Technical Summary

The eReefs Marine Modelling component has delivered a modelling suite capable of predicting the hydrodynamic, sediment transport and biogeochemical characteristics of the Great Barrier Reef (GBR). This is achieved through a nested suite of models, whereby a regional 4 km resolution model is nested within a global general circulation model, and a 1 km resolution model is subsequently nested within the 4 km model. These models provide outputs of sea level, currents, temperature, salinity, suspended sediment, primary and secondary production, nutrients and optical characteristics throughout the GBR domain. The models operate in near real-time, such that current conditions may be monitored, and a hindcast archive exists back to September 2010 for the 4 km model and December 2014 for the 1 km model. The archive is kept up-to-date by continuously appending the near real-time outputs. A Relocatable Coastal Ocean Model (RECOM) has been developed which is an automated re-locatable modelling system capable of generating high resolution models of hydrodynamics, waves, sediment transport and biogeochemistry (BGC) that are nested within the 4 km or 1 km regional models. This package is designed for non-specialist users, whereby the user simply and intuitively interacts with the models via a graphical workflow interface.

Hydrodynamic models at the 4 km and 1 km scale (GBR4 and GBR1 respectively) are operating routinely in near real-time within the CSIRO real-time framework (TRIKE). These model outputs are routinely posted on the web (https://research.csiro.au/ereefs/models/model-outputs/), and are publically available (http://dapds00.nci.org.au/thredds/catalogs/fx3/catalog.html). A five year archive currently exists of the 4 km output, which is appended using the routine near real-time output. The 1 km model began routine operation in December 2014. These models have been subject to calibration and validation, both in hindcast and near real-time, using available Reef Rescue monitoring data, data from Australian Institute of Marine Science and CSIRO cruises, data from the Integrated Marine Observing System and satellite observations. Skill assessment indicates that the models are performing well at the surface for temperature in terms of the annual and weatherband cycles. Surface salinity shows good agreement in the timing and magnitude of flow events. Biases exist in temperature and salinity at depth, which are speculated to be due to initial / boundary conditions. Diurnal and low frequency sea level correlate well with observations if a dual-relaxation open boundary scheme is used for boundary relaxation that accounts for the intrinsic temporal differences in tidal and low frequency motions. Average skill metrics are summarized in Table 5.1.3 and Table 5.2.2 of this report.

Algorithms for sub grid-scale parameterisation have been developed, based on existing bottom roughness parameterisation and a unique ‘porous-plate’ approach where kinetic energy is extracted from the system by vertical mixing to account for the impact of the reef matrix on flow. This is a function of the cross sectional area the reef occupies with respect to a model grid cell. The methodology of this reef parameterisation is incorporated into the hydrodynamic models.

The hydrodynamic model code has been re-configured to run in parallel on distributed memory architectures (as opposed to shared memory architectures which it can currently do). The methodology is based on master-slave data distribution, however, gather-scatter operations are performed in a slave-slave environment which introduces significant efficiencies when compared to the traditional master-slave transfers. In a benchmarking exercise, the GBR 4 km model was shown to outperform an identical model simulated using the MOM4 ocean code. Additionally, the GBR 1 km model was shown to scale linearly up to 78 processors. This allows the models to be implemented in super-computing architectures.

Data assimilation (DA) is a method that is employed to merge the solution from a numerical model with available observational data to produce a 3-D time varying fields. The output from DA is considered to be the “best estimate” of the system state, where model uncertainty is reduced, and sparse observation data is dynamically interpolated using the numerical model. Within the context of eReefs, DA has been applied to both the marine hydrodynamic and biogeochemical (BGC) models. It has been used for both parameter estimation in the hydrodynamic model, and also state updating in the hydrodynamics and BGC.

Observations of temperature from remote sensing (Sea Surface Temperature), moorings and gliders, have been assimilated into the hydrodynamic model. Two approaches were used. The first assimilation approach was to constrain three parameters relating to the transmission, attenuation and bottom reflectance of short wave radiation. These parameters vary according to water clarity, bottom type and errors in surface heat fluxes. By including these variables in the data assimilation system, spatially varying fields were produced (see figures 4.3.20-22), that were subsequently used in the production run of the hydrodynamics. By estimating the spatially varying short wave radiation parameters, we reduced the bias of the hydrodynamic model by up to 3 degrees C, and reduced the RMS error to less than 1 degree C when compared to a withheld dataset.

The second approach used an efficient Ensemble Optimal Interpolation system for sequential updating of the model state (temperature) to assimilate observation from January 2011 – December 2014 in the hydrodynamic model, to create the first version of a high resolution reanalysis product for the GBR region. The average forecast error for temperature ranged between 0.4 and 0.9 degrees C, depending on observation density, typically related to cloud cover.

