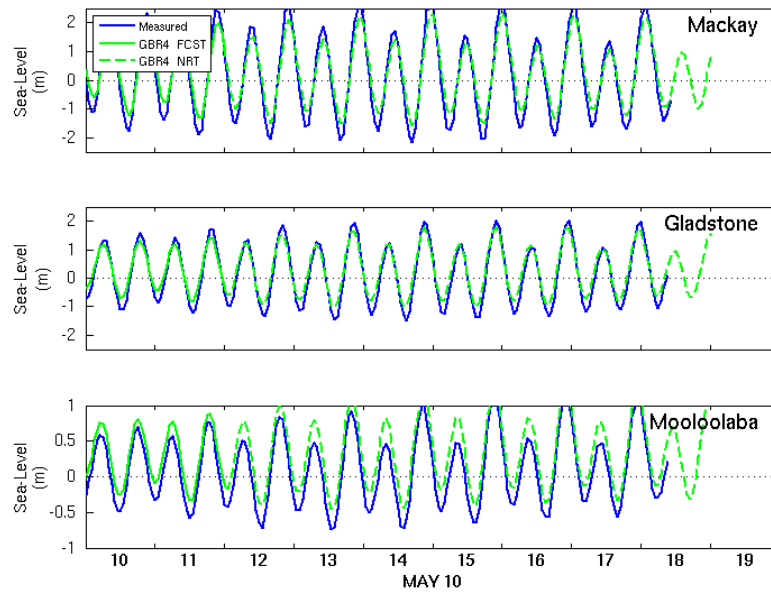


Figure 8 continued.

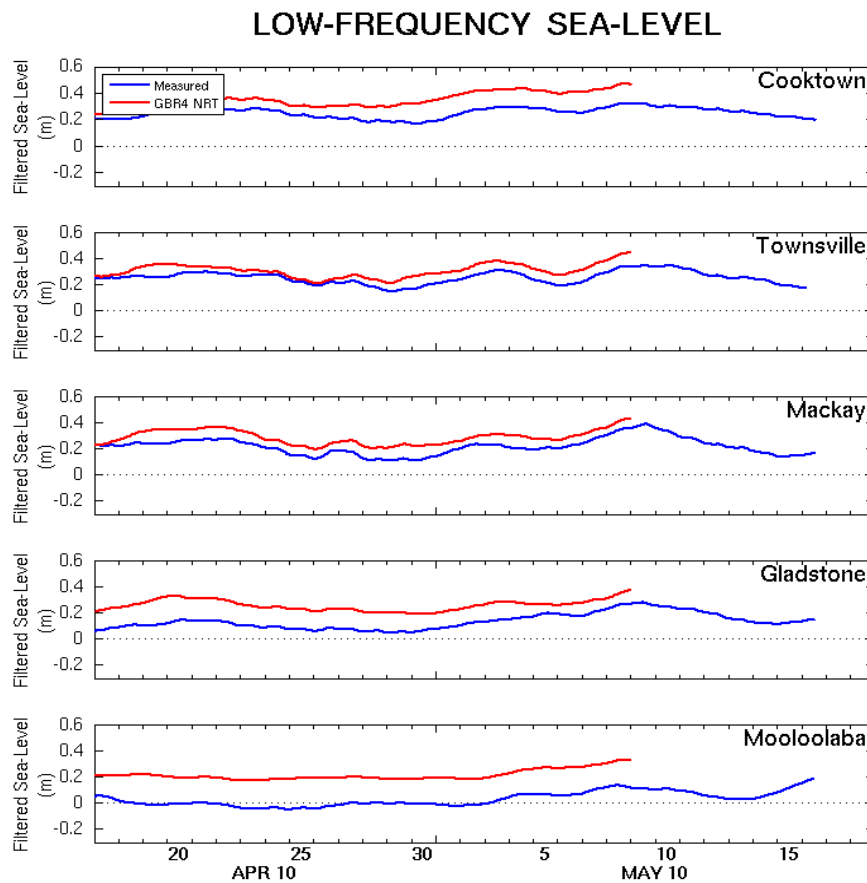


Figure 9 Observed and predicted low-frequency sea-levels at coast stations within the domain of the GBR regional model.

Results from the model also provide a glimpse into the internal ocean structure along the shelf edge (Figure 10). The southward flowing EAC is known to cause a shallowing of the thermocline along the shelf edge in the central and southern GBR, and movement of the thermocline in response to variability in the strength of the EAC is known to drive episodic upwelling and intrusions of cool water along the shelf edge of the southern and central GBR (Steinberg 2007). In contrast, the northward flowing Hiri current drives a general deepening of the thermocline along the edge of the Northern GBR, north of Cape Flattery. This general synoptic understanding of internal temperature structure is captured in the model simulations. The temporal and spatial dynamics of shelf-edge upwelling and downwelling along the GBR are still poorly understood, and the present model provides a tool to support further research into quantifying the shelf-ocean exchange in this region.

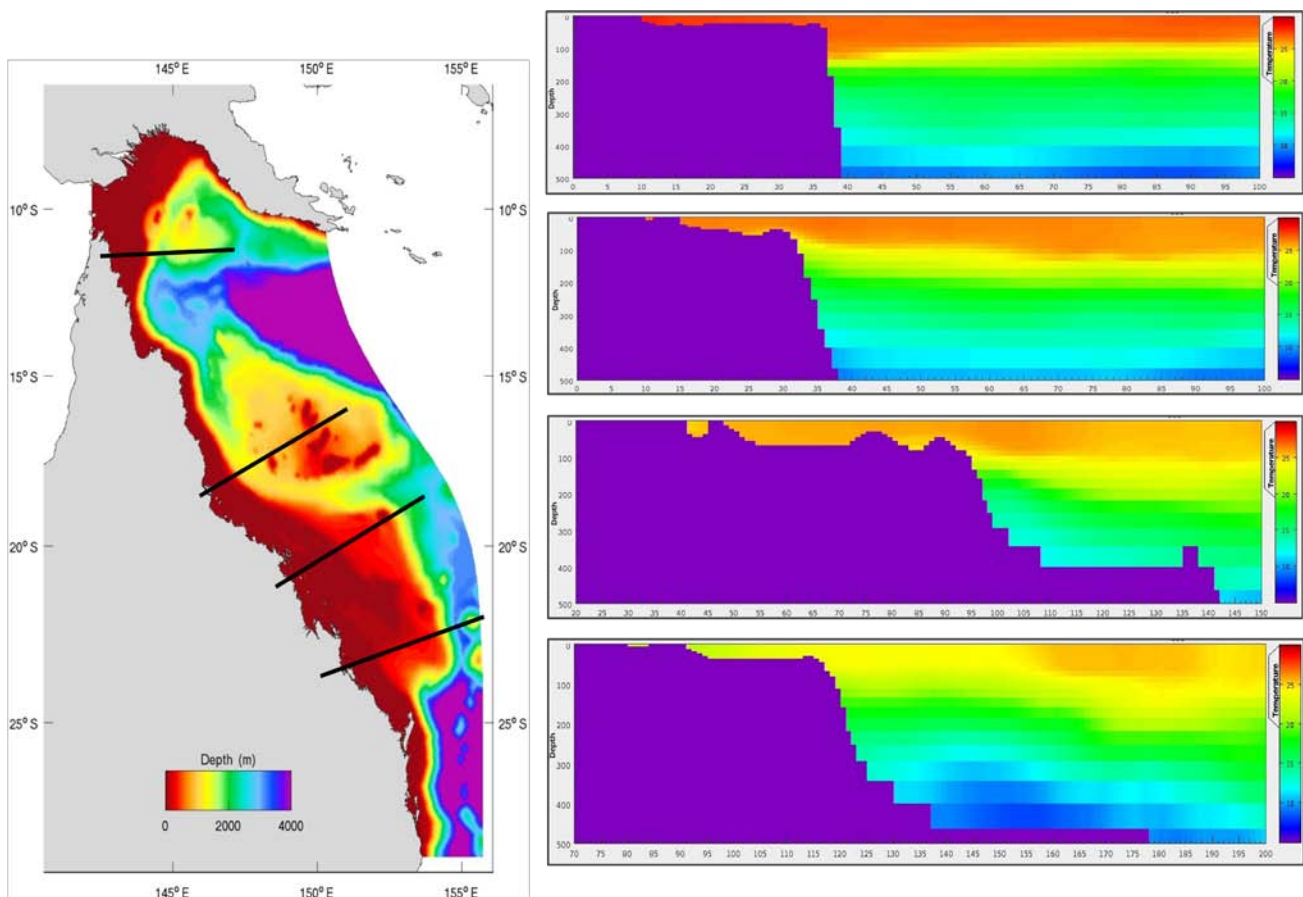


Figure 10 Vertical sections of simulated temperature at 4 cross-shelf transects. Transect locations are shown in left panel. Temperature section panels (right; from top to bottom) correspond to sections (top to bottom) shown as black lines in left panel.

Validation against GBROOS data

The Great Barrier Reef Ocean Observing System (GBROOS) is an observation network that seeks to understand the influence of the Coral Sea on continental shelf ecosystems in north-east

Queensland including the GBR Marine Park. Observational infrastructure deployed as part of GBROOS includes a number of oceanographic moorings deployed along the continental slope at the oceanic margin of the GBR and shelf based moorings within the GBR 'lagoon'. Moorings extend from north of Lizard Island to Heron Island in the Southern GBR (Figure 11), and each mooring typically consists of an Acoustic Doppler Current Profiler (ADCP) and temperature and salinity loggers to observe the vertical structure of currents, temperature and salinity within the water column.

