eReefs: Modelling the Great Barrier Reef

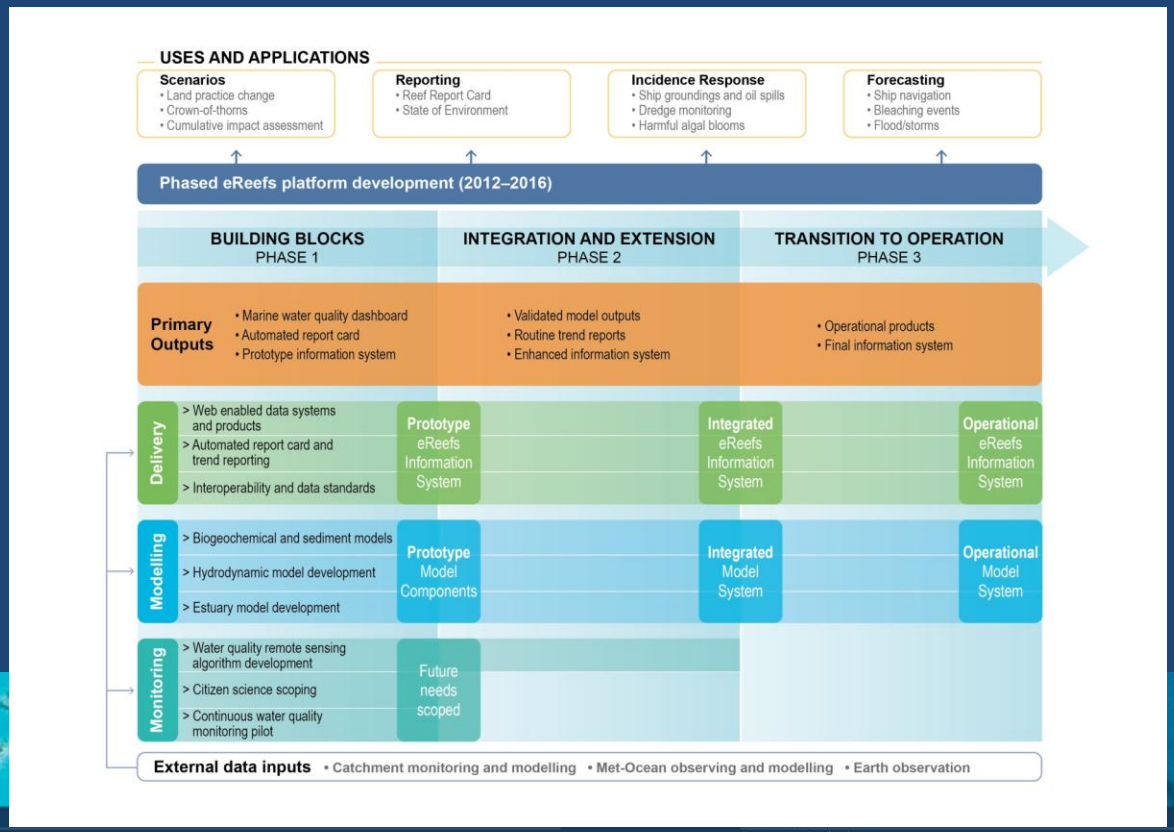
M. Herzfeld

eReefs is a collaboration between:
GREAT BARRIER REEF foundation
Australian Government Bureau of Meteorology
CSIRO
Australian Government
Australian Institute of Marine Science
Queensland Government

Supported by funding from:
Caring for Our Country
Queensland Government
Science and Industry Endowment Fund
bhpbilliton resourcing the future
BMA BHP Billiton Mitsubishi Alliance

The eReefs project aims to develop an information system for the GBR.

- Catchment ➡ estuaries ➡ lagoon ➡ shelf ➡ open ocean
- Catchment ➡ hydrodynamics ➡ waves ➡ sediment transport ➡ BGC
- Operational forecast, scenario modelling products



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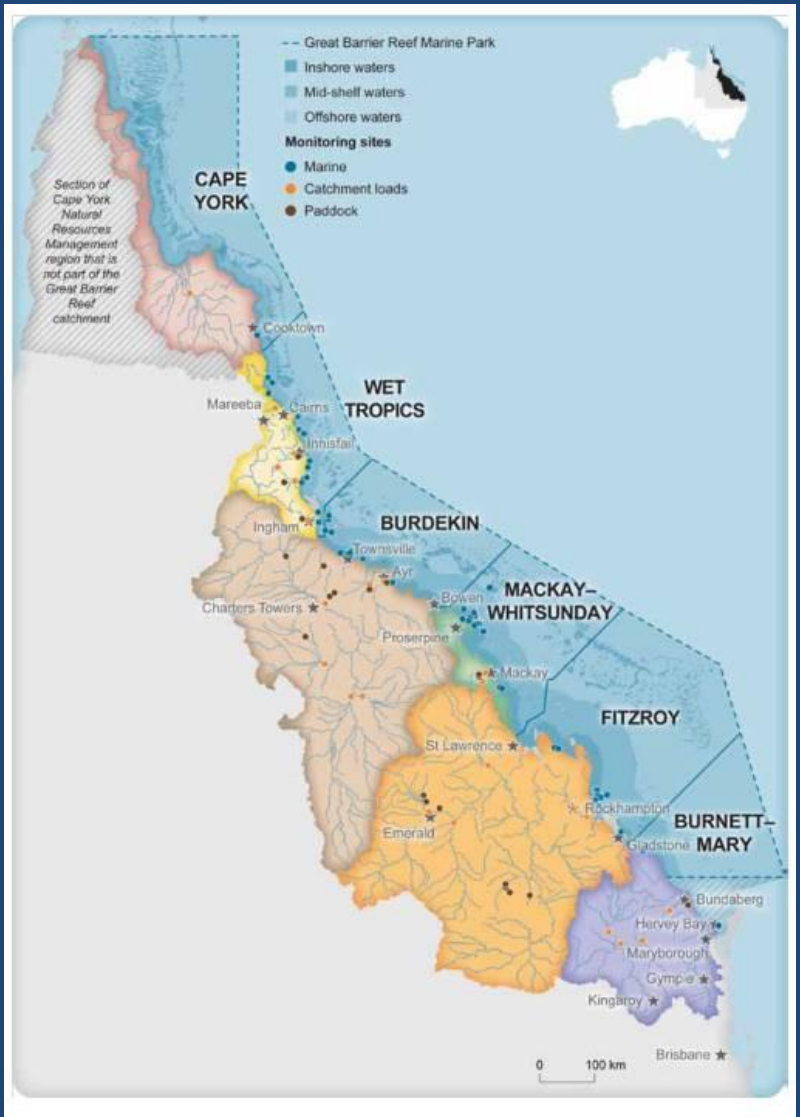
GBR : One of seven Natural Wonders of the World



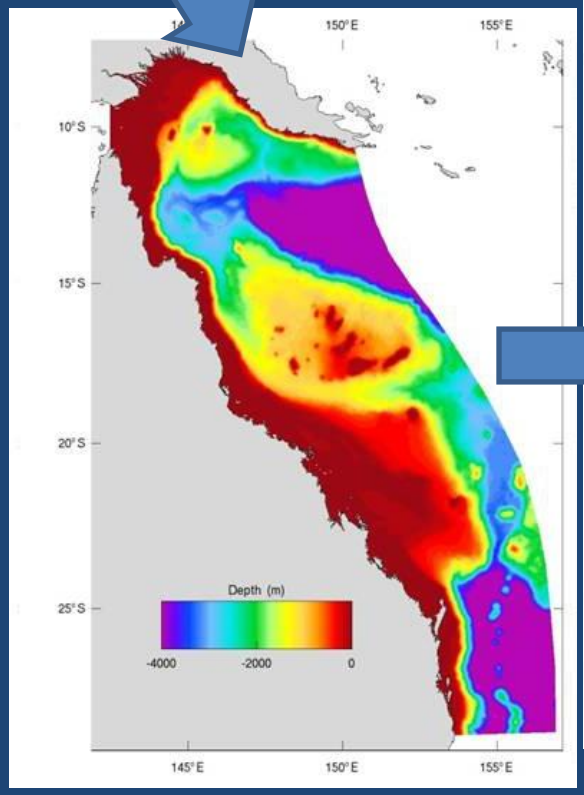
- UNESCO World Heritage Area
- 2600 km long reef & lagoon complex
- 344,000 km^2 area
- 2800 reefs
- 450 species of hard coral
- >1620 species of fish
- ~500 species of seaweed
- 2000 species of sponges
- 23% of known global species diversity

- Coral cover is in decline (50% loss over the last few decades)
- Management of the GBR requires access to information.

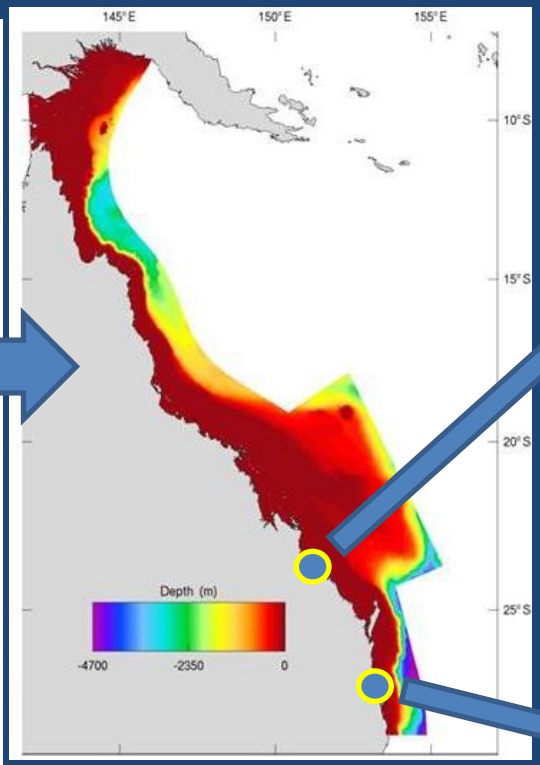
Nested approach to traverse scales

Global products:
- OceanMAPS (10km)
- ACCESS-A (12km)

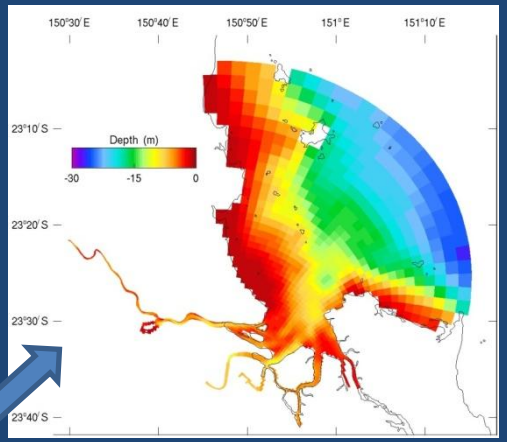
- **Downscaling to the reef/estuary scale is required (local models),**
- **Multiple nests are required to achieve boundary ratios ,**
- **20 estuaries with freshwater input represented.**

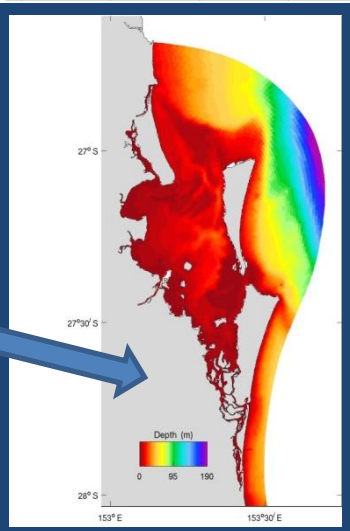


Bridging models (4km)