The assimilation system was also applied to the biogeochemistry, with observations from satellite remote sensing products being the only assimilated data. A simple ensemble optimal interpolation system was applied and the forecast error from this system was approximately half that of the control run. By applying a more advance ensemble Kalman filter system, there was a further reduction in forecast error, with the domain wide error reducing by a further 5-10 % when compared to the simple data assimilation system. It should be noted that recent BGC model developments and further improvements to the BGC DA scheme has led to the mean absolute prediction error dropping from 75% in earlier versions, to 25% in the latest system.

Wave models are required to provide accurate wave-enhanced bottom stress for the sediment transport model. Hindcasts for the wave models have been performed using both the WaveWatch III and SWAN models. As each of these models has certain advantages over the other, the aim is to identify the model most suitable for the GBR region, and capable of performing in an operational capacity. The WaveWatch III model has also been implemented in near real-time, and is capable of providing inputs to downstream models. Due to difficulties in obtaining the boundary information from the Bureau of Meteorology’s (BoM) operational models required to force this model, the near real-time operation has been terminated. The BoM AUSWAVE wave products are used directly for downstream models, at coarser resolution than the WWIII model. The SWAN model has also been applied to an estuarine environment (Fitzroy Estuary) for testing purposes, and subsequently included in the relocatable coastal model framework.

An offline transport model must be used to drive both the sediment transport and biogeochemistry (BGC), as these models are computationally too expensive when fully coupled to the hydrodynamic model. The Flux Form Semi-Lagrange Method (FFSL) used in the meteorology community has been implemented as the advection scheme in the transport model. The FFSL scheme conserves mass almost perfectly locally and can be run with longer time-steps to increase computational efficiency. The transport model was assessed against the 3D hydrodynamic model for a number of passive tracers and found to be suitable in terms of distribution of tracers, conservation characteristics and computational efficiency for driving the sediment and BGC libraries.

The suspended sediment model represents the resuspension and settling of fine sediments between the water column and 4 benthic layers of sediment. The model is initialised with the observed distribution of gravel, sand and mud on the seabed of the shelf region. Catchment sediments discharged into the GBR over the simulation period are represented in the model by two size classes of particles having varying settling velocities. The model tracks the distribution of these particles separately from the distribution of the historically accumulated sediment in the region. This arrangement underpins its capacity to discriminate between the local resuspension event and the input of sediments from catchments. The transport of modelled sediments is driven by simulated hydrodynamics and wave data. The sediment model supports biogeochemical model simulations and provides input to nested fine-resolution relocatable model RECOM. The sediment transport model produces a stable, realistic simulation, even when subject to extreme forcing events such as cyclone Yasi. The model is now routinely running in near real-time, using the transport model as a driver and WaveWatch III outputs as forcing fields.

The sediment transport model was calibrated in two stages. First, the model parameters (initial conditions and spatially varying bottom roughness) have been refined through the ensemble assimilation of 6 months of remote sensing data for total suspended solids (TSS). Ensemble of models, produced through the assimilation step, have been reduced to a single model, which was subsequently validated against time-series of the observed turbidity (i.e. data from coastal sensors and GBROOS shelf moorings). The validation of the 4-year run of the model revealed a long-term drift of the solution which was handled through the manual adjustment of the model parameters. The quality of the calibrated model varies across the GBR region and with time (as was expected). The distribution of the simulated suspended sediment on GBR, in general, is consistent with observations. The model tends to overestimate suspended sediment levels in northern Queensland and underestimate TSS levels in Torres Strait.

The sediment transport model is capable of predicting the broad patterns of suspended sediment in the GBR, and variability at tidal and seasonal time-scales, and is suitable for use in scenario analyses. Due to the inherently stochastic nature of the sediment processes on the shelf and due to resolution and process limitations of the model itself, there is uncertainty in forecasts of sediment concentrations at specific locations in space and time.

A number of preliminary scenarios have been simulated with the calibrated model. Numerical experiments highlight the role of very fine fraction of catchment sediments (representing either tails of the sediment size-distribution or flocs of fine particles characterised with a low settling velocity) as a carrier of sediment signals propagating from catchments to the GBR region. Scenarios with varying loads of sediments from catchments illustrate spatial and temporal variability of changes of suspended sediment levels on GBR. The response of TSS to varying loads from catchments in these scenarios is expressed in terms of changes of the annual mean probability for TSS to exceed 2 mg/L. This threshold (2 mg/L) represents GBRMPA (2009) guideline trigger value for TSS effects on marine ecosystems in open coastal and midshelf waters of GBR.