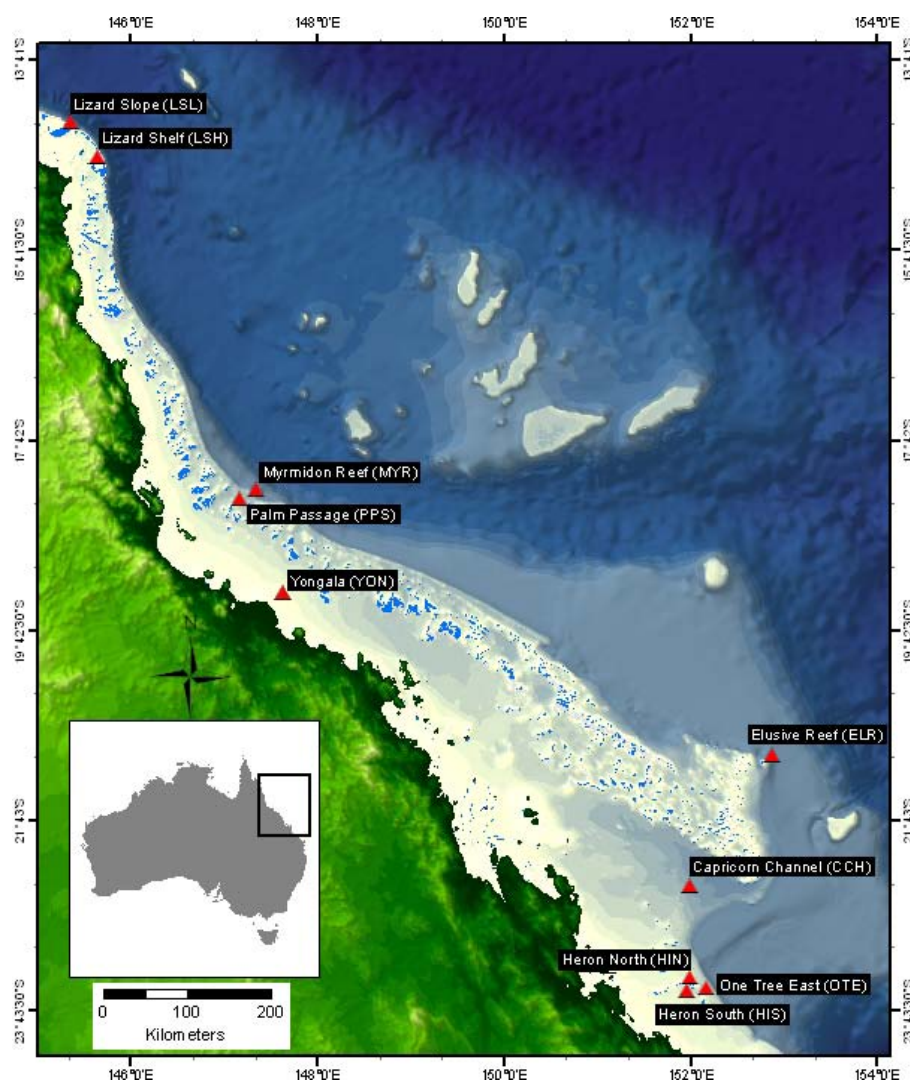


Figure 11. Locations of GBROOS moorings along the GBR. Data from LSL, MYR and CCH were used for model performance evaluation.

Model performance evaluation included comparing observed and simulated time series of currents and water column temperatures at three strategic locations. The mooring at Lizard Island Slope (LSL) is situated in the region where a westerly flowing jet of the South Equatorial Current encounters the continental shelf and bifurcates, forming the southward flowing East Australian Current (EAC), and the northward flowing Hiri Current. Myrmidon Reef offshore from the central GBR sits slightly offshore from the outer reef barrier and the mooring in this location (MYR) provides clear observation of the EAC. The Capricorn Channel represents a pathway for lagoonal waters – those

constrained between the coast and the offshore reef matrix – to exit the GBR to the south. This flow is often referred to as the inshore branch of the EAC, and the Capricorn Channel mooring (CCH) is ideally located to observe this flow and thus provide a good evaluation of the model's ability to accurately simulate the transport of water through the central lagoon of the GBR.

As part of the model evaluation, comparisons of observed and simulated current and temperature were undertaken for the period between June and November 2010 at the locations described above. Comparison of temperatures, particularly at depths below the thermocline (>70m depth), provide information on how well the model simulates the lower frequency transport of water masses along the outer GBR margin. Conversely, temperatures nearer the surface provide information on the ability of the model to simulate both low frequency cycles (e.g. seasonal heating and cooling) and higher frequency events such as temperature changes due to weather events, mixing due to tides and other tidally driven processes.

Figures Figure 12 and Figure 13 present comparisons of observed and simulated temperatures at mooring locations MYR and CCH. At the MYR mooring, there is general agreement between model temperatures and observations, particularly at a depth of 190m. At this depth the model performs well in simulating the phase and magnitude of the inter-month temperature variability. This temperature variability, of the order of 2 deg C, is typical of the signature associated with warm, meso-scale eddies impacting upon and advecting along the outer GBR shelf. Closer to the surface, at ~20m depth, there is more variability in the observed temperatures, but the model reproduces the general observed season cycle of cooling during winter and heating during spring. At CCH, which is a shelf location removed from the variability of oceanic eddies, the observed temperature shows less variability and displays typical winter cooling. At a depth of ~85m at CCH, there is evidence of near sea-bed intrusions of cool water (during July), consistent with the thermal signature of intrusions associated with the Capricorn Eddy (see Weeks et al 2010). While the model successfully reproduces the general seasonal cooling at this location, the higher frequency temperature variability is not captured in the simulation. This may be due to the inadequately resolved bathymetry of the 4-km grid (see Figure 6).

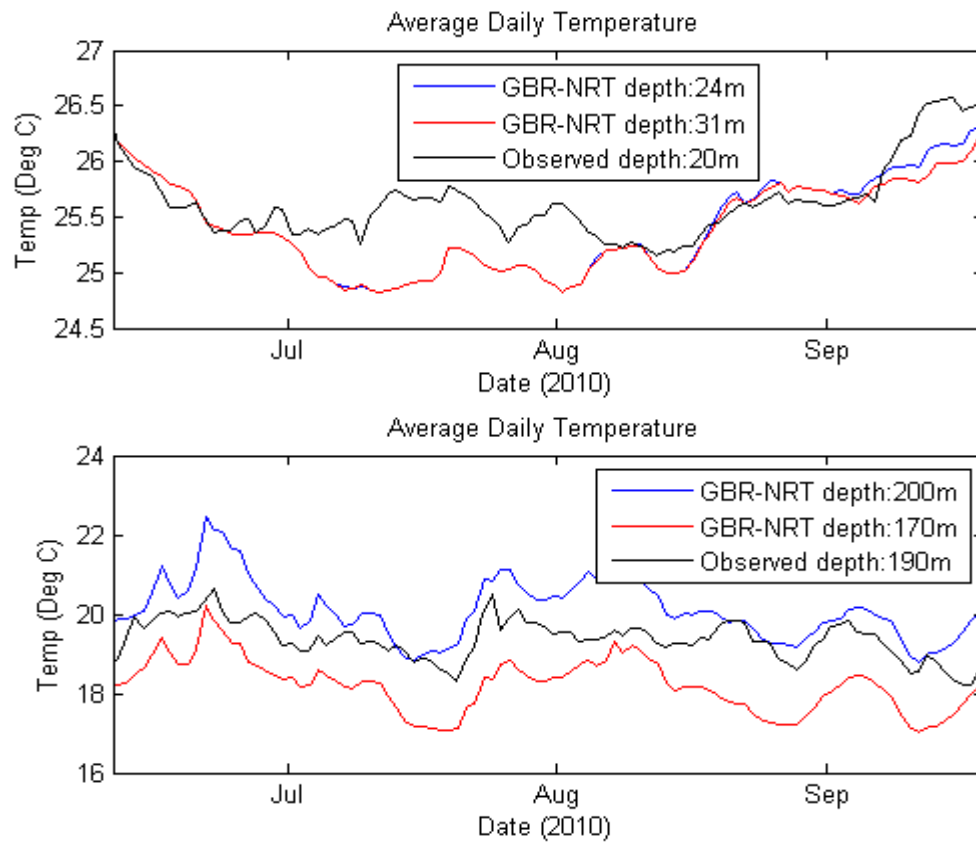


Figure 12. Timeseries of simulated (blue, red) and observed (black) temperature at MYR mooring site at depths of ~20m (top) and ~190m (bottom).

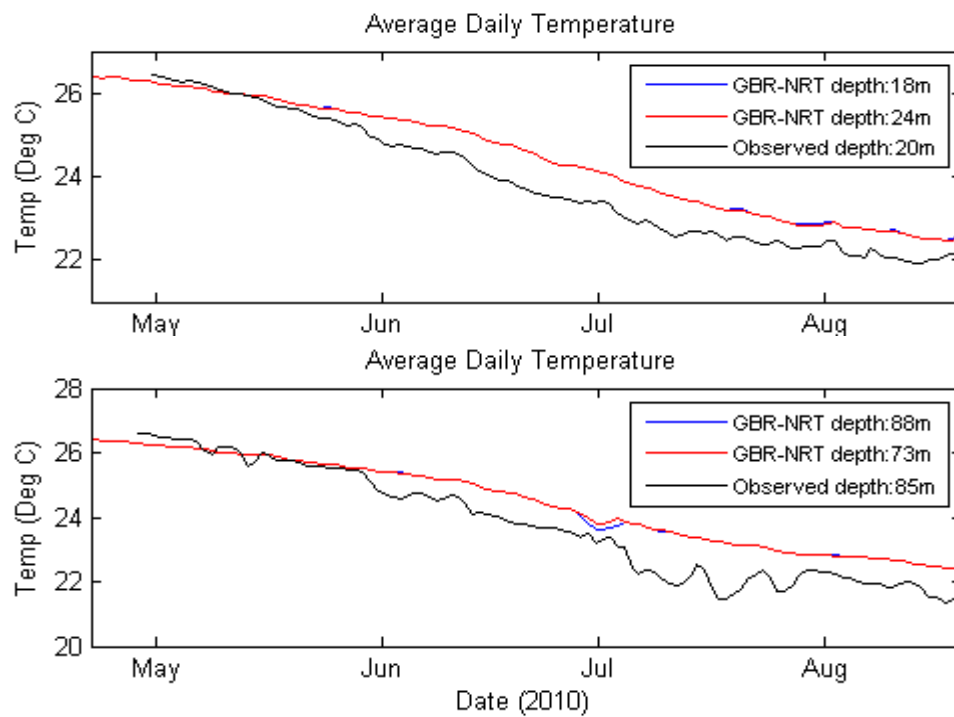


Figure 13. Timeseries of simulated (blue, red) and observed (black) temperature at CCH mooring site at depths of ~20m (top) and ~85m (bottom).