Hi-res regional (1km)



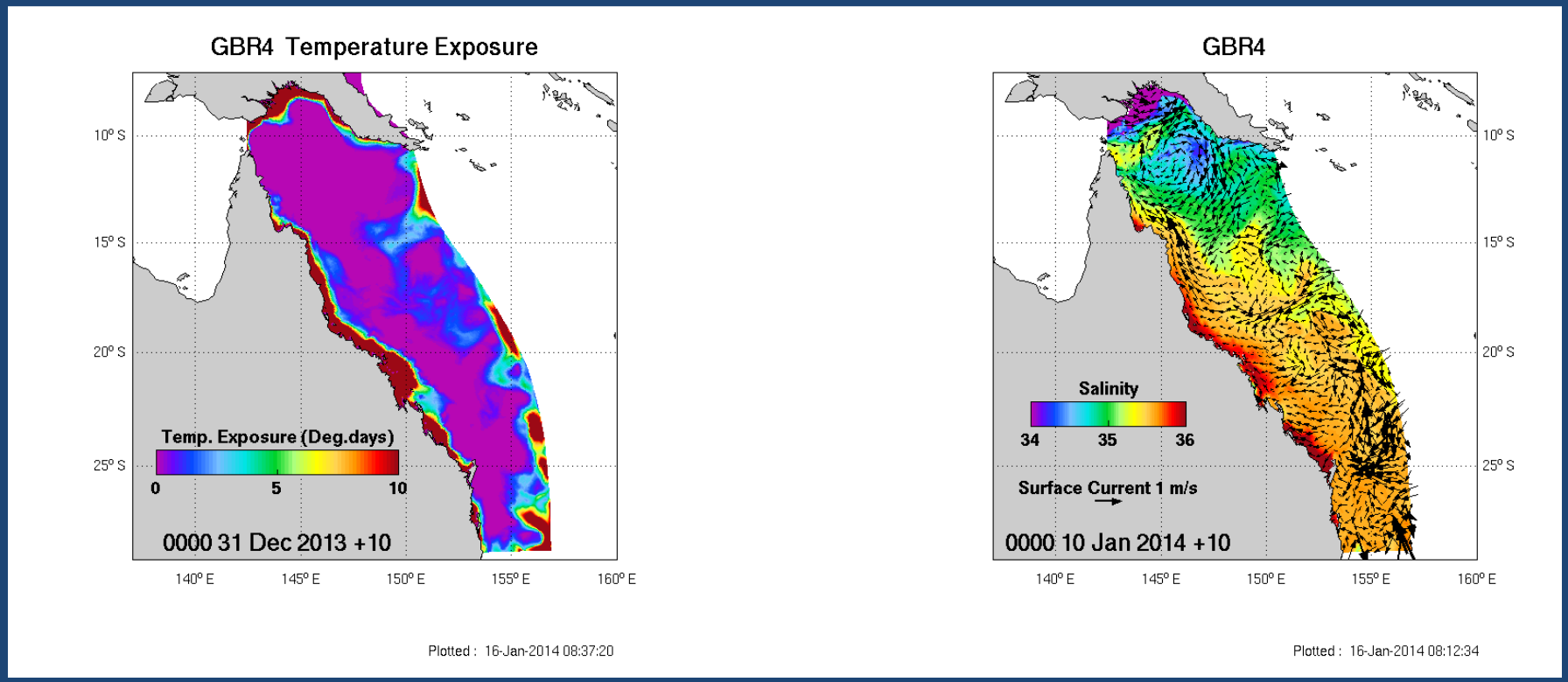


Local models

http://www.emg.cmar.csiro.au/www/en/emg/projects/eReefs.html

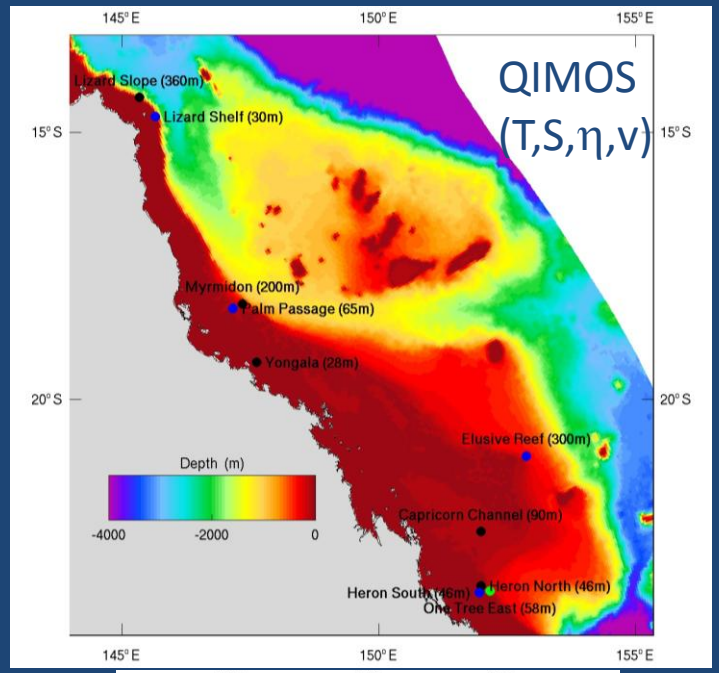
GBR4 and GBR1 operate routinely in real-time

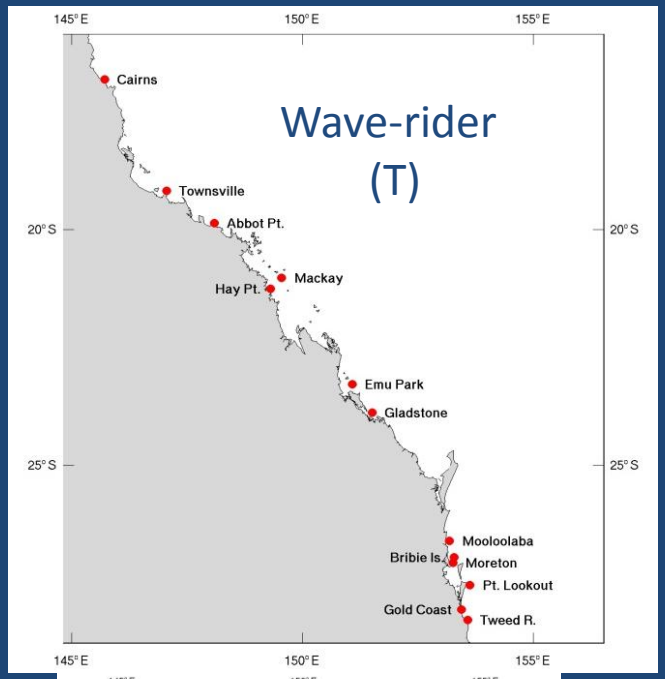
http://www.emg.cmar.csiro.au/www/en/emg/projects/eReefs/Results/4km-Near-Real-Time.html

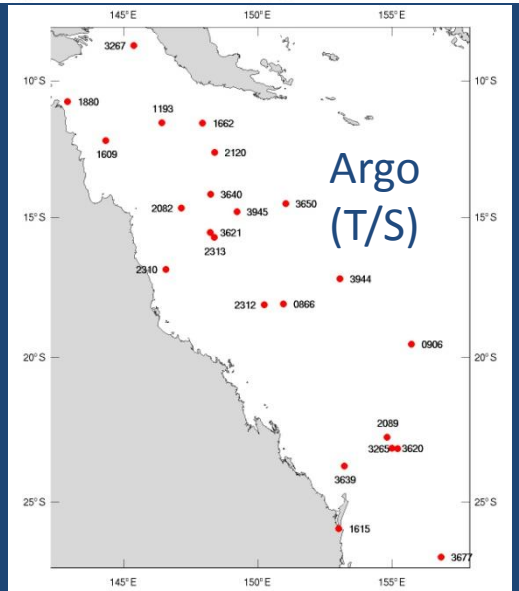


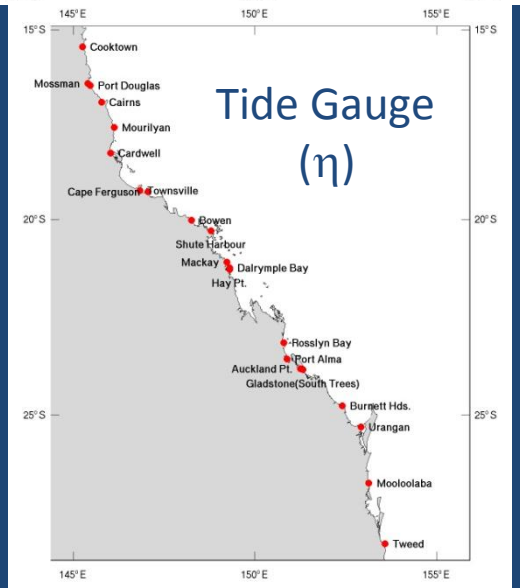
GBR4 : Model results archived since July 2010
GBR1: Model results archived since July 2013