Preliminary analysis of these simulations suggests a relatively short term-response of the GBR system to changes in catchment loads. Scenarios with a 4-year run of the model having elevated loads from catchments does not show an incremental, multi-year build-up of the excessive TSS levels in the region. Instead, the TSS response to the increased load from catchments is most pronounced during wet years (and, according to some scenarios, during the first dry year following wet years). During the subsequent dry years changes in catchments have a much smaller impact on the probability for TSS to exceed 2 mg/L.

The ecological processes represented in the biogeochemical model include the photosynthetic growth of 4 categories of phytoplankton and of seagrass, macroalgae, and coral zooxanthellae, secondary production by zooplankton and corals, gas exchanges of oxygen and carbon dioxide, and transformations of nitrogen, phosphorus and carbon in various forms. Key ecological processes that were developed specifically for GBR waters include a host-symbiont representation of coral dynamics, a multi-type seagrass model, equilibrium carbon chemistry calculations, Trichodesmium nitrogen fixation, and a spectral-resolved optical model for accurate representation of the in-water light field and water-leaving optical properties. The new processes for GBR waters have been developed in collaborations with experimental and observational scientists at AIMS, JCU, UQ and UTS and published in the peer-review literature to ensure the robustness of their formulation. A complete description of the optical and biogeochemical model is given in Appendix B.

The biogeochemical model is driven by the hydrodynamic model using an offline transport model that is computationally efficient and conserves mass. Initial biogeochemical model conditions and parameters were derived from climatologies, historical observations and literature values, with ocean boundary conditions scaled against density profiles for synchronisation of mesoscale forcing. Coastal nutrient and sediment loads were derived from SOURCE catchment model loads for 21 major river systems along the Queensland coast and atmospheric nutrients were deposited into the upper ocean with rain.

Results from a 4 year hindcast were compared with observations from a range of model platforms, sensors and analytical techniques to assess model skill. The model reproduced the observed nutrient climatology, the spatial gradients in remotely-sensed ocean colour and in situ water quality observations with sufficient skill for the purpose of a water quality (phytoplankton, nutrients, turbidity, oxygen) hindcast, near real time and scenario simulation in the GBR World Heritage Area. Of the quantities available for comparison with in situ observations, model skill was highest for carbon chemistry properties. Compared to the 14 AIMS Reef Rescue inshore sampling sites, pH had a root mean square (rms) error of +/- 0.03, while aragonite saturation had an rms error of +/- 0.23. Comparison with chlorophyll fluorescence from the Reef Rescue mooring sites with simulated chlorophyll a showed a bias of only -0.07 mg chl *a* m-3, and a rms error of 0.33 mg chl *a* m-3. A summary of skill metrics are available in Table 5.5.5, and a complete analysis in Appendix A.

The Relocatable Coastal Model (RECOM) is designed for non-expert modellers to generate high resolution models over limited area coastal or reef domains within the GBR, and produces hydrodynamic, sediment transport, wave and biogeochemical outputs. It uses initial and boundary conditions from the GBR1 or GBR4 regional models, and surface fluxes from ACCESS. Wave conditions are predicted using the SWAN model. RECOM has undergone extensive testing on arbitrary domains within the GBR, and three regions have been simulated and examined in detail to assess the accuracy of the RECOM outputs. Interaction with the RECOM software is via an intuitive and simple graphical workflow interface. The elements of the workflow include orthogonal curvilinear grid generation via a graphical 'point and click' interface, selection of parameter 'sets' for sediment transport and biogeochemistry to be applied to the models, and selection of the forcing products and time period for the simulation. Extensive run monitoring options are available for the user to monitor the progress of the models. RECOM is similar to BLUElink's re-locatable model (ROAM), with added functionality of general orthogonal grid generation and capability of simulating suspended sediments and BGC with minimal expert user interaction.

The three test cases to which RECOM was applied were the Fitzroy Estuary (for a freshwater impacted estuarine environment), Heron Island (for a reef environment) and the Whitsunday Islands (for a non-river impacted bay). Users were able to successfully generate RECOM output in these test cases that compared generally favourably to optimized models of the same region or observations. RECOM is able to produce pilot models that are capable of reproducing first order dynamics. To improve the realism and obtain a fully calibrated and validated state requires careful assessment against observations, and heuristic optimization by an experienced modeller familiar with the dynamics of the ocean and the numerical implementations that approximate them. RECOM has shown to be a perfect tool for non-specialists to generate a first view of the dynamics of a local region, and to effortlessly produce a solid basis for further model optimization for more experienced users. RECOM should not be considered as one final product, but one capable of evolution based on user feedback.