Comparison of observed and predicted currents show, in general, good agreement at all three mooring sites (Figures 7, 8). At both LSL and MYR, observed surface currents (at ~20m depth) show more scatter than the model predictions, due to higher frequency processes in the surface layer due to, for example, local winds. There is also greater uncertainty of ADCP derived current measurements near the ocean surface from deeply moored ADCPs, due to both mooring lean and surface scattering and interference of the acoustic measurement signal. At depth, however, there is good agreement between observed and simulated current direction and strength at both LSL and MYR.

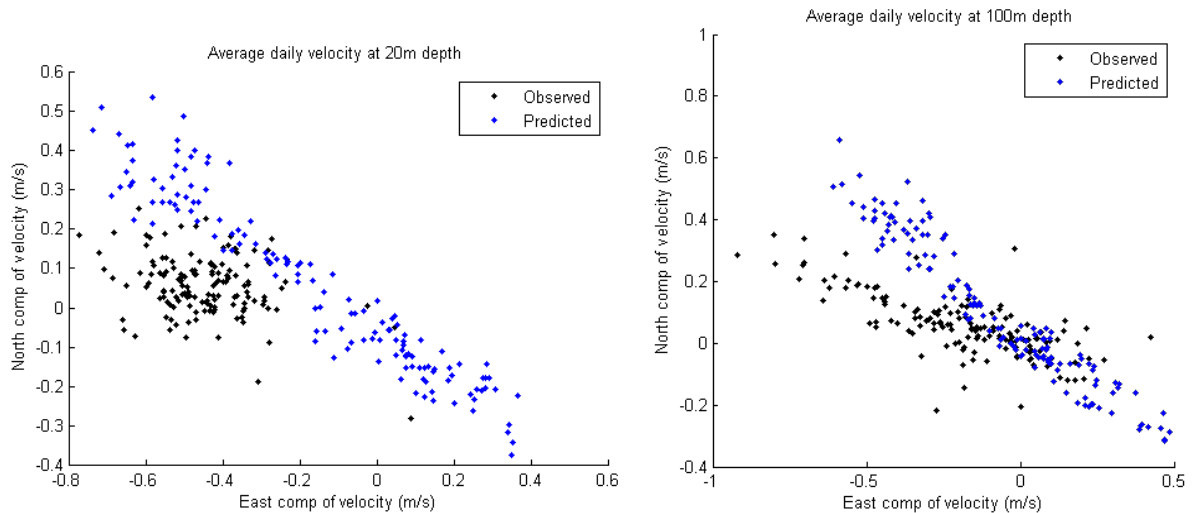


Figure 14. Scatter plots of observed (black) and simulated (blue) currents at LSL mooring site at depths of ~20m (left) and ~100m (right).

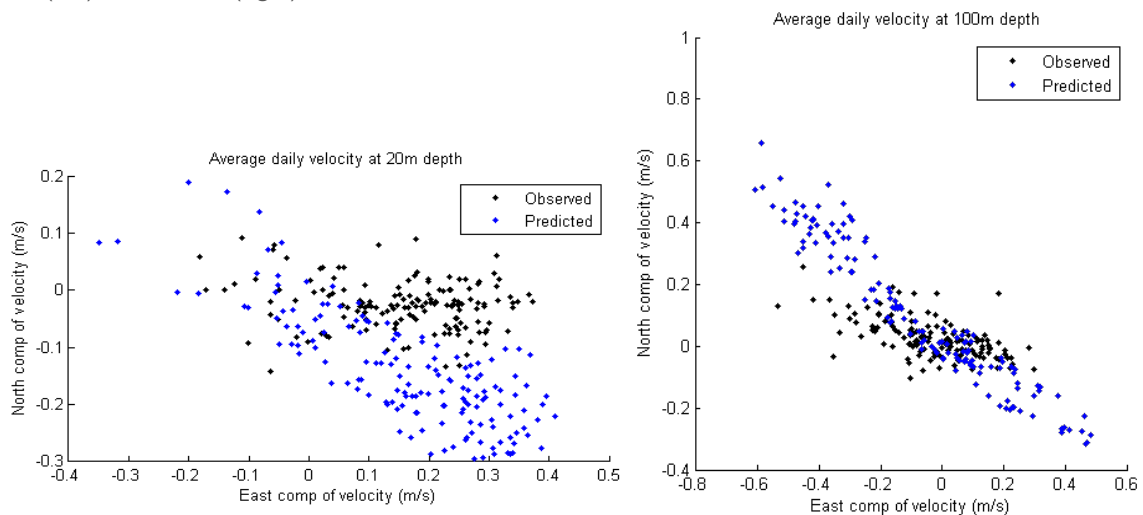


Figure 15. Scatter plots of observed (black) and simulated (blue) currents at MYR mooring site at depths of ~20m (left) and ~100m (right).

Site CCH is a shelf location more influenced by tides than MYR and LSL. Full depth profiles of the observed North and East components of current clearly show the strong spring – neap tidal signature at CCH, with the spring-neap cycle more evident in the east component of the velocity (Figure 16). These features are reproduced by the model, with current magnitudes of a similar order of magnitude. Further, there is strong agreement between observed and simulated time series of north and east components of velocity at 2 depths at CCH for the period May – Sept 2010 (Figure 17), suggesting that the simulated flow at CCH is representative of flow at this location, and more generally, that the model adequately captures the major dynamics of the flow in this region.

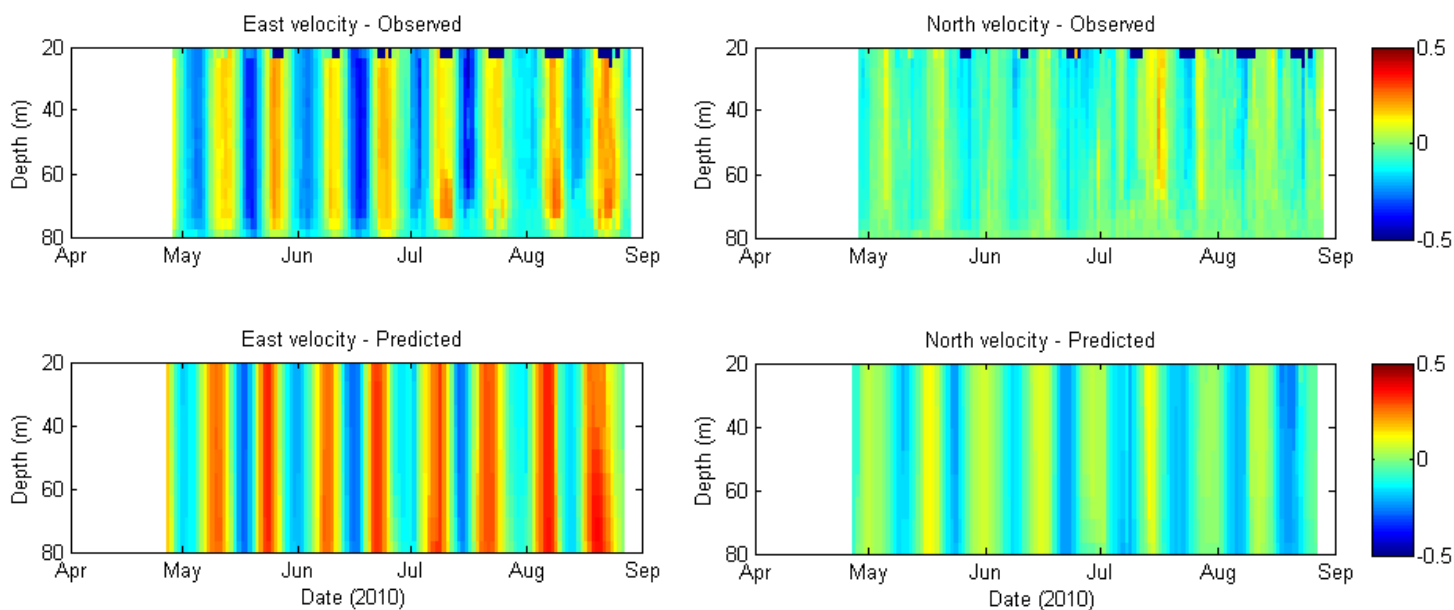


Figure 16. Colour filled plots of East (left) and North (right) component of full water column velocity at CCH. Colour map shows current strength in ms^{-1} .

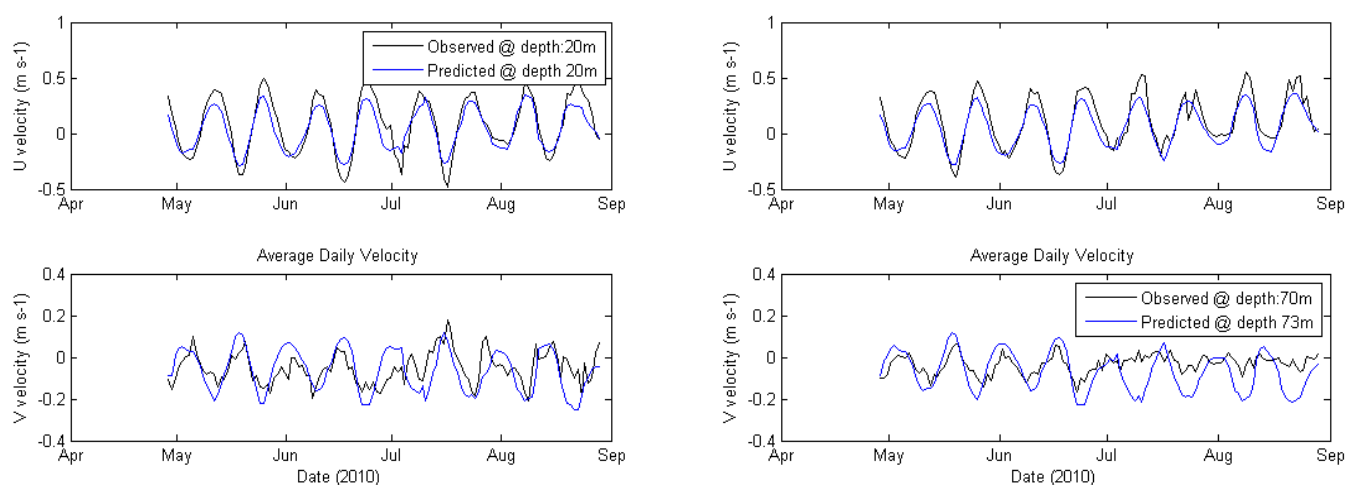


Figure 17. Time-series of Observed and predicted of East (left) and North (right) components of current velocity at CCH at depths of $\sim 20\text{m}$ (left) and 70m (right). Note; observations and model output are sampled at 24 hours, hence the diurnal signal is not represented and the oscillations observed correspond to the neap-spring cycle.