Observation sites

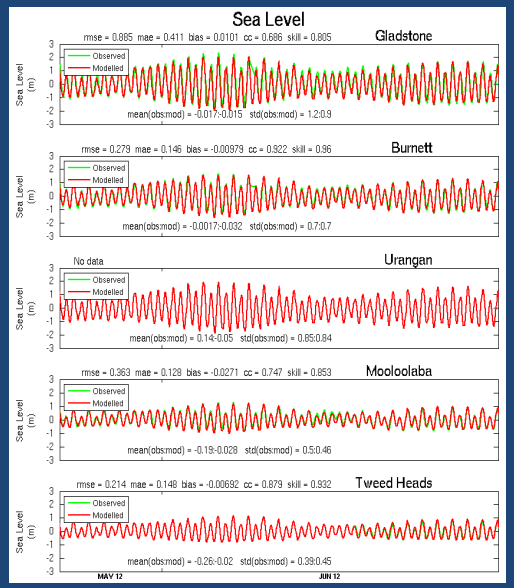


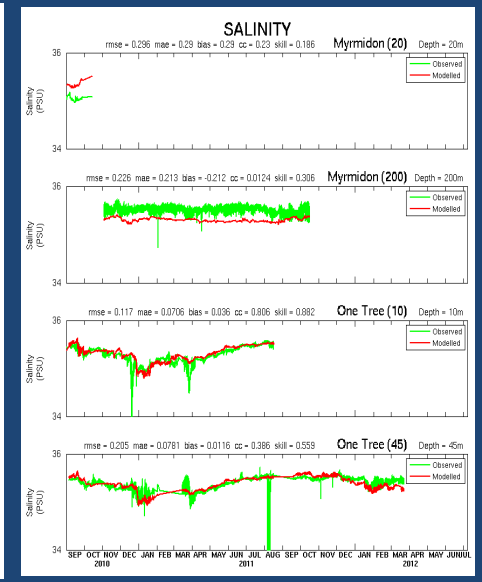


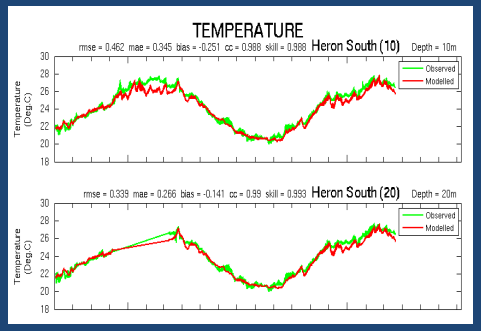


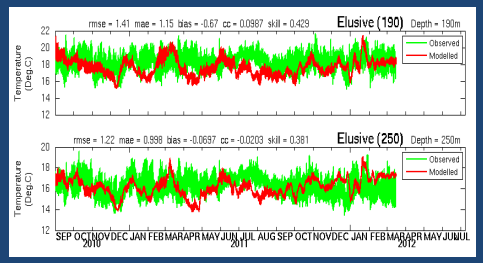


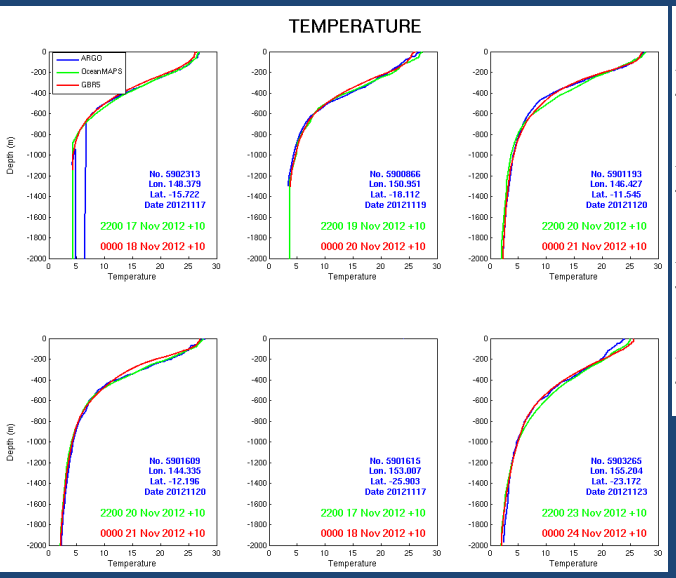
Calibration: free running model

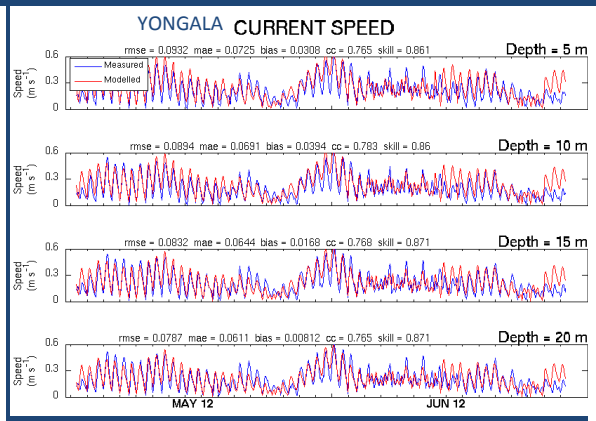


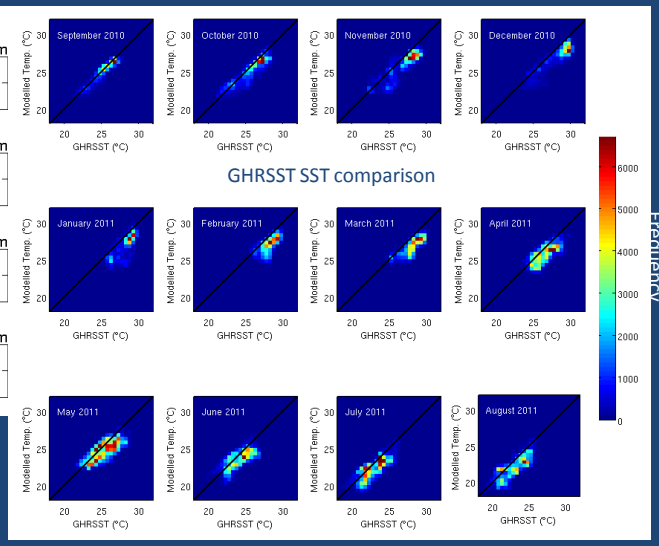












Use of DA

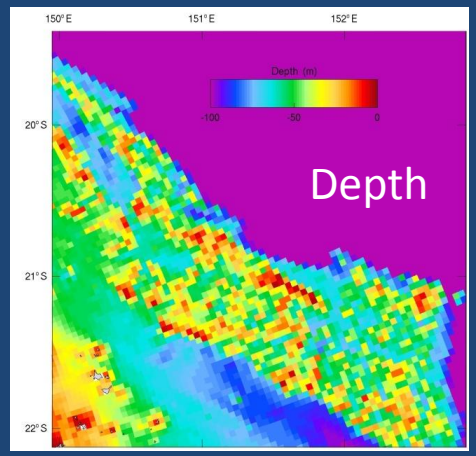
- Correct the sources of error rather than cover the symptoms,
  - Correct model forcing and parameters and remove persistent bias
  - Use of EnKF, hybrid EnOI-EnKF
- Avoid adjusting hydrodynamic state to maintain equilibrium between pycnocline and nutricline (cause of spurious blooms in BGC).
- Avoid adjusting the state to perform scenario simulations.
- EnOI used to diagnose error sources – not suitable for state update generally;
  - Observing system is insufficient at scales modelled, especially sub-surface during stratified (flood) conditions
  - Must use techniques to only constrain mesoscale – fine scale structure at higher resolution should be unaltered
  - Performs poorly during extreme episodic events (cyclones, floods) not captured by the background ensemble
- EnKF allows joint state and parameter estimation, captures flow dependent errors.

Challenges

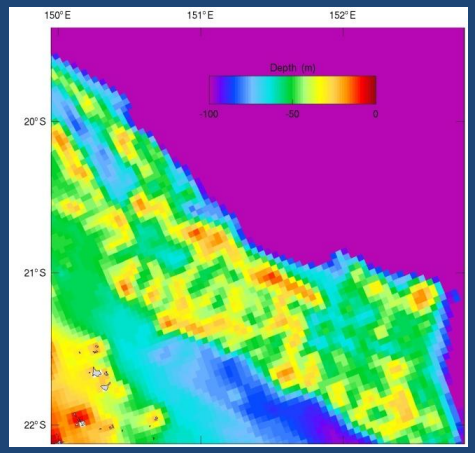
- Bathymetry
  - Wetting and drying,
  - Sub-grid reef parameterization.
- Open boundaries
  - Dirichlet method developed (Herzfeld & Andrewartha, 2012),
  - Dual relaxation in flux adjustment to account for low and tidal frequencies,
  - Conserves mass and volume in the boundary cell.
- River input
  - Based on the Dirichlet method,
  - Allows for brackish input at the coast,
  - Dynamic pycnocline adjustment.
- Short wave parameters
  - Uses bottom absorption,
  - Spatially varying using EnKF parameter estimation.
- 1km model throughput
  - Distributed processing cast for slave-slave transfers.
- 2-way nesting capability
  - Autonomous push-pull data transfer.

Capricorn Bunker Group Bathymetry

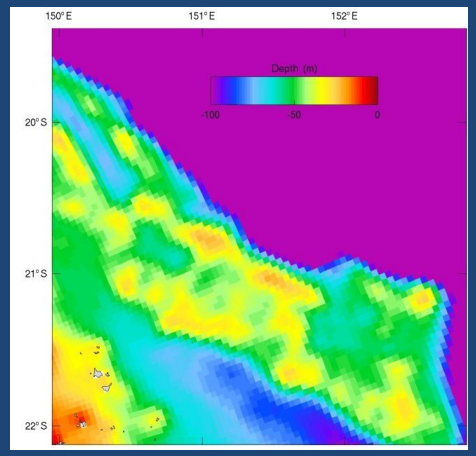
- Reef matrix generates small scale structure and deflects the large scale flow,
- Resolving the reef is critical to accurate dynamics in the lagoon.