In general, model results shows very good agreement between with observed temperature and current fields at the three strategic mooring locations used for the evaluation. The evaluation of the model performance demonstrates that the regional model produces realistic simulations of the temperature and current field along the oceanic margin of the GBR. Further, the model accurately simulates exchanges through the Capricorn Channel. Exchanges across the GBR-Coral Sea boundary strongly affect cross-shelf gradients of water quality, carbon and biological communities within the GBR, and validation of the model's ability to simulate these processes adds credibility to the utility of the model as a research tool to provide accurate broad-scale description of GBR hydrodynamics and waterborne material transport.

Graphical output from the near real-time regional model is available at :

<http://www.emg.cmar.csiro.au/www/en/emg/projects/GBR/Near-Real-Time-Results/4km-model.html>

Shelf Model

The near real-time implementation of the shelf model is running operationally using output from regional model. Due to the low run-time ratios of the shelf model, the forecast cycle is not performed and only the nowcast is delivered. Snapshots of synoptipc distributions of surface currents, temperature and salinity showing comparison between the shelf and regional models are presented in Figure 18.

Graphical output from the shelf model are available at :

<http://www.emg.cmar.csiro.au/www/en/emg/projects/GBR/Near-Real-Time-Results/1km-model.html>

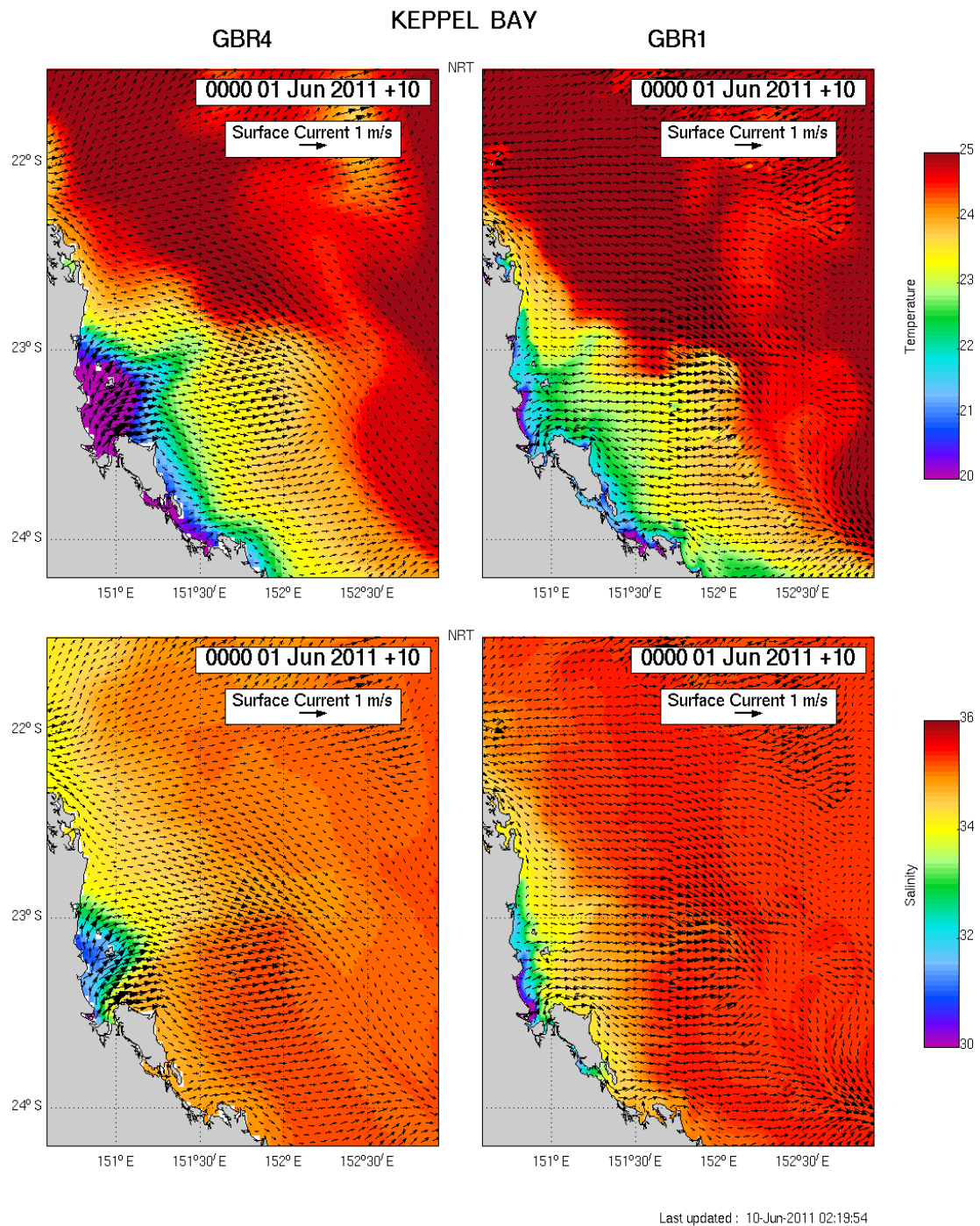
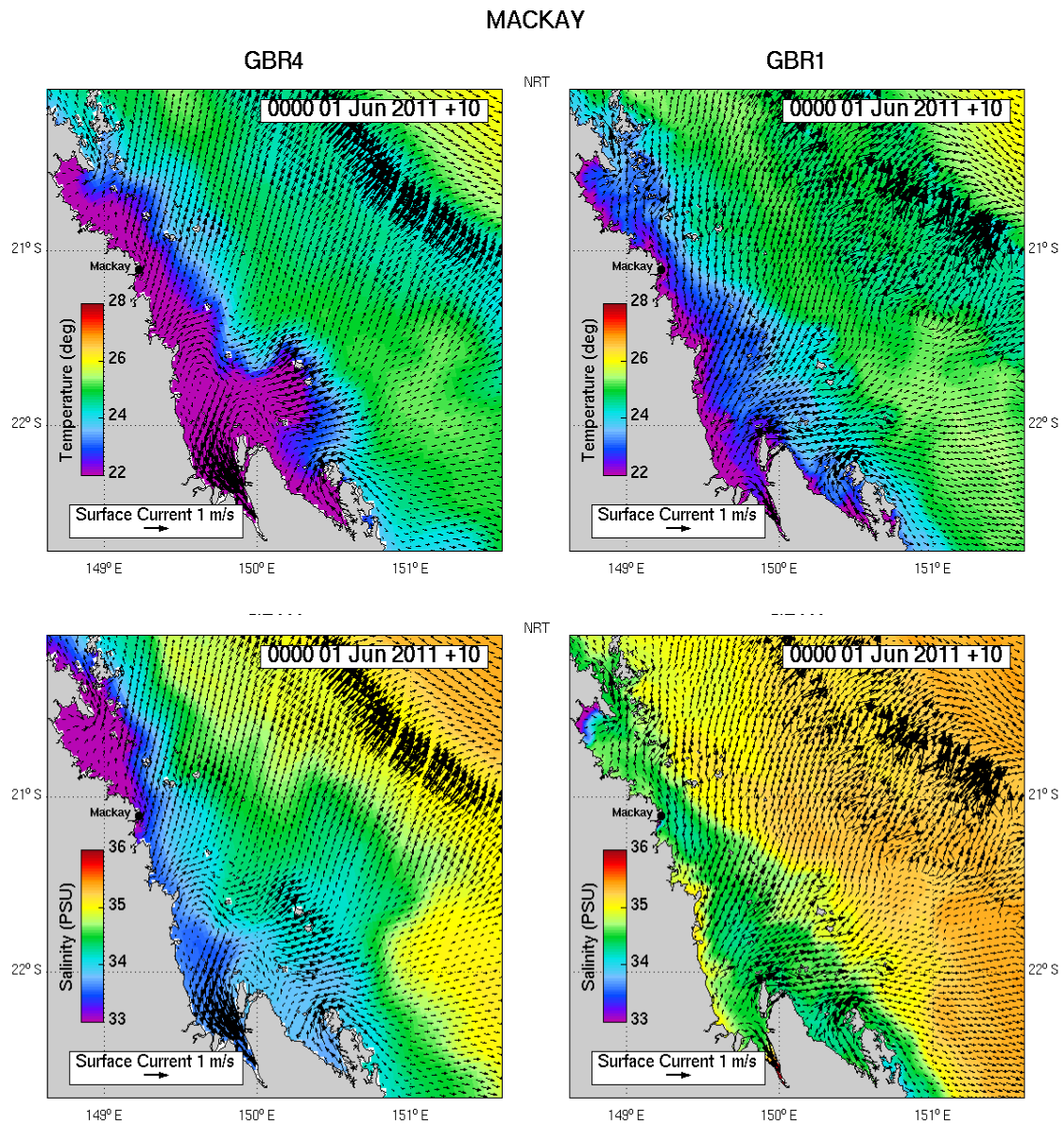


Figure 18 Synoptic distributions of surface current, temperature (top) and salinity (bottom) in Keppel Bay, for the regional (left) and shelf (right) models.



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Figure 19 Synoptic distributions of surface current, temperature (top) and salinity (bottom) in the Mackay region for the regional (left) and shelf (right) models.

2008-2009 wet season hindcast - regional model

A key deliverable for this project is a hindcast simulation of the 2009 wet season, using the regional 4km model and including all significant river inflows that occurred during the hindcast period, which was taken to be from 01-November-2008 to 01-April-2009. The hindcast was performed with model forcing provided by archived OceanMAPS and MesoLAPS modelled ocean and atmospheric forcing products, and river inflows as observed at the most downstream river gauging stations. River inflows used in the hindcast simulation are given in Table I, and river flow rates during the hindcast period are shown in Figure 20.