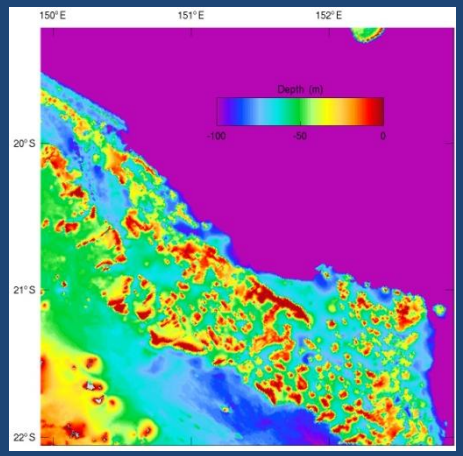
GBR4: No smoothing



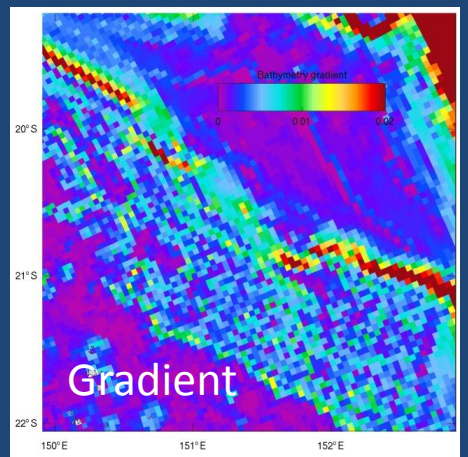
1 pass

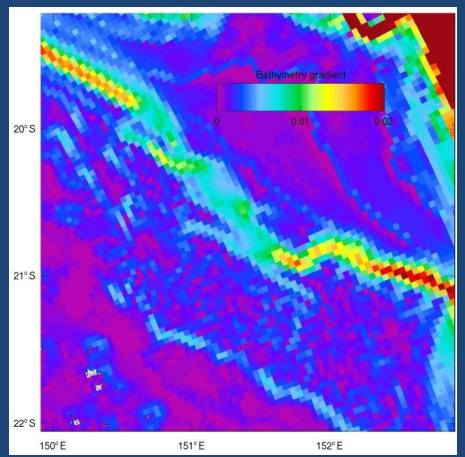


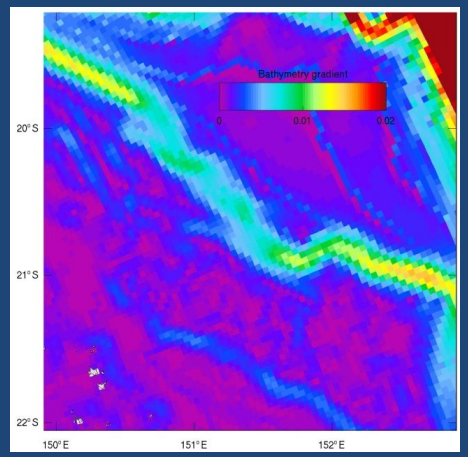
3 passes

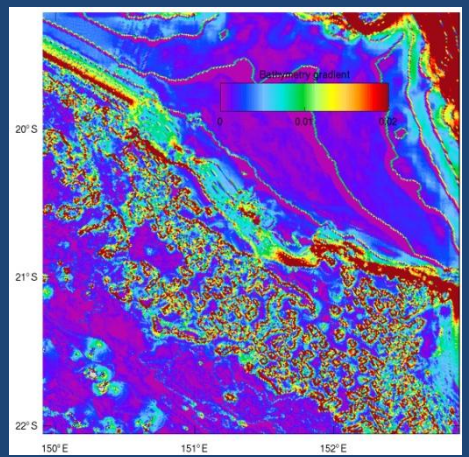


GBR1: No smoothing

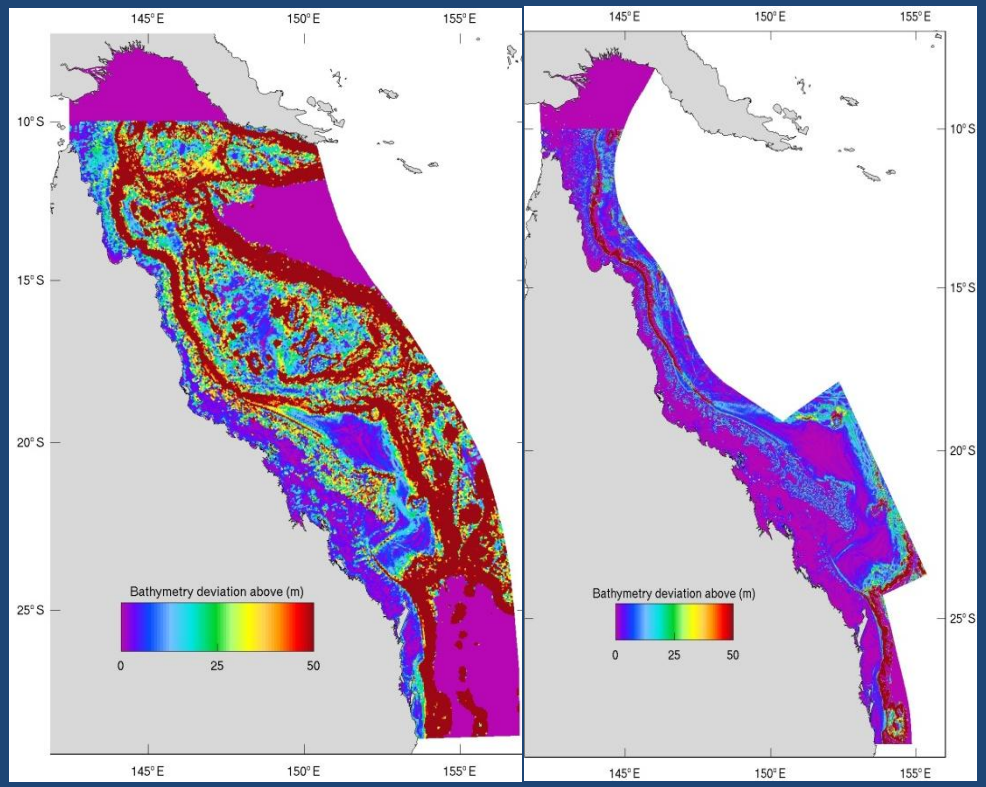








Bathymetry analysis

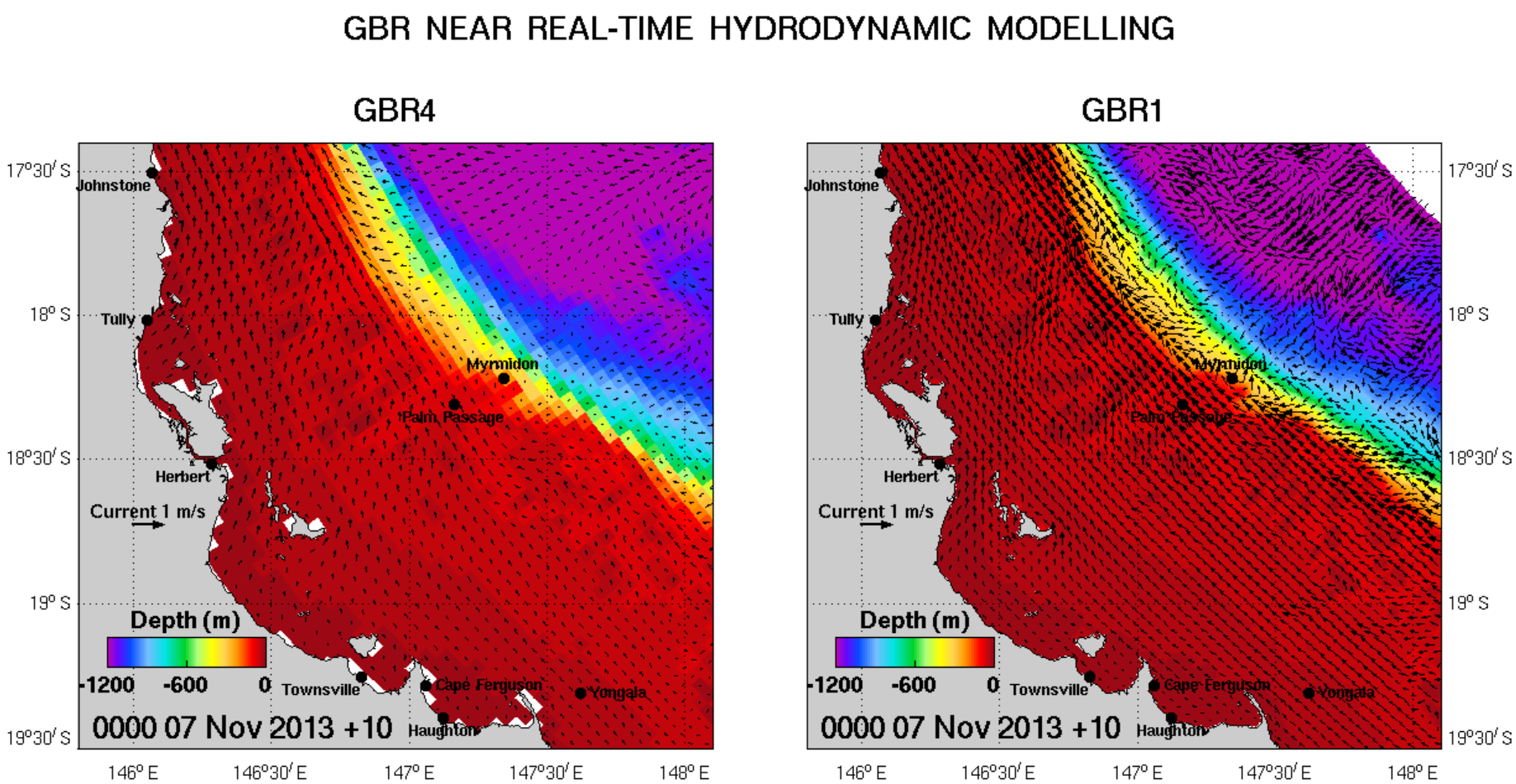


4km 1km

Difference between shallowest and gridded bathymetry

- Database used to average the bathymetry onto the model grid is 100m (i.e. reef resolving),
- Compute the maximum difference between model bathymetry (@4km/1km) and the shallowest depth in the database (@100m),
- GBR4 resolves the reef poorly.

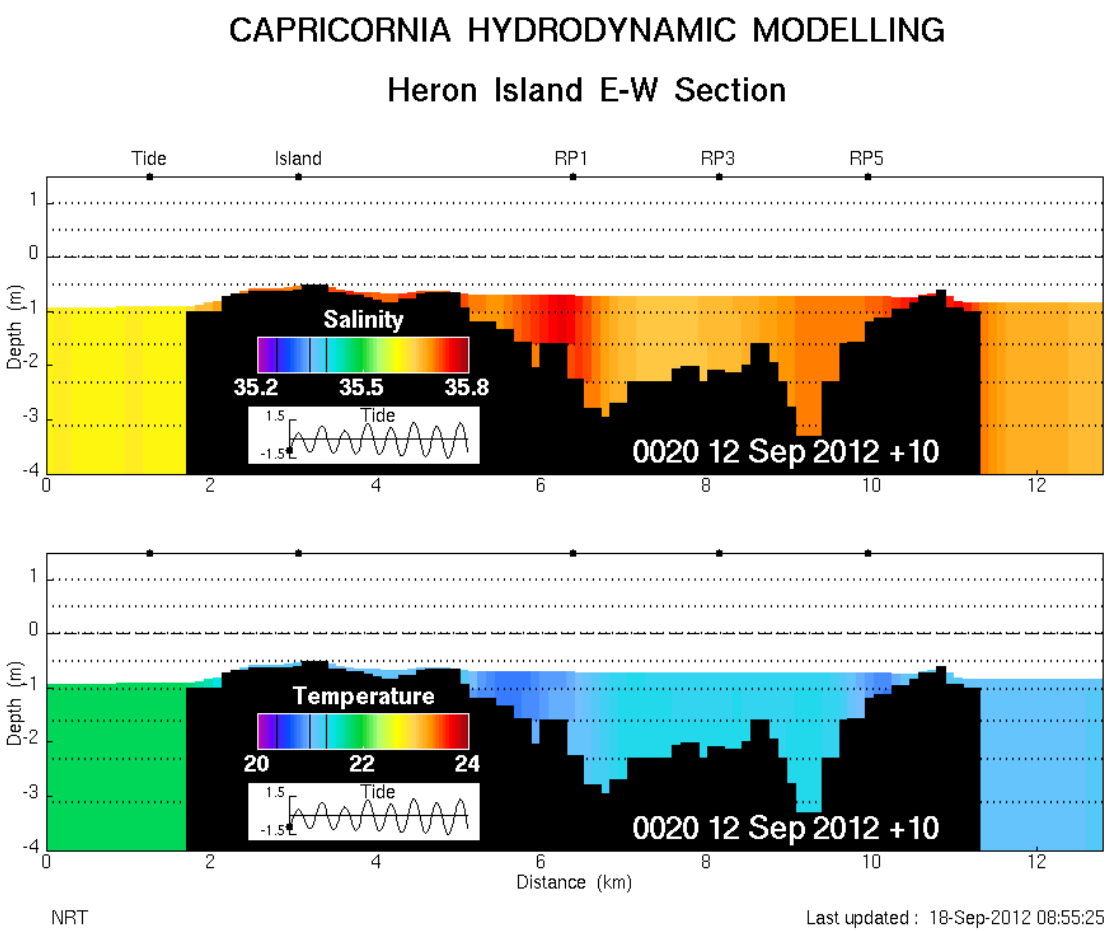
Increased reef effects in the 1km model

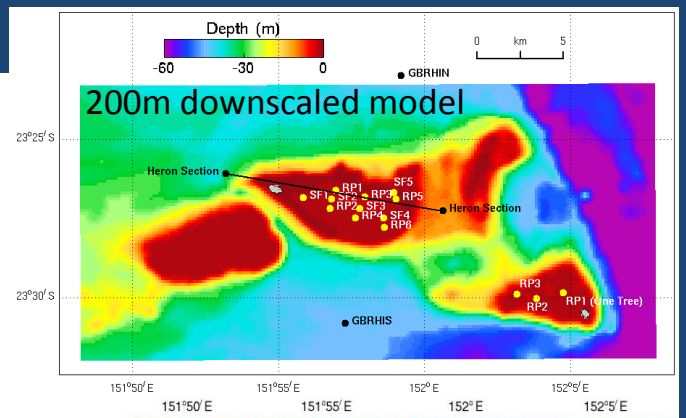


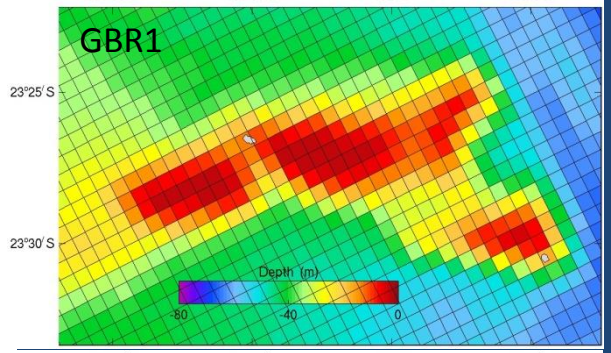
http://www.emg.cmar.csiro.au/www/en/emg/projects/eReefs/Results/1km-Near-Real-Time.html

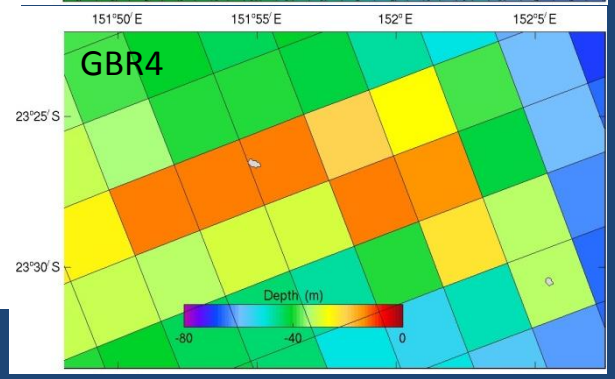
Plotted : 19 Nov 2013 09:00:14

Water properties on drying reefs



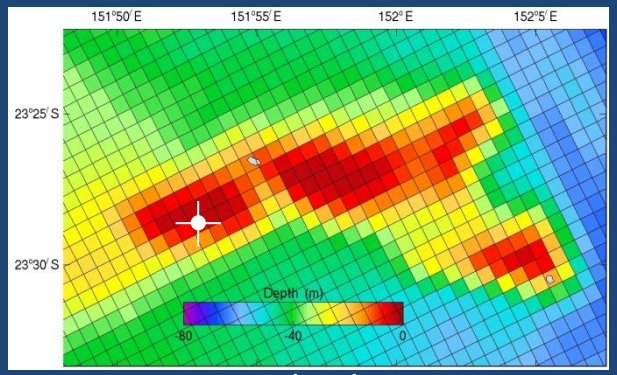




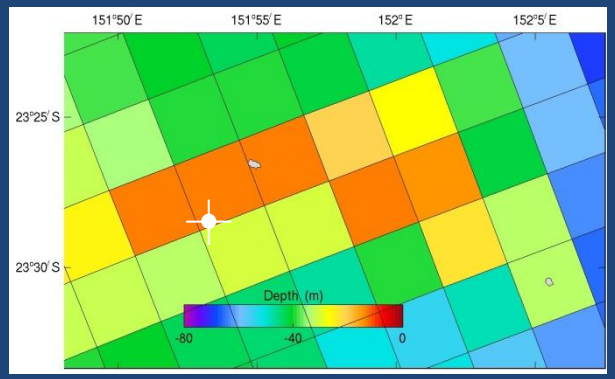


Diurnal temperature change

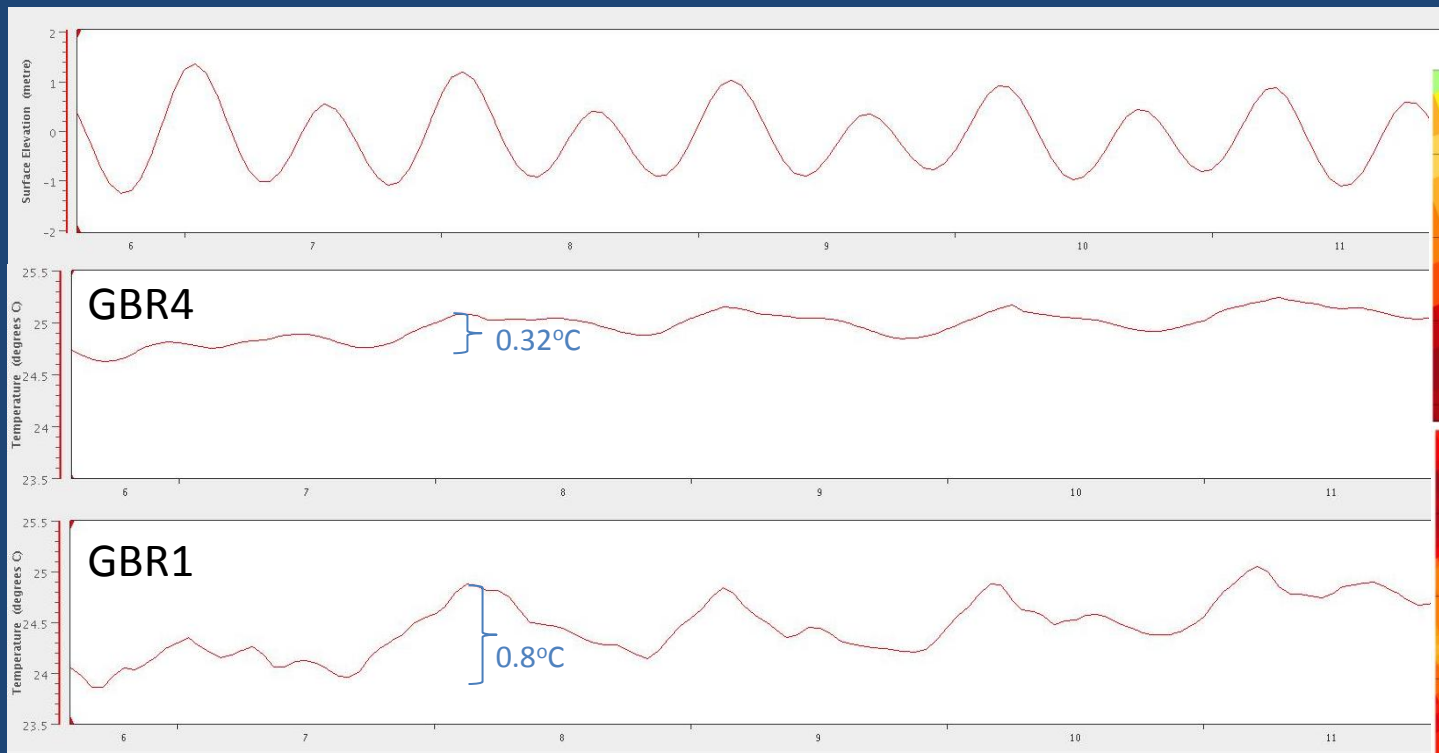
Wistari Reef;
Heron Island

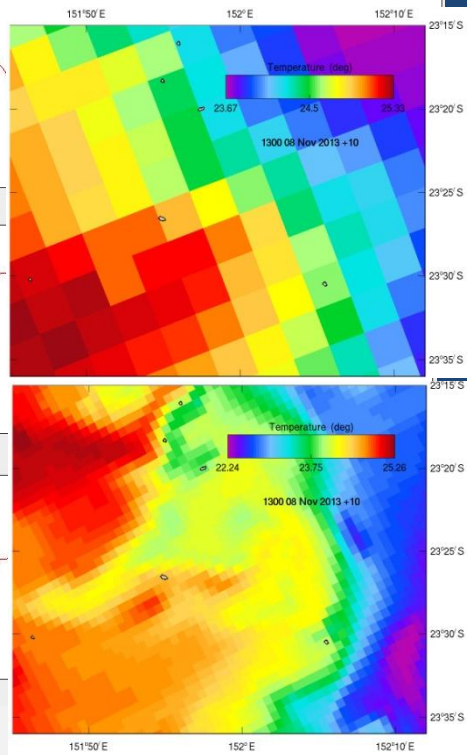


GBR1: depth = 3.7m



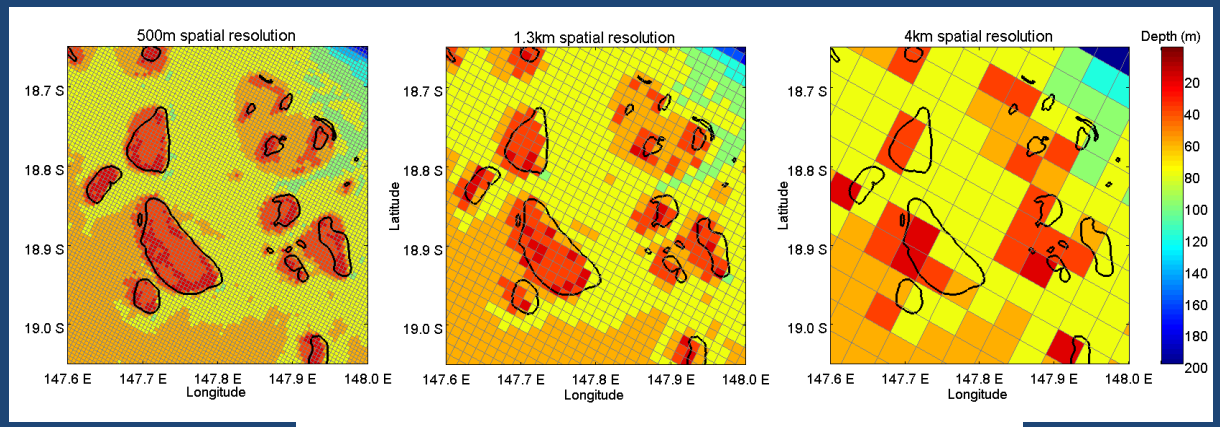
GBR4: depth = 13.4m

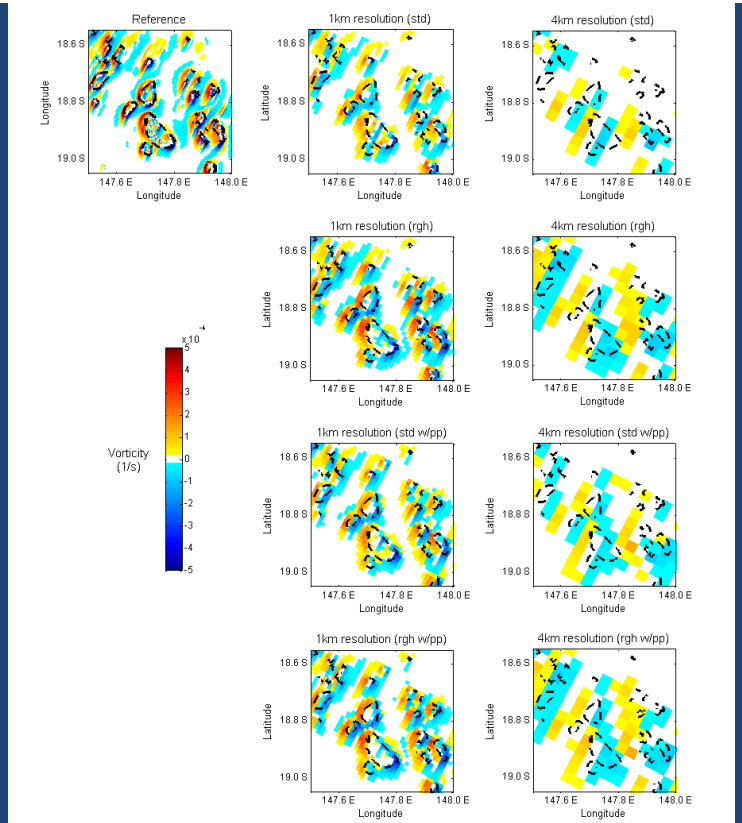




November 2013

Sub-gridscale parameterisation

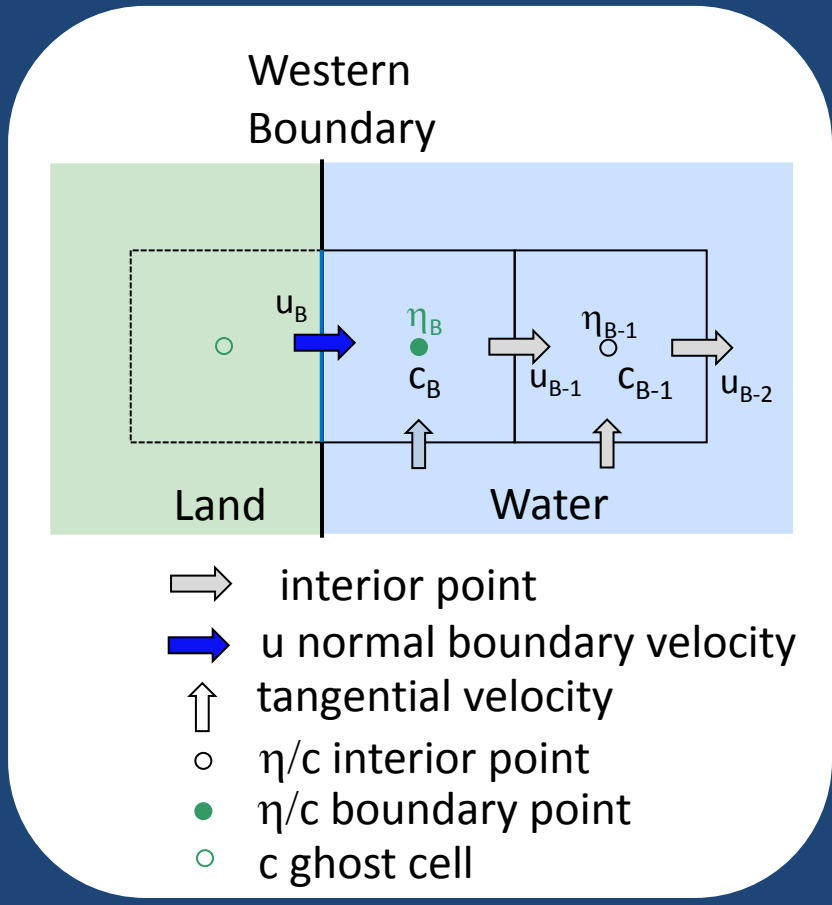




- Use 'porous plate' approach, based on obstruction of flow imposed by an obstacle,
- Previously used in bridge design,
- Parameterises energy loss due to the reef in each cell using a loss term in the vertical momentum mixing scheme,
- Also use increased bottom roughness approach,
- Not a magic bullet,
- Best option to capture reef dynamics is to resolve the reef matrix.