The 2008-2009 wet season was characterised by a peak in most river flows in the first few weeks of February 2009, with the exception of the Fitzroy which peaked in March 2009. Flows from the Burdekin and Herbert Rivers were an order of magnitude larger than those from other rivers, and our evaluation of model performance will focus on the qualitative assessment of the simulated salinity distributions associated with these catchment drainages.

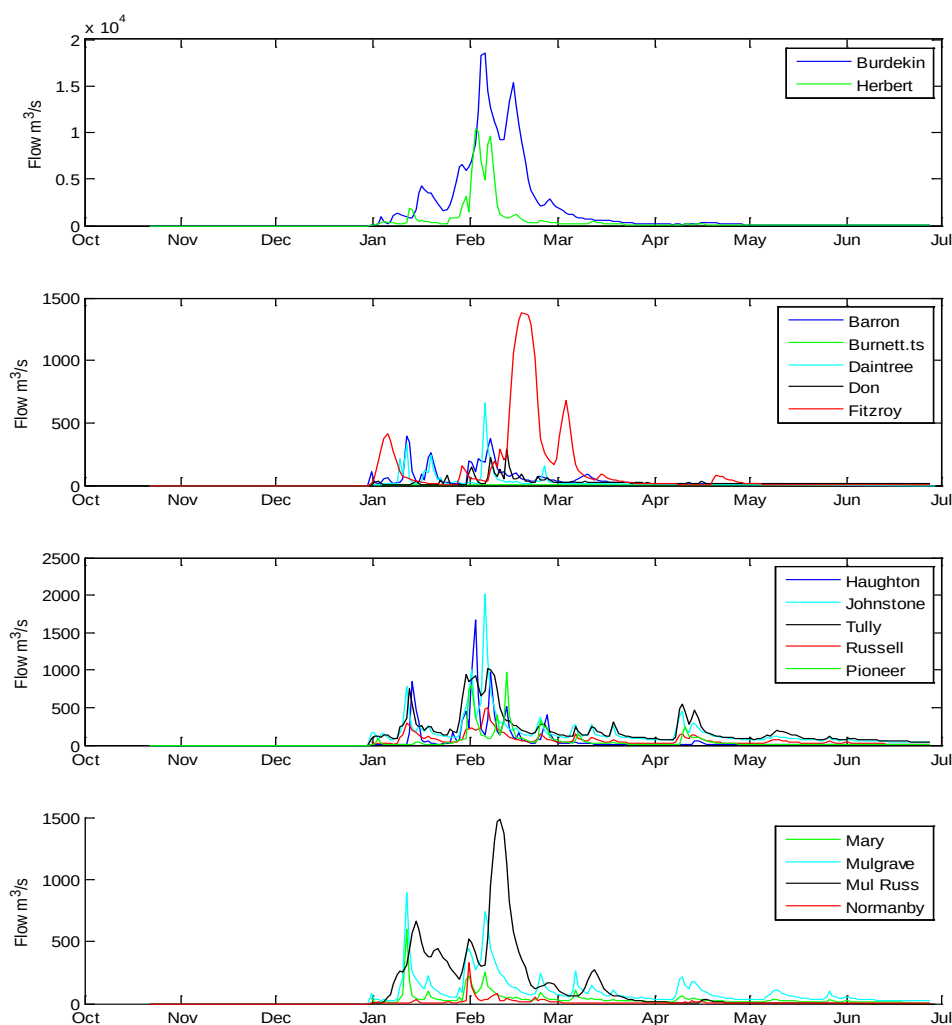


Figure 20 Observed river discharges for October 2008-Jun 2009 used in the 2008-2009 wet season hindcast. Note different flow axis scaling on each subplot. River discharges prior to 01 Jan 2009 are not shown

Observational time series of near bed and near surface salinity were obtained from the IMOS Yongala Reference Mooring located east of Cape Bowling Green (see http://data.aims.gov.au/gbroos_moorings/mooringspages/toc.html), north of the mouth of the Burdekin River. At this site salinity, temperature, turbidity, dissolved oxygen and fluorescence are logged at 15 minute intervals, at water depths of approximately 10m and 29m. A comparison of observed and predicted salinity time-series at 10m water depth shows very good agreement (note the lack of temporal resolution in the predicted time series is an artefact due to a large output time step of model results). Predicted surface salinity also shows good agreement with observed temporal changes and trends of the observational data at 10m depth (Figure 21).

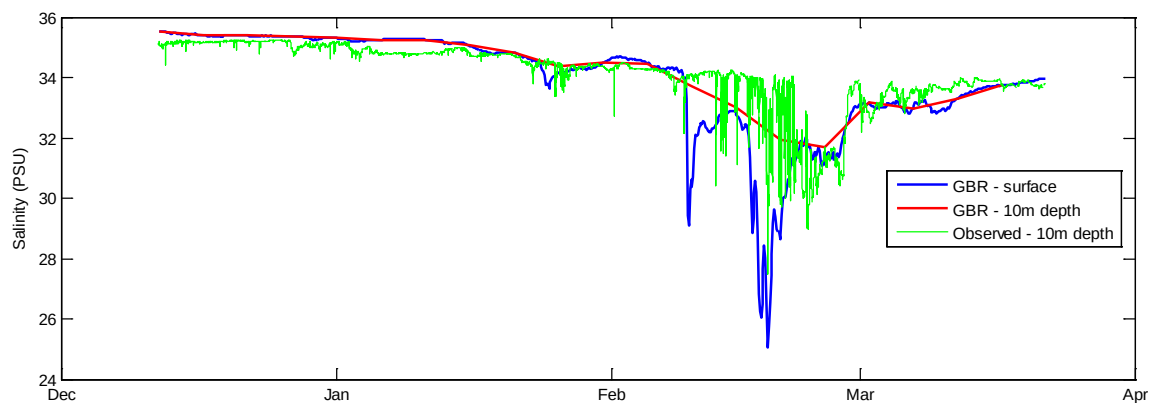


Figure 21 Comparison of observed and predicted salinity time series at the Yongala National reference station mooring, 2009.

A broad view of the central GBR during the high flow period in February (Figure 22) shows the interaction of river discharges from different catchments and highlights the substantial spatial extent of the surface freshwater plume.

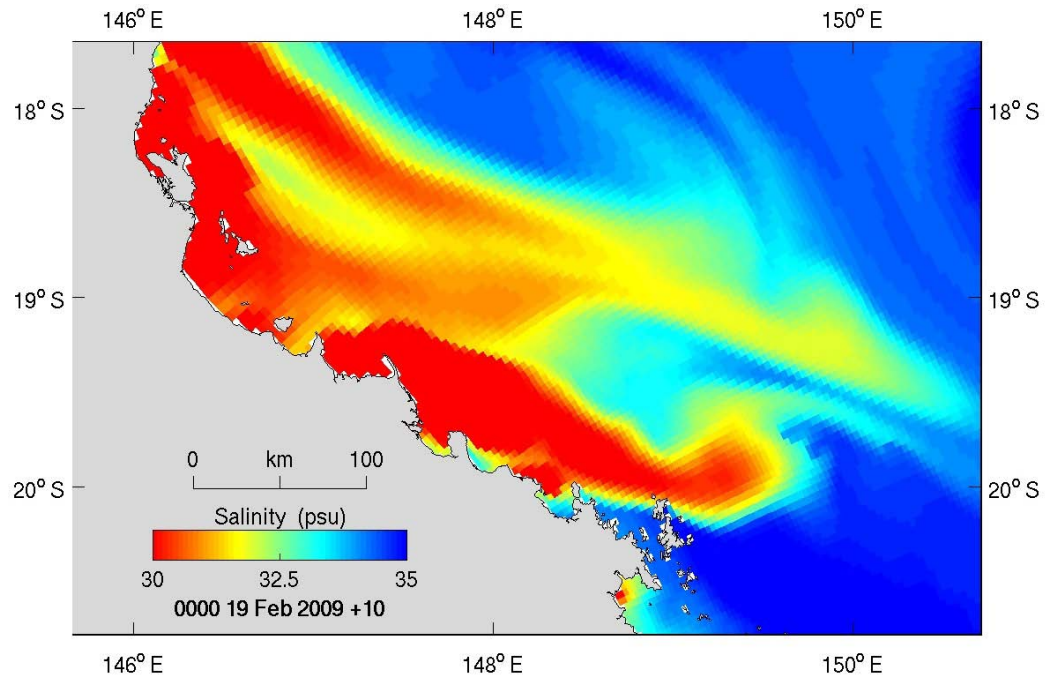


Figure 22 Synoptic view of predicted spatial extent of surface fresh water plume for the central GBR, 19 February 2009.

Remotely sensed plume distributions and predicted surface salinities were compared during a high flow event in the Burdekin River to qualitatively assess the performance of the model in simulating the spatial extent of the surface fresh water plume (Figure 23). Whilst this assessment approach is somewhat subjective, the general agreement in extent and timing of the predicted surface fresh water plume and the remotely sensed plume distribution, in conjunction with the agreement of the observed and predicted sub-surface salinity time series, adds credibility to the models performance in simulating the synoptic distribution of freshwater plumes on the GBR.