Open boundaries

- Use a clamped (Dirichlet) condition,
- Boundary implementation is 'normal velocity outside elevation' (NVOE).
- u_B is defined via external data.
- Boundary cell η is solved via continuity equation.
- Extra 'ghost' cells added beyond the boundary to interpolate external tracer data onto.
- Boundary tracer c_B is solved via conservation equation using internal advection scheme.
- Resulting scheme conserves mass and volume in the boundary cell.



Flux correction to avoid volume drift.

- Basin-wide divergence (basin filling/emptying) can occur due to bathymetry differences and interpolation error.
- Depth averaged velocities are perturbed so that divergence in the boundary cell achieves a 'target' elevation over a specified time-scale.
- Elevation is left unconstrained.
- Perturbation flux is derived by inversely solving the continuity equation given the target elevation is specified:

$$F_{BT} = \frac{h_1 h_2}{2\Delta t_{2D}}(\eta^{t-1} - \eta_T) + h_2 D_I V_I + h_1 (D_2 V_2 - D_1 V_1)$$

- Perturbation velocity is then:

$$V_B^t = V_B - \frac{\Delta t_{2D}}{\tau_f}(V_B - \frac{F_{BT}}{h_2 D_B})$$

- Note the relaxation time τ_f

Dual relaxation

- Must reconcile tidal boundary forcing (active OBC) with low frequency sea level oscillations due to wind (passive OBC).
- Use method of fractional steps to split the continuity equation into contributions from tidal and low frequency fluxes:

$$\frac{1}{2}\frac{\eta'-\eta^t}{\Delta t_{2D}/2}=\frac{\eta'-\eta^t}{\Delta t_{2D}}=\frac{F_T}{A}-\frac{\Delta F}{2A}$$

$$\frac{1}{2}\frac{\eta^{t+\Delta t}-\eta'}{\Delta t_{2D}/2}=\frac{\eta^{t+\Delta t}-\eta'}{\Delta t_{2D}}=\frac{F_L}{A}-\frac{\Delta F}{2A}$$

$$\Delta F = F_{i+1}+F_{j+1}-F_j$$

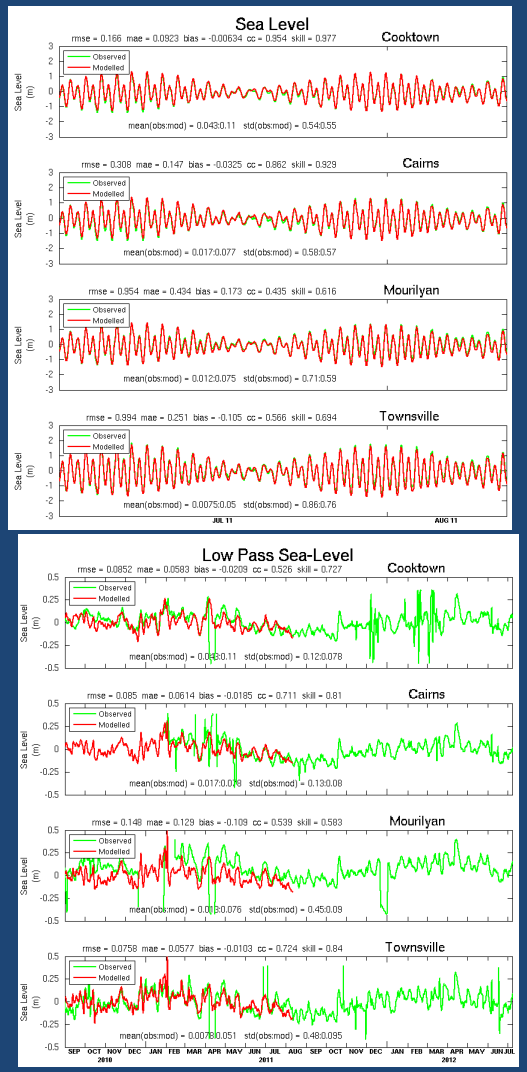
- With two target velocities (V_T and V_L) and time-scales (τ_T and τ_L):

$$V'_{BT}=V_B-\frac{\Delta t_{2D}}{\tau_T}(V_B-V_T)$$

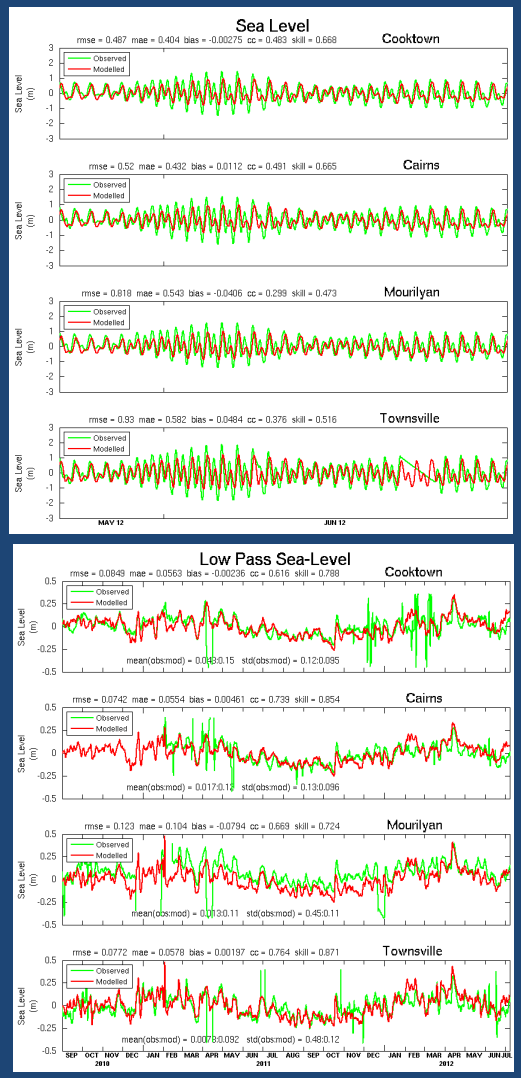
$$V'_{BL}=V'_{BT}-\frac{\Delta t_{2D}}{\tau_L}(V'_{BT}-V_L)$$

- V_B = old boundary velocity, V_T = boundary velocity required to achieve tidal target exactly and V_L = boundary velocity required to achieve low frequency target exactly.

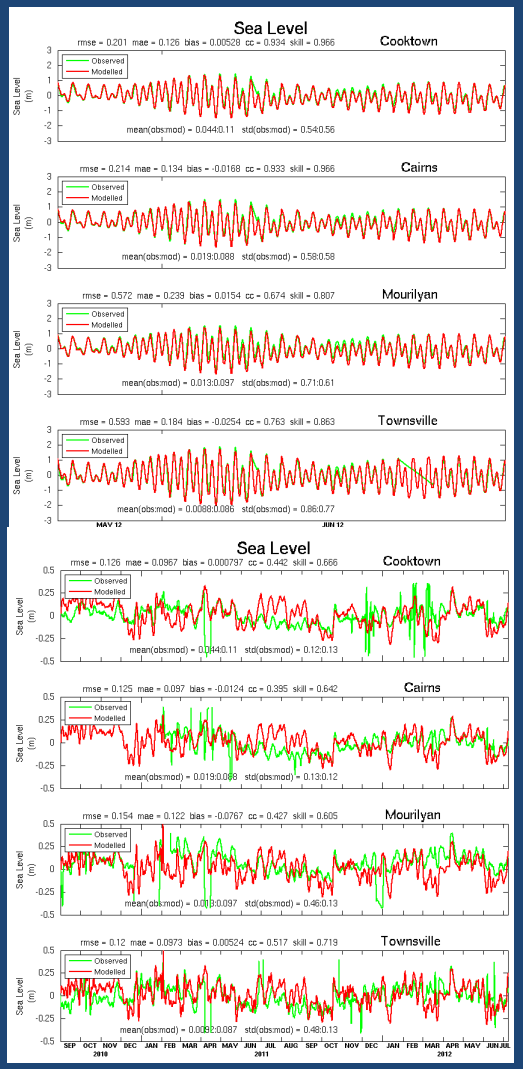
Optimum sea level achieved with dual relaxation



Hard relaxation (unstable)
OBC over-specification



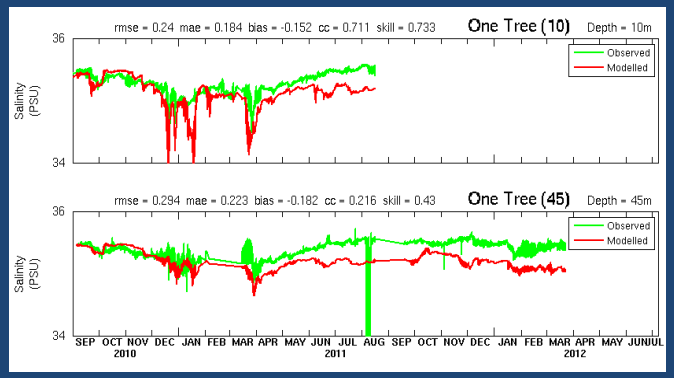
'default' relaxation (tide suffers)
OBC under-specification



Dual relaxation (optimum)

River inflow : 3 issues

- Fresh (S = 0) input at the coast results in the lagoon becoming too fresh.



- A simple inlet at the coast generates a numerical response,
  - Type 1 plume: steady state with small offshore bulge, downstream coastal current and no upstream intrusion,
  - Type 2 plume: non-steady upstream intrusion with anticyclonic circulation into the downstream coastal current,
  - Type 3 plume: non-steady growing offshore bulge with negligible coastal current.
- Point source and flow inputs require a predefined depth distribution.