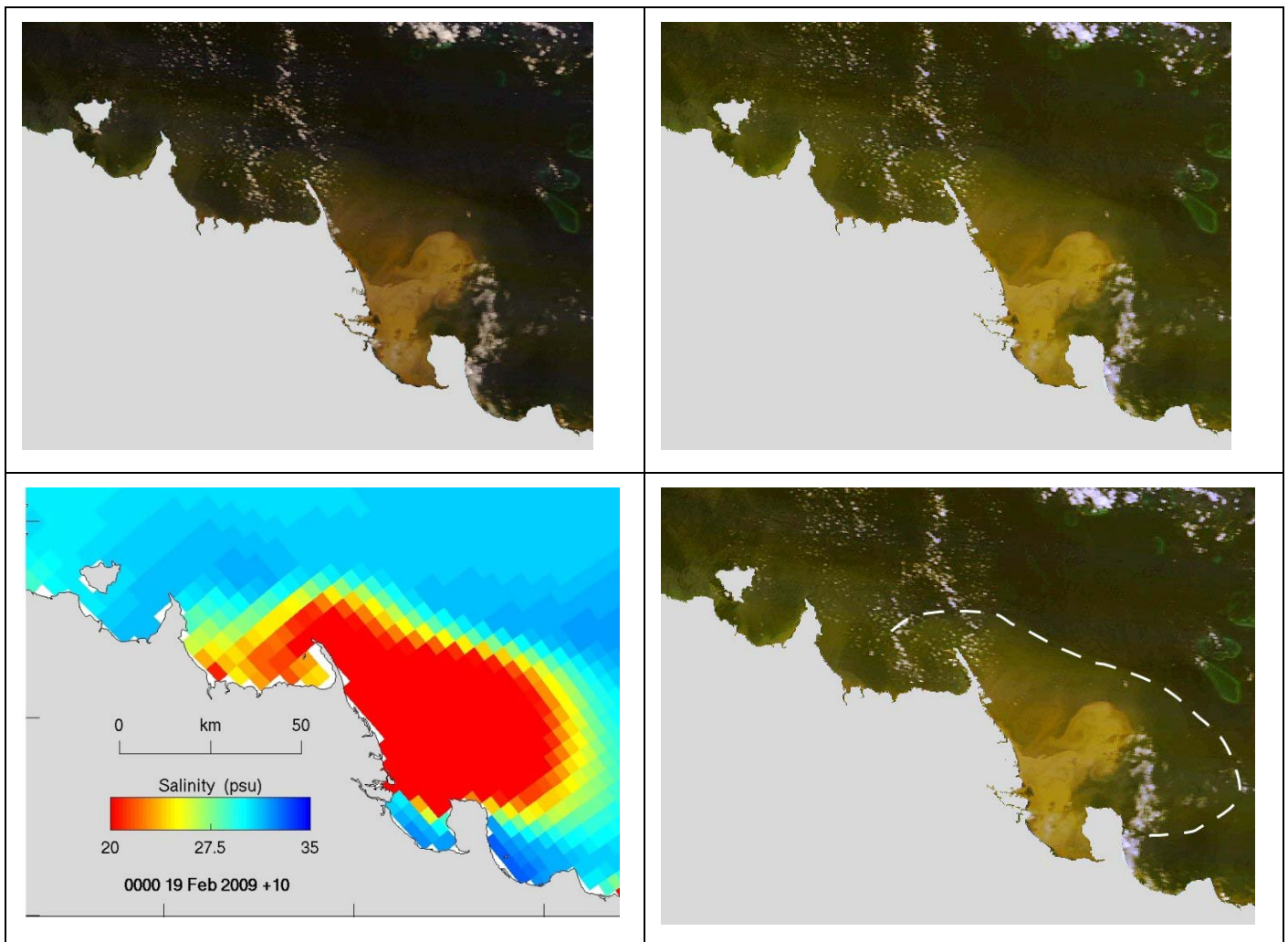


Figure 23 True colour imagery of Burdekin and Herbert Rivers, 19 February 2009. Top left: true colour image with land mask. Top right: enhanced true colour image with land mask. Bottom left: synoptic view of predicted spatial extent of surface fresh water plume from Burdekin and Haughton Rivers, 19 Feb 2009. Bottom right: enhanced true colour image with plume front highlighted by dashed line.

Coastal water of the GBR are often hypersaline (> 37 PSU) at the end of the dry season, and this is captured by both shelf and regional models (Figure 24). While both models provide a general description of the spatial salinity distributions, the shelf model provides much greater spatial detail, particularly in the definition of the hypersalinity in coastal embayments and in the emergence of coastal river plumes.

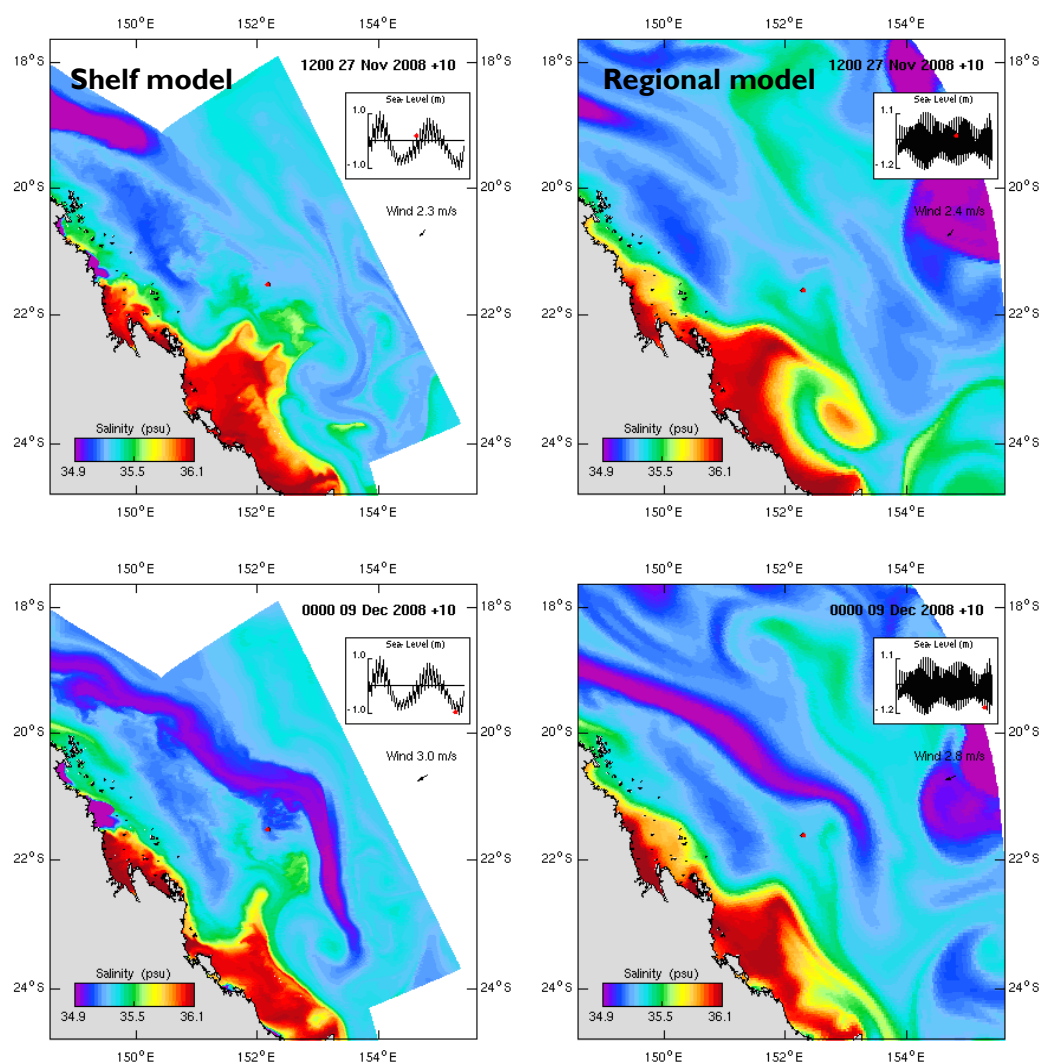


Figure 24 Spatial distributions of surface salinity during November and December 2008 for the shelf and regional model.

A particularly useful application of the 2008-2009 hind cast was to examine the impact and spatial extent of riverine inflows in to the GBR. Passive tracers were input at all the river open boundaries with a value of zero, with the passive tracer initialized to 35 over the model grid. The impact of the rivers in the salinity solution is often confounded with low salinity tropical water advected from the north and low surface salinity due to rainfall, which is rapidly mixed out. The passive tracer allows only the impact of freshwater from the rivers to be assessed. Distributions of tracers show the transport of river inflows along the GBR and clearly indicate the coastal interactions of inputs from multiple catchments. Tracer experiments such as this will enable better description of the fate of individual rivers, and allow the identification of marine regions of influence of individual catchments.

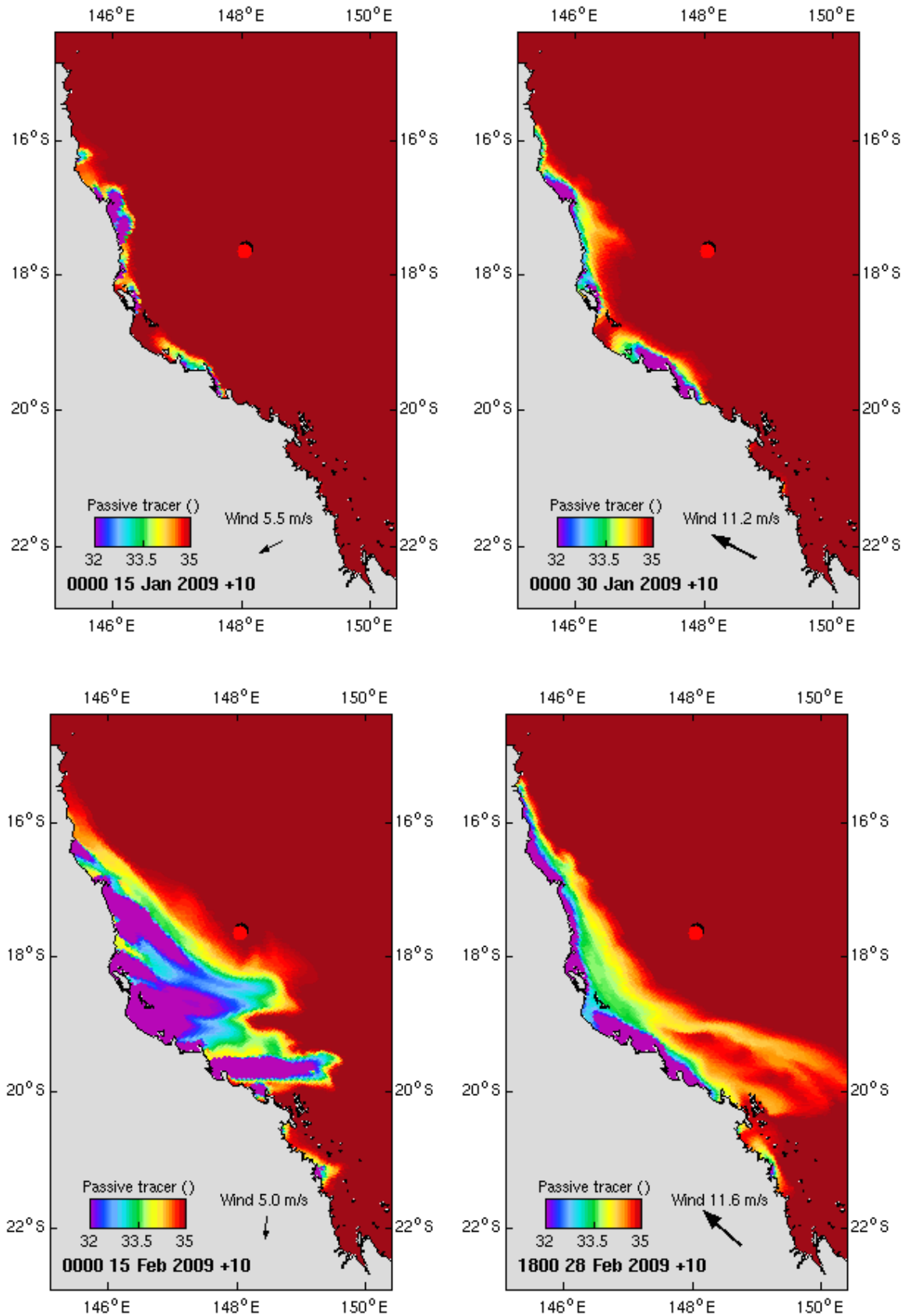


Figure 25. Spatial distributions of passive tracers released from rivers in the regional model during the 2008-2009 wet season hind cast. Panels show snapshots of distributions at selected dates.

Results and animated model output from the 2008-2009 wetseason hindcast can be found at:

<http://www.emg.cmar.csiro.au/www/en/emg/projects/GBR/Results/2008-2009-Hindcast.html>

Assessment of the suitability of sub-grid parameterization schemes

Assessment of the suitability of sub-grid parameterization schemes appropriate for application within finite difference models GBR model was to follow the operational implementation of the shelf model, however AIMS has been unsuccessful in recruiting a modeller to perform the sub-grid parameterisation work on this project. However, some assessment of the performance of regional and shelf models in regions of substantial sub-grid topography is being undertaken in conjunction with the nearshore hydrodynamics and sediment modelling being undertaken in MTSRF Project 3.7.2 around Dunk Island and the Tully River mouth.

As part of MTSRF Project 3.7.2 the finite-element model RMA2 was employed to simulate the 2-dimensional (depth-averaged) hydrodynamics in the vicinity of Dunk Island. The finite element grid established around Dunk Island had a horizontal resolution (taken as the longest side of the grid element) that ranged from between ~5 km at the mid-shelf model boundaries to ~150 m around the coastline of Dunk Island (Figure 26). The model boundaries were forced by output from the regional scale SHOC model.

Only qualitative comparison between the regional and finite-element models has been undertaken, but the substantially higher resolution of the finite element model allows it to produce highly detailed descriptions of the flow in the vicinity of the islands and coast. The purpose of future comparisons between SHOC and higher resolution models will be to determine how the detailed flow elucidated by the higher resolution models contributes to the broader scale circulation and determine if it is possible to explicitly parameterise this contribution in more coarsely resolved models. This will be particularly important, for example, in providing correct exchanges through dense reef matrices, or for accounting for small scale flow features that may result in enhanced trapping, retention and residence times of water trapped within reef boundary layers.

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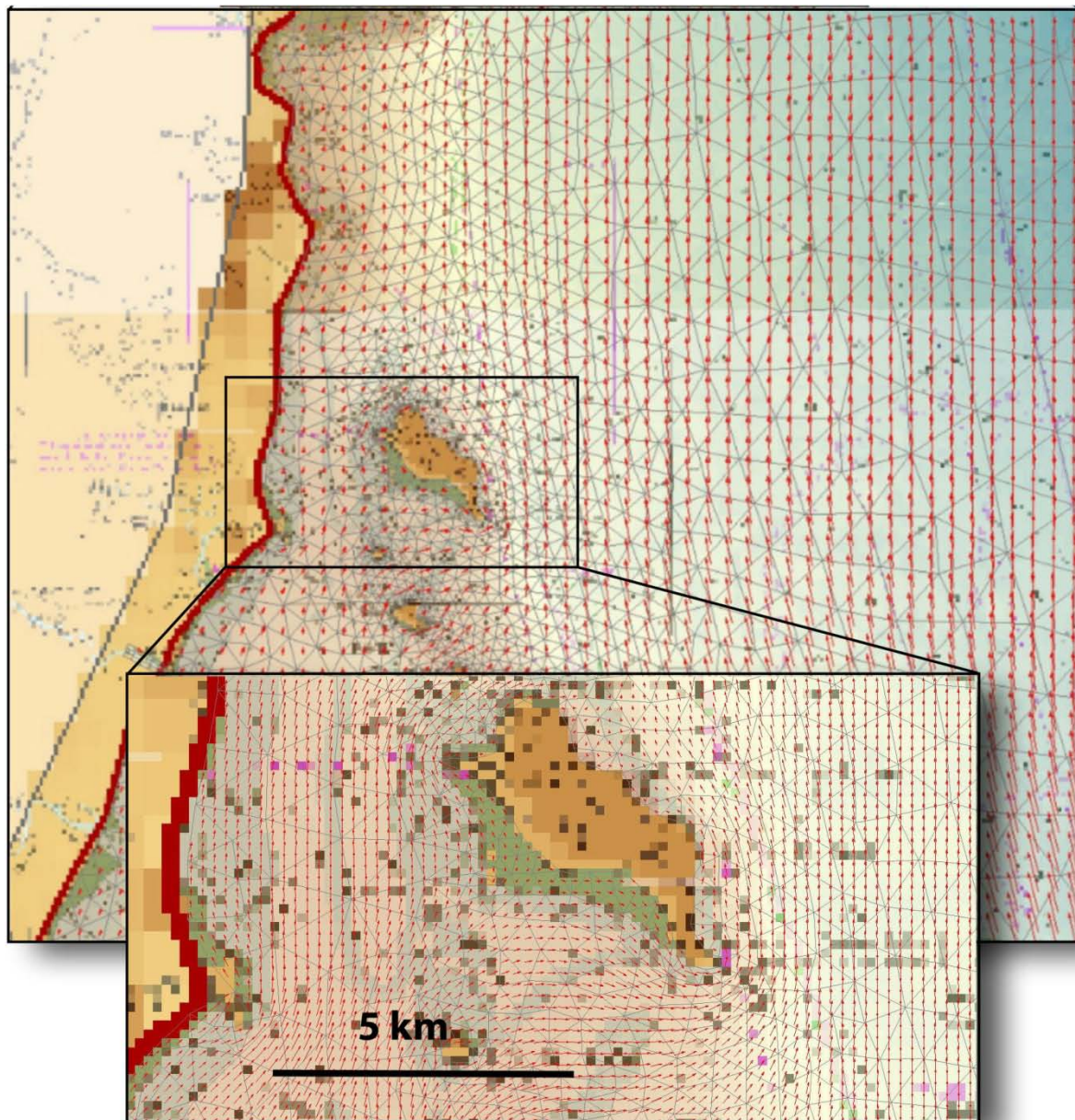


Figure 26 Output from finite volume modelling in the vicinity of Dunk Island. Top panel show larger extent of finite volume grid; bottom panel shows detail of grid and flow vectors. In bottom panels model grid is shown as grey triangles, velocity vectors are shown by red arrows.

Discussion and Conclusions:

The primary objectives of this study were to develop a whole of GBR 3-dimensional baroclinic hydrodynamic model at a resolution capable of capturing the key oceanographic processes impacting the GBR, and to demonstrate proof of concept of a whole of GBR model through the simulation of the circulation within the GBR lagoon during a significant wet season. To achieve these objectives, the project was structured around 4 main tasks:

- 1. Development of pilot models.*
- 2. Implementation of models in near real-time*
- 3. Evaluation of models using available data.*
- 4. Running the 4 km for the 2008-2009 wet season.*

This project has successfully developed pilot hydrodynamic models at two nested levels. A regional model covers the continental shelf from Moreton Bay to the mainland of Papua New Guinea, extending eastwards into the Coral Sea. This regional model is nested within the OceanMAPS global circulation model. A more finely resolved model (the shelf model) is nested within the regional model to cover the continental shelf areas and the adjoining tract of the Coral Sea. By using operational models to provide ocean and atmospheric forcing data, the regional model has itself been implemented in a real-time operational capacity, and performs a routine near real-time/forecast cycle. The shelf model, due to slower run times, operates in a near real-time mode only. The near real-time application of both models includes the input of river flows for a number of rivers with real-time gauging.

Model evaluation has been undertaken using the archive of results generated by the near real-time application of the regional model. Model results have been compared with observations of coastal sea levels and with current and temperature observations at scattered locations along the GBR collected as part of the Great Barrier Reef Ocean Observing System program. Given the proof of concept nature of the project, thorough calibration of the model was not undertaken, however comparison of predicted and observed features of the hydrodynamics indicate that the models perform well and capture the dominant tidal and large-scale features associated with the general circulation within the GBR.

The 2008-2009 wet season was chosen as the case study to demonstrate the utility of the models to simulate the spatial distribution and fate of freshwater inflows during a significant wet season. For the hindcast period, model results were compared with limited sub-surface salinity observations and remote sensing imagery. Simulated surface salinity distributions showed qualitative agreement with observations of the extent and timing of the predicted surface fresh water plume, and predicted sub-surface salinity time series compared well with observed salinity time series that captured the propagation of Burdekin River plume. The models performance for this test case adds credibility to the models performance in simulating the synoptic distribution of freshwater plumes on the GBR.

Further development priorities and strategy for continued development of the hydrodynamic model as a fundamental component of a large scale water quality model

In their review of Receiving-Water Water Quality Modelling activities in the Great Barrier Reef, Webster et al. (2008) presented a framework for the development of a large-scale receiving waters model that could simulate the transport and transformation of fresh water, sediments, nutrients and pesticides derived from catchment modelling or from measurement. Such a model would be comprised of linked hydrodynamic, sediment transport, and biogeochemical models (see Figure 2). The model would allow for the effects of the interaction between plumes from multiple rivers, and when applied at timescales of decades, would address also the issue of acute exposure of the reef by contaminants in flood plumes as well as more chronic exposure during the dry season. A modelling framework such as this could play a critical role in underpinning the development of WQIPs by providing prediction of the likely impacts of alternative management strategies on indicators of environmental health under prescribed scenarios, underpinning target-setting and strategy selection.