Dynamic salinity input

1. Analytic halocline depth at the estuary mouth (Keulegan, 1966)

$$H_{ck} = H(1 - \frac{1}{2^{2/3}}\left[\frac{2v_r}{v_\Delta}\right]^{2/3}$$

2. Prescribe a parabolic velocity profile at the boundary face with vertical integral equal to river flow.

$$v_{OBC}(z) = \frac{Flow}{\int_{-H_{ck}}^{\eta}(z - H_{ck})(z + H_{ck})h_{OBC}dz}(z - H_{ck})(z + H_{ck}) \qquad z > -H_{ck}$$

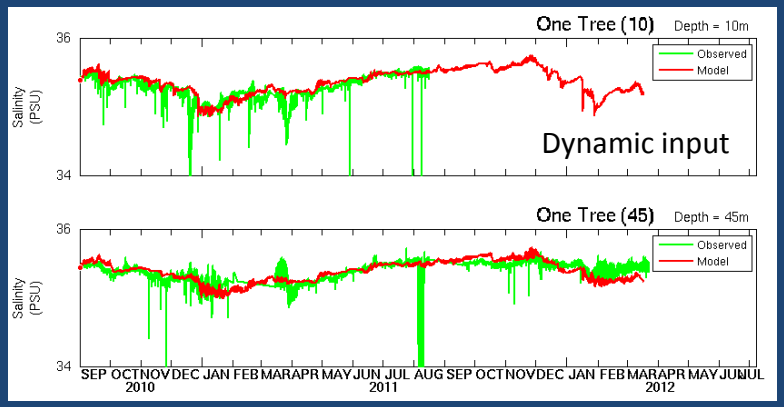
3. Compute density in 'ghost cells' and modify parabolic river profile with baroclinic contribution:

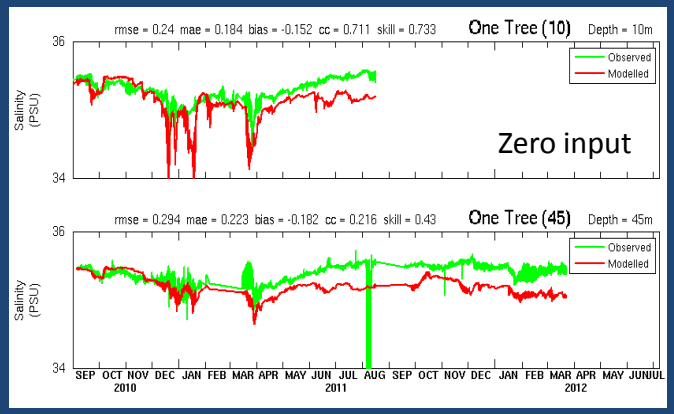
$$v_{BC}(t,z) = \frac{g}{h\rho}\int_{z}^{\eta}\frac{\partial\rho}{\partial n}dz$$

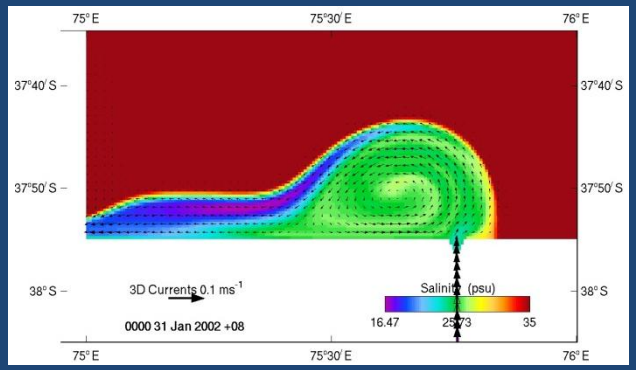
4. Modify the 'ghost cell' salinity using upstream advection:

$$S_g^{n+1} = S_g^n + \frac{\Delta t}{h}\left[(\mathrm{v_{OBC}} - |\mathrm{V_{OBC}}|)(S_{B-1} - S_B) + (\mathrm{v_{OBC}} + |\mathrm{u_B}|)(S_B - 0)\right]$$

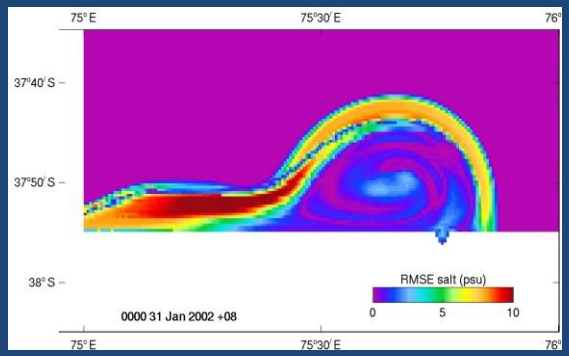
Dynamic input performance



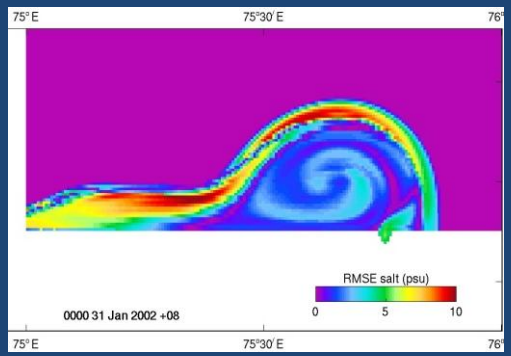




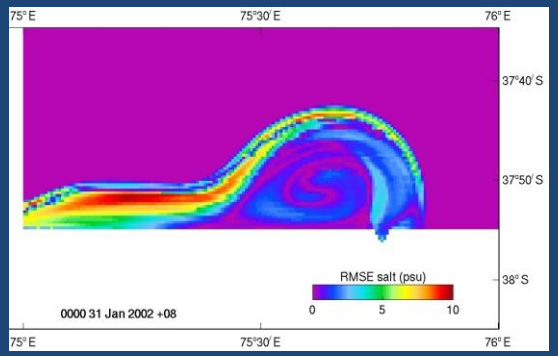
Baseline response where the estuary is resolved to beyond salt wedge propagation



Simple inlet with flow input

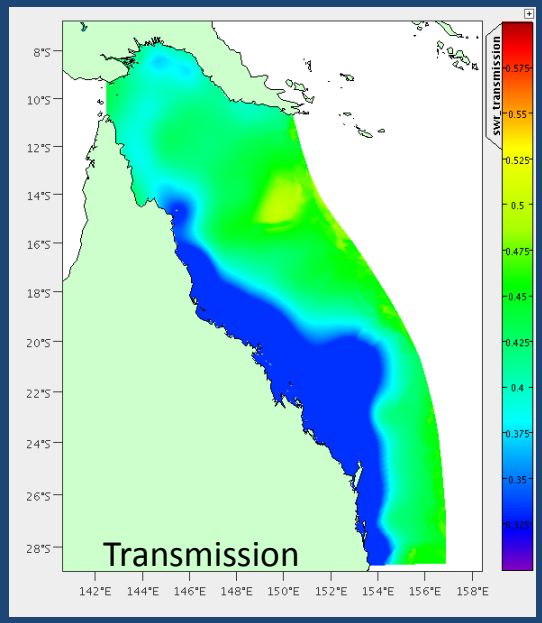


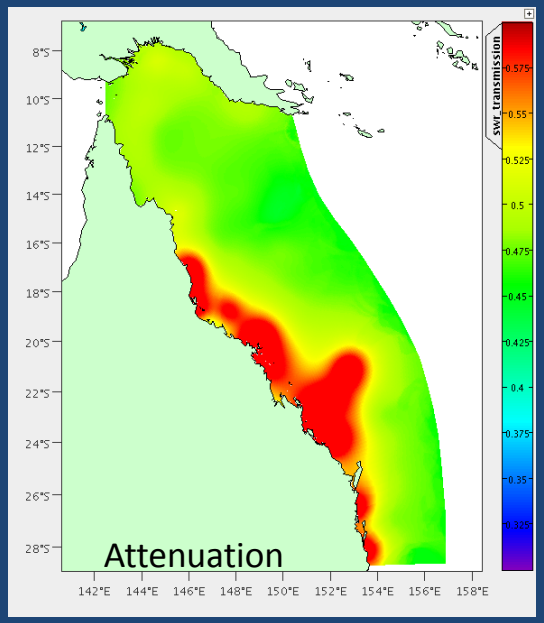
Simple inlet with point source input

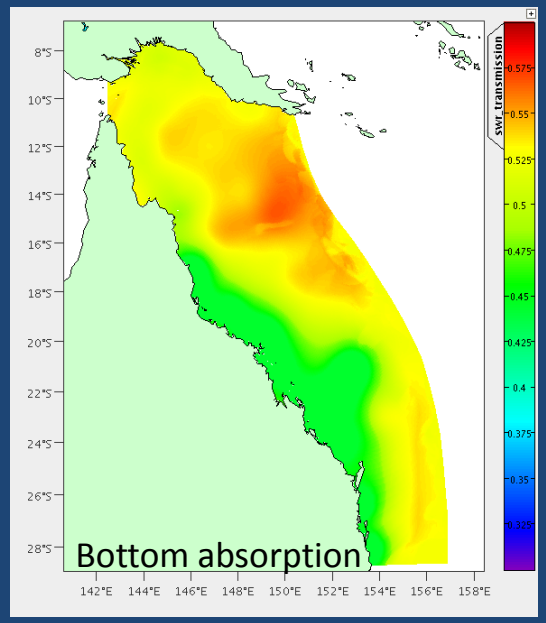


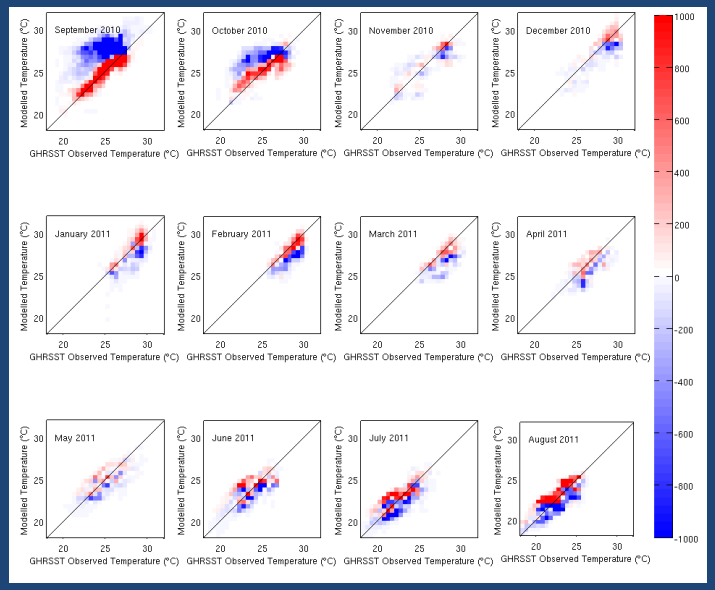
Simple inlet with dynamic input

SWR parameterization using EnKF





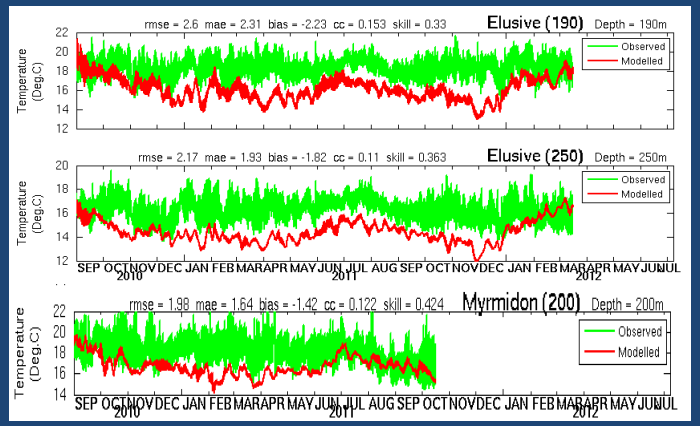




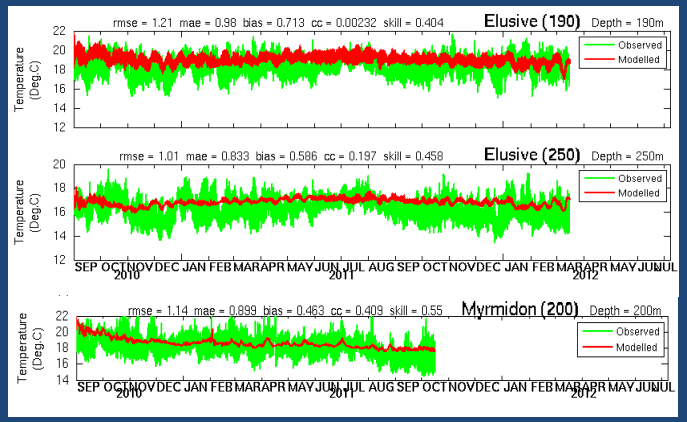
Difference between 2D histogram of control run (atten=0.1, trans=0.7, abs=0.5) and assimilated run. Red denotes areas where the assimilated data density has moved to from the control run.