Development of large-scale water quality model remains a shared goal of CSIRO and AIMS, and both organisations continue to explore avenues to support the further development of the hydrodynamics and, ultimately, of the greater goal of an integrated suite of hydrodynamic, sediment transport and biogeochemistry models that would form the basis of a large-scale receiving water quality model. Ongoing development should include strong, formal stakeholder involvement to ensure that the modelling initiative remains responsive to the evolving needs of management. In this regard it is vital that model development is seen as an ongoing long-term commitment, analogous to a commitment to monitoring, not a one-off short-term project.

Hydrodynamic models are the foundation element upon which other components of receiving water quality models rely, and immediate development priorities for the pilot hydrodynamic models developed as part of this project are now discussed.

Whilst evaluation of the pilot regional and shelf models demonstrates good performance in simulating dominant physical processes that control currents, mixing, temperature and salinity within the GBR, it must be recognised that the models have not been fully calibrated. AIMS possesses or has access to a vast archive of historic and contemporary oceanographic observations that would be suitable for use in model calibration. These data sets include: the AIMS temperature logger program which provides high spatial coverage of temperature observations along the majority of the reef tract; sustained ocean current and temperature observations from at a limited number of shelf and slope mooring locations; ocean temperature and salinity structure from IMOS gliders transiting in the Western Coral Sea, contemporary; surface current estimates within the reef matrix derived from satellite tracked surface drifters deployed opportunistically within the GBR.

Model calibration requires numerous runs to be performed, and calibration should ideally be performed at both grid nesting levels. The relatively low model runtime ratios, particularly for the

shelf scale model, implies that the calibration process will be time consuming, and this will impact on the level of calibration to be performed for each model.

There may be some inconsistencies between real-world bathymetry and the way that it is represented in the model, particularly in coastal and reefal environments, and outside of frequently used areas. There should be effort directed to ensuring that the most accurate bathymetry data is used to underpin the model grid, e.g. the recently produced Digital Elevation Model of the GBR produced at 100 m spatial resolution (Beaman, 2010).

The heat flux calculations within SHOC rely on the prescription of light extinction and bottom reflectance coefficient. At present these co-efficients are spatially constant but could be input as 2-D spatially varying fields to more accurately simulate the water column heating in response to insolation. Additionally, sensitivity to the bulk schemes used to derive sensible and latent heat fluxes should be explored.

In regions of large salinity gradients (e.g. river plume/ shelf water interfaces, hypersaline fronts etc) there should be sensitivity analysis of the vertical mixing schemes to ensure accurate representation of these density driven features.

Finally, a high priority remains the assessment of suitability of sub-grid parameterization schemes for future incorporation into the whole of reef model. Much of the reef matrix contains bathymetric features that have spatial scales below the resolution of the model grids, and are therefore not accounted for directly in the model simulations, although the processes that these features generate affect momentum balances and mixing at large scales in the real world. The purpose of future comparisons between regional, shelf and higher resolution models will be to determine how the detailed flow elucidated by the higher resolution models contributes to the broader scale circulation and determine if it is possible to explicitly parameterise this contribution in more coarsely resolved models. This will be particularly important, for example, in providing correct exchanges through dense reef matrices, or for accounting for small scale flow features that may result in enhanced trapping, retention and residence times of water trapped within reef boundary layers.

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Appendix I:

2010 and 2011 Stakeholder workshop

A user/stakeholder workshop was convened at AIMS on June 11, 2010, and at the GBRMPA on June 08, 2011. The invitees included representatives from GBRMPA, local NRM bodies and the broader scientific community (JCU, CSIRO, AIMS).

Both workshops consisted of two sessions:

Session 1 focused on the presentation of project results, primarily outlining the implementation 4km regional model, general results and assessment of model performance, and a review of the preliminary results of the 2008/2009 wet season hindcast.

Session 2 focused on potential applications of the model results to support improved management of the GBRMP and/or other research activities on the GBR.

A summary of key ideas, opportunities and issues discussed at the stakeholder workshops are summarised below:

Issue	Potential application of GBR simulations
Oil spill trajectory prediction/hindcast	Recent examples have highlighted the difficulty in simulating the trajectory of oil spills in a complex marine environment. Output from the 4km and ultimately 1km model should be made available in near real time to oil-spill modelling specialists to better inform their oil spill trajectory modelling. Current results from the NRT model can be used easily and offline in SHOC transport model to track the release of passive particle. Relevant particle behaviour (settling), can be included in the transport models.
Connectivity, larval transport	Use model to better describe trajectories and connectivity of waterborne larvae (coral, fish) between Marine Park Zones and individual Reefs. Particle tracking is implemented in SHOC and can be run in offline mode to perform multiple runs with differing source locations. The current particle track implementation in SHOC includes vertical behaviour, settling, mortality and swimming behaviour.

	Regional model output has been linked to Connie (Connectivity interface developed by CSIRO: see http://www.csiro.au/connie2/) for statistical connectivity. AT present, results from 2008-2009 hindcast period are available to underpin transport estimates from Connie.
High resolution climatologies	As the time series of results increases, it will be possible to calculate high resolution climatologies of temperature, salinity, current stress, etc. Climatologies of temperature, for example, could help identify regions that consistently experience exposure to cool water, either via upwelling or other shelf intrusion processes. Such information would greatly inform any future zoning reviews.
Flood plume trajectories :	Particle tracking is implemented in SHOC and can be run in offline mode to perform multiple runs with differing source locations. The current particle track implementation in SHOC includes vertical behaviour, settling, mortality and swimming behaviour.
Response times for measurable change	A key challenge for water quality assessment models will be the development of techniques to correct for or remove effects on lagoon water quality of interannual variation in rainfall and runoff from long-term records. Interannual variation is very large, especially in the dry subtropics, and its effect on catchment loads and on GBR water quality and health will likely mask any effects of incremental changes in landuse practices for many decades, unless it can be corrected. It should be possible to use model results to develop spatio-temporal footprints for catchment loads to assist with this, in a manner analogous to the current use of spatial footprints from flood plume models.
Planning observational campaigns (short and long term)	Plume sampling during the wet season relies heavily on remote sensing to provide intelligence about sampling regions and locations. However, attempts to locate plumes and salinity fronts are often hit and miss, as imagery is often obscured by cloud. Results from the NRT can provide operational intelligence to help direct flood response sampling. In a more strategic way, model results could be employed to develop spatio-temporal footprints for target parameters to help inform the design of sampling programs.
Continued development towards a large-scale receiving water quality	There was agreement that there remains an urgent need to continue the development of the components of a modelling framework as described in the Webster modelling review (Webster et al 2008). A

model.	large-scale receiving water quality model, applied at the scale of the GBR Lagoon, would allow for simulation of the fate and impacts of terrestrially derived contaminants as they impact on the GBR. Such as model would be comprised of linked hydrodynamic, sediment transport, and biogeochemical models. The model would allow for the effects of the interaction between plumes from multiple rivers, and when applied at timescales of decades, the model would address also the issue of acute exposure of the reef by contaminants in flood plumes as well as more chronic exposure during the dry season. Such a modelling framework could play a critical role in underpinning the development of WQIPs by providing prediction of the likely impacts of alternative management strategies on indicators of environmental health under prescribed scenarios, underpinning target-setting and strategy selection.
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Communications, major activities or events

Presentations:

- “Hydrodynamics at the whole of GBR scale”, R Brinkman, M Herzfeld, J Andrewartha, C Steinberg, S Spagnol for the MTSRF Annual Conference, Cairns. May 2010
- “Hydrodynamics at the whole-of-GBR scale” - A foundation for receiving water quality models (AIMS, CSIRO)“ was presented as an internal AIMS seminar: July 2010
- “Advances in Observing and Modelling Physical Oceanographic Impacts on the Southern Great Barrier Reef, Australia” Steinberg, C.R., R. Brinkman, A. Mantovanelli, M. Herzfeld, M. Heron, S. Weeks, F. McAllister, S. Heron, D. Wisdom and A. Revelard, Australian Coral Reef Society. Coffs Harbour, Australia, 10-12 September 2010.
- “Advances in Observing Physical Oceanographic Impacts on the Southern Great Barrier Reef, Australia” Steinberg, C.R., S. Heron, M. Heron, A. Mantovanelli, P. Rigby, S. Weeks, J. Jaffrés, R. Brinkman, M. Herzfeld and D. Wisdom Australian Marine Sciences Association. Wollongong, Australia, 5-9 July 2010.

Workshops/Meetings:

- “Hydrodynamics at the whole-of-GBR scale - A foundation for receiving water quality models (AIMS, CSIRO)“ was presented at the Annual marine monitoring program workshop: Sept 2009
- An overview of the project was presented at the “IMOS Model-Data Synthesis Workshop”, October 2009.

- “Hydrodynamics at the whole-of-GBR scale - A foundation for receiving water quality models (AIMS, CSIRO)” Stakeholder workshop, June 2010
- Progress reports presented to RRRC GBR Operations and Water Quality Operations committee meetings.
- Informal meetings with GBRMPA about the use of the model to support Reef management during extreme events: November 2010, January 2011, February 2011
- “Hydrodynamics at the whole-of-GBR scale - A foundation for receiving water quality models (AIMS, CSIRO)” Stakeholder workshop, June 2011

Web pages:

- Operational results from the near-real-time regional model can be found at:
<http://www.emg.cmar.csiro.au/www/en/emg/projects/GBR/Results/Near-Real-Time-Results.html>
- Results from the 2008-2009 regional hindcast simulation can be found at:
<http://www.emg.cmar.csiro.au/www/en/emg/projects/GBR/Results/2008-2009-Hindcast.html>
- Project summary and metadata have been added to e-Atlas:
Hydrodynamics at the whole of Great Barrier Reef scale (MTSRF Project 2.5i.1)
<http://data.aims.gov.au/geonetwork/srv/en/metadata.show?uuid=ffbf4b5-e860-407e-a4d8-6d81f93157fb>