Global model forcing: BRAN3.5 vs OceanMAPS

- OceanMAPS = operational product, BRAN3.5 = re-analysis
- OceanMAPS contains bias in 200-500m range,
- Forcing with BRAN3.5 results in a superior solution,
- First order improvements in model skill can be accomplished by removing the bias in forcing data, using DA methods.



OceanMAPS

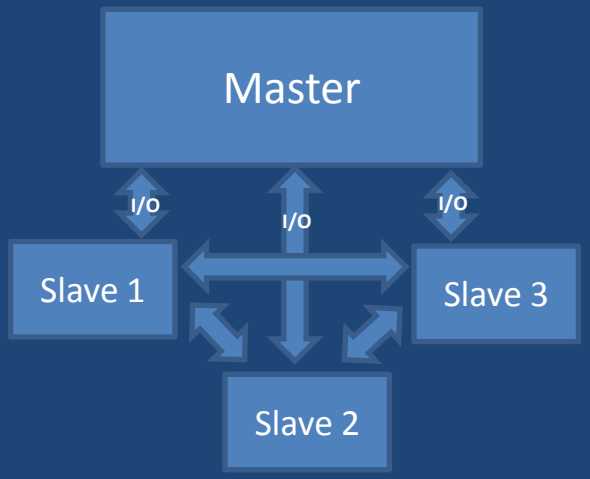


BRAN3.5

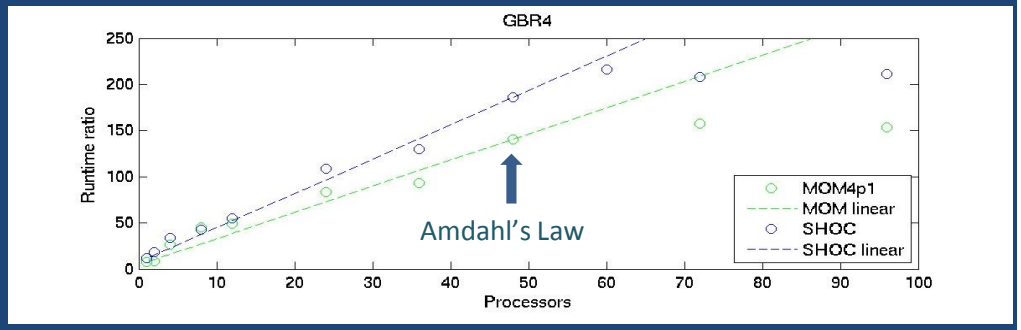
Slave-slave distributed processing

GBR1 = 1.2M surface cells, 24%wet.
GBR4 ~ 40:1, GBR1 ~ 2:1 (12PEs)

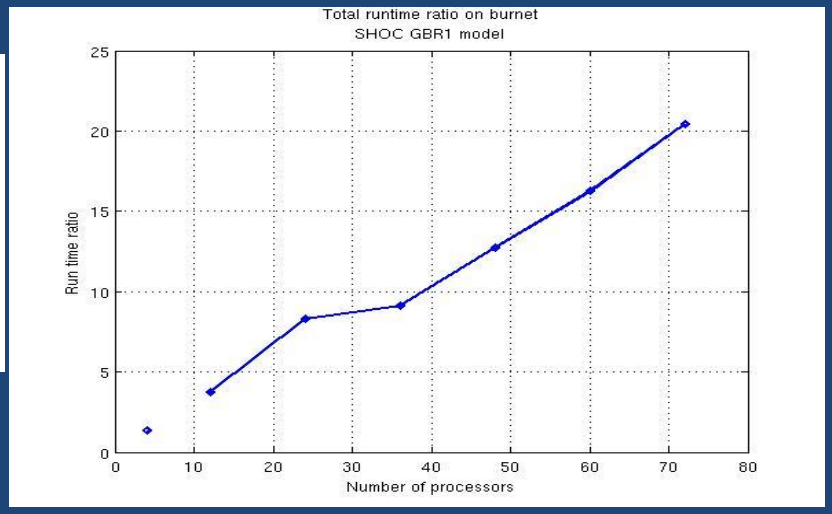
Master-slave distributed processing



Slave-slave distributed processing

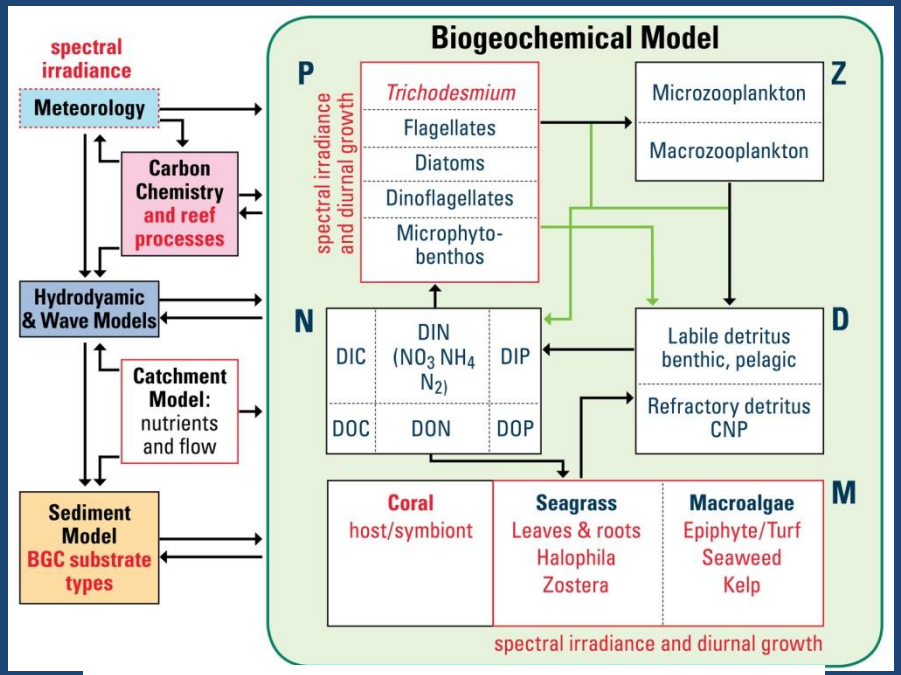


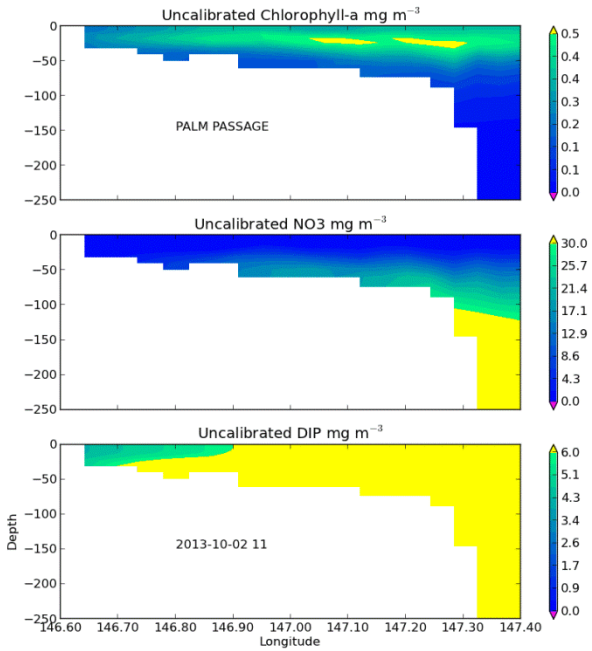
MOM4p1 vs SHOC on 4km grid

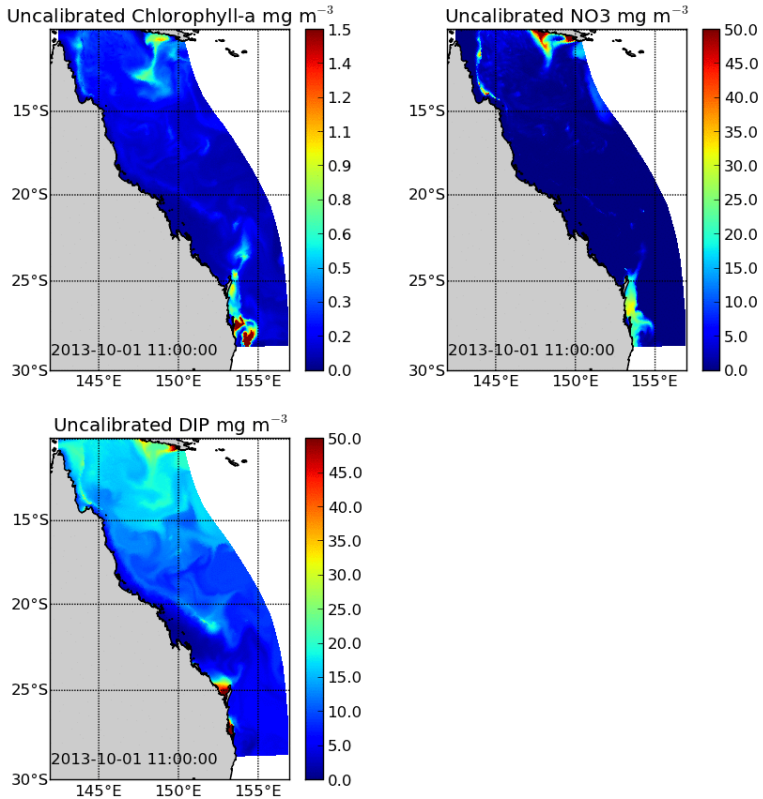


SHOC on 1km grid

BGC model


Biogeochemical Model
spectral irradiance
Meteorology
Carbon Chemistry and reef processes
Hydrodyamic & Wave Models
Catchment Model: nutrients and flow
Sediment Model BGC substrate types
P
spectral irradiance and diurnal growth
Trichodesmium
Flagellates
Diatoms
Dinoflagellates
Microphyto-benthos
Z
Microzooplankton
Macrozooplankton
N
DIC
DIN (NO_3 NH_4 N_2)
DIP
DOC
DON
DOP
D
Labile detritus benthic, pelagic
Refractory detritus CNP
M
Coral host/symbiont
Seagrass Leaves & roots Halophila Zostera
Macroalgae Epiphyte/Turf Seaweed Kelp
spectral irradiance and diurnal growth


Uncalibrated Chlorophyll-a mg m^{-3}
PALM PASSAGE
Uncalibrated NO3 mg m^{-3}
Uncalibrated DIP mg m^{-3}
2013-10-02 11
Depth
Longitude


Uncalibrated Chlorophyll-a mg m^{-3}
Uncalibrated NO3 mg m^{-3}
Uncalibrated DIP mg m^{-3}
2013-10-01 11:00:00
15°S
20°S
25°S
30°S
145°E
150°E
155